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# Failure consequences in flood engineering

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## Abstract

When a dike breach occurs, huge amounts of water will flow into the protected area causing substantial damage in most cases. These damages are multi-dimensional and relate to the vulnerability of human, economic and environmental values. Consequences are far from deterministic. Differences in time and place of breaches in the primary protection system may cause substantial differences in inundation patterns. Also the behaviour of internal elements like roads and regional dikes is unpredictable. Different flood patterns in their turn will give rise to completely different consequences in the various damage categories. Additionally, flooding of one area may or may not have influence on the safety of other regions. Questions related to uncertainties encountered in the consequence analysis will be addressed. The first issue is about dealing with uncertainties in estimating the risks and subsequently how to deal with them in the decision analysis. How do uncertainties affect the optimal mitigating measures, both from the economic optimization point of view as also from the aspect of human safety.

## 1. Introduction

Protection against floods is an essential and basic activity in many parts of the world. The annual numbers of casualties following from floods and the economic damages are very high. The selection of proper measures is a common task for governmental and local decision makers in cooperation with many experts in social and engineering sciences. In this process, risk analysis and risk management are becoming increasingly a generally recognised tool.

However, carrying out a risk analysis is a difficult engineering job and it may be even more difficult to communicate the results and implications with other people like politicians and citizens. What do the result actually mean, in particular if risks are partly based on subjective Bayesian probability estimates? In addition, what level of risk is acceptable, especially in the low probability high consequence category? Do people accept safety differentiation if they happen to live in the lower safety area.

The acceptance criteria themselves are a matter of political debate. Once established, laws and habits need to be updated from time to time due to a continuous change of circumstances and insights. If risks are considered as being too large for direct acceptance, one should look for adequate measures. Possible measures can be technical as well as administrative, and may cover a wide range of measures in the safety chain, including:

-The design and maintenance of the hydraulic infrastructure (dikes, sluices, etc.);
-The use of retention areas;
-Measures, taken shortly before or during the flood (e.g. evacuation);
-Rescue operations, taken in case of an actual flood.

Usually, an economic and societal balance between measures and risk reduction should be achieved. In the end, one has to accept the (remaining) risk.

## 2. General approach

Failure of flood protection systems may be caused by heavy rains and storms but also by events like human errors, ship collision, structural failures and so on. These hazards may cause the development of initiating events like one or more dike breaches. For a discussion on the probabilistic analysis of these systems and the calculation of the failure probability $P_F$, reference is made to (Steenbergen et al, 2004, and Vrouwenvelder, 2001).

The consequences of a breach have to be derived from simulation calculations that are based on an integrated model of the river or sea system and the flooded area. The results of a flood simulation are items like water depth, rise, flow velocity, wave height, duration and water quality. Next, more specific consequences are quantified depending on data like land use, building characteristics and population distribution. Consequences of floods may be classified into a number of categories, as for example:

- Casualties: fatalities and (mental) injuries;
- Damage to buildings, infrastructure and other material goods;
- Direct economic losses to industry and agriculture;
- Indirect economic losses due to the disruption of production chains;
- Ecological and cultural losses.

If the consequences are deterministic and do not depend on the particular failure scenario, the risk may be written in the well known standard form:

$$R = P_F\, C. \qquad (1)$$

where $P_F$ is the (annual) failure probability and $C$ is a numerical number representing the consequences of failure, for instance expressed in monetary units. In most cases, however, consequences are not deterministic and may also depend on the failure scenario, which then leads to:

$$R = E(C) = \sum_i P_i E\{C_i\} \qquad (2)$$

Here $P_i$ is the annual probability for branche or failure scenario $i$ and $E(C_i)$ is the expected value that may be associated with the corresponding adverse consequences. In this paper $C_i$ is supposed to be positive. Negative values of $C$ (indicating benefits) are treated separately. Note that branches scenarios represent exclusive sequences of events. Consequently, the sum of $P_i$ is equal to the probability of failure: $P_F = \Sigma P_i$.

Usually, a standard reliability analysis does not lead to a set of scenario probabilities, and it may be necessary to do some post processing. Consider as an example a small system of two dike elements. In that case, we would have to calculate:

$$R = P_1\, C_1 + P_2\, C_2 + P_{12}\, C_{12} \qquad (3)$$

where $P_1$ is the probability that only element 1 fails, $P_2$ the probability that only element 2 fails and $P_{12}$ the probability that both elements fail. If inundation does not change the physical conditions, we simply have:

$$P_1 = P\ (Z_1<0) - P\ (Z_1<0 \cap Z_2<0) \quad (4a)$$
$$P_2 = P\ (Z_2<0) - P\ (Z_1<0 \cap Z_2<0) \quad (4b)$$
$$P_{12} = P\ (Z_1<0 \cap Z_2<0) \quad (4c)$$

However, in most cases the conditions are for each scenario depend on the physical circumstances. For instance, if the weakest element fails first in time, it may unload the other element. As a result that element will not fail at all and consequently $P_{12} = 0$. This is a reasonable scenario for river dikes. In that case the values of $P_1$ and $P_2$ follow from ($Z$ being the limit state function for failure):

$$P_1 = P\ (Z_1<0 \cap Z_1<Z_2) \quad (5a)$$
$$P_2 = P\ (Z_2<0 \cap Z_2<Z_1) \quad (5b)$$

indicating that one element fails and the other element is stronger. Note that this formulation requires a similar metric for both mechanisms $Z_1$ and $Z_2$ that enables a direct comparison. For other types of dike failure mechanisms, the downstream elements may be unloaded, but not the upstream ones. In that case we have, element 1 being the upstream element:

$$P_1 = P(Z_1<0) \quad (6a)$$
$$P_2 = P(Z_2<0 \cap Z_1>0) \quad (6b)$$

Actually, we should also include the hydraulic circumstances, as they may influence the course of events. We will revisit this issue in section 4.

## 3. Consequences

Consequence analysis in the case of flooding starts with a hydrodynamic calculation of water flow from the river, sea or lake into the flooded area. This requires a good description of the terrain, preferably using a GIS model and a two dimensional flow model. The model should take account of the interaction between the water in the area and the water in the river or on the lake. There is also an interaction with the development of the breaches: water movements depend on the breach dimensions but breach development also depends on the water flow velocities.

Given the hydraulic consequences of a flood, the consequences in terms of economic losses and loss of life should be quantified. In the Netherlands a standard for the estimation of consequences in case of flooding has been developed (Vrisou van Eck and Kok, 2000). The basic formula is given by:

$$C = \Sigma\ n_k\ \alpha_k\ (d, v,..)\ c_{k\ max} \quad (7)$$

where $c_{k\ max}$ is the maximum possible loss, $n_k$ the number of objects (or square kilometres) and $\alpha_k(d, v,..)$ a reduction factor between zero and one, depending on the local flood characteristics like the water depth $d$, the flow velocity $v$ and so on. The index $k$ refers to the various damage categories like roads, buildings, agriculture and so on. The loss for some area may be calculated by means of a GIS model, combining the geographical information and flood characteristics.

The damage inflicted to the economy in case of a flood may be subdivided into direct damage (damage to capital goods in the dike-ring area) and indirect damage (interruption of production). Direct damage consists of loss of properties, recovery damage to recourses and recovery damage to production means. The direct losses include the loss of production for a certain period after the flooding. Floods will also affect lifelines like gas, water and electricity supply systems, infrastructure for transport and so on. The direct damage is a function of the water depth (and sometimes other flood factors) on the site where the properties are located. Indirect economic losses refer to impact of the flood on a larger economic system. For instance, flooding may lead to a blockade of roads and railways, and hamper economic activities in area that may be outside the flooded area. The indirect damage may be calculated according to a so-called 'input-output model' assuming that 50% of the production loss is overtaken by areas outside the dike-ring (Van der Veen, et al, 2003).

Loss of life may be the result from drowning or from indirect causes like collapse of a building, a heart attack or electrocution. Drowning is affected by the water depth, the current and the rapid rising. Like in other fields of risk analysis, also in flood analysis dose response function can be used to estimate the individual probability of death (Jonkman, 2007). The total number of fatalities in a group is found by summing up the individual outcomes. The variability in the number of fatalities will be determined by dependencies between individual failures. In case of large dependency, we have for a given flood a fixed number of casualties. In the case of independency, we have a mean and a scatter.

The probability of drowning may be reduced when evacuation is carried out. Barendregt et al. (2002) developed a simple conceptual method to simulate a preventive evacuation. Such a preventive evacuation consists of three stages: the decision-making, initiation of the evacuation, and the evacuation itself. The time needed for each phase depends on the degree of preparedness, the number of people to be evacuated and the available infrastructure. The available time for evacuation depends on the predictability of the water levels at sea or in the river and the failure mechanism. While extreme river discharges often can be predicted up to several days' ahead, extreme sea water levels have a much shorter prediction time (several hours). Failure of a dike is relatively easy to predict in case of overtopping, but is much more difficult to foresee in case of the failure mechanism piping. Note further that a good and successful evacuation requires a good communication with the population. People may do opposite as requested and stay at home, when asked to leave or vice versa.

## 4. Uncertainties in flood related consequences

If consequences are independent from the variables determining the failure process, one may calculate consequences and failure probability separately and find the risk by a simple multiplication, as indicated by (1). In many cases, and certainly for flood risk calculations, this however, is not the case. Consequences may for instance depend on the location of the failing element, the particular failure mechanism, the hydraulic and weather conditions leading to failure, the point in time when the breach occurs, the time scale of the erosion process and so on. One of the important uncertain issues in this respect is the development of other failing elements after the first breach. In the case of a storm surge induced inundation there probably will be more then just one failed dike section. The number of failed dike (or dune or structural) elements is very important with respect to the final inundation characteristics. In the case of river induced inundations, the inundation itself may influence the water levels on the river, upstream as well as down stream. In some cases this reduction may be sufficient to prevent further elements to fail, in other case it is not.

The flood characteristics inside the area of consideration, of course, also depend strongly on the behaviour of internal elements like roads, railways, levees and embankments. This behaviour is difficult to predict. In a similar way, the resistance of building structures in current and wave attack is highly uncertain, let alone the preventive or reactive human behaviour. Finally there is big epistemic uncertainty with respect to the consequence models discusses in section 4. Errors up to a factor of 2, both in maximum damage as in the depth-damage curves $\alpha_k(d, v,..)$ are easily imaginable. Similar statements can be made about the dose response functions in the loss of life estimates.

Of course also the degree of detailing in the model is a factor contributing to scatter. In principle, it is possible to model every house for collapse, every person for drowning and every car for evacuation. But these refined models will be too time consuming in the first place and may even be not reliable. The best strategy is probably to use the refined models for calibrating the simpler ones. At the same time these models should be calibrated to real world data as far as possible.

In cost benefit based decision analysis is usually sufficient to calculate the expectation of the damage. The scatter is in principle of no use. This, however, does not mean that we can neglect uncertainties in consequence analysis. In the first place, neglecting uncertainties may lead to incorrect estimates of the damage expectation, as in general $\mathrm{E}(C(\mathbf{X}))$ is not equal to $C(\mathrm{E}(\mathbf{X}))$, except for linear relationships. Another possible omission is the assumption that measures like the use of retention areas or evacuation will be deterministically successful. Also these measures have a probability of failure that should be taken into account. An evacuation started too late, for instance, may cost many lives.

## 5. Risk Calculation

At present, flood risk calculations in the Netherlands start with a straight forward probability analysis. Next a number of distinct and meaningful failure scenarios are determined, e.g. failure of section p and q by overtopping. Based on a crude post processing of the reliability calculations, the probabilities of each failure scenario are calculated. Next the consequences for each scenario are estimated by flood simulation and the final risk per year is calculated using (2). A worked example can be found in (Van Manen and Brinkhuis, 2003).

As the number of possible branches, however is too large for a really rigorous analysis, a new method is under development, which may be summarised in three steps:

- In *Step 1* a classical probabilistic systems analysis of the dike system performed, based on FORM analyses per mechanism and element. This way the failure probability $P_F$ is known.
- In *Step 2*, a set of say 10 000 Monte Carlo Importance Sampling runs is made, aiming at say a subset of 100 runs leading to failure.
- In *Step 3*, for this subset, a complete flood inundation simulation is started up, one or several per failure. For some of the internal variables, again, importance sampling may prove to be efficient.

Now, in principle, we could estimate the risk from:

$$R = E(C) = \frac{1}{N}\sum C(x,y)(f(x)/h(x)) \qquad (8)$$

The summation is over all runs leading to inundation, N is their total number or runs, $C(x,y)$ is the damage, $f(x)$ is the original multi dimensional probability density function, $h(x)$ the density function for the importance sampling and $x$ the vector of random variables responsible for initiating failure. The variables $y$ refer to the uncertainties after the initiating failure. In this formulation it has been assumed that no importance sampling with respect to these variables was necessary.
This formulation (8), however, might require quite a lot of simulations in order to get sufficient uncertainty. For that reason we may better derive from the Monte Carlo the conditional cost expectation:

$$E(C\,|\,F) = \sum \frac{C(x,y)}{I(x)}\frac{f(x)/h(x)}{f(x)/h(x)} \qquad (9)$$

where the denominator is the Monte Carlo Importance estimator of the failure probability. Next the risk may be estimated from:

$$R = \mathrm{E}(C) = P_F \, \mathrm{E}(C|F) \tag{10}$$

Where $P_F$ results from *Step 1* and $E(C|F)$ from *(11)*.The point is that we believe $P(F)$ from *Step 1* to be accurate enough and the determination of E(C|F) not so time consuming as (8) as the numerator and denominator in (8) are heavily correlated. Note for instance that in the case of C being deterministic, only one run is necessary. In order to assess how many Monte Carlo runs in *Step 2* are necessary, assume that we accept an error of 10 percent. A sufficient number of runs is then obtained if:

$$\sigma(C|F) / \sqrt{(N)} < 0.10 * \mathrm{E}(C|F) \tag{11}$$

Here N is the number of runs leading to inundation and $\sigma(C|F)$ and $\mu(C|F)$ are the estimators of the conditional mean and standard deviation following from the importance sampling.

In order to save time, the Monte Carlo calculation may be carried out on a set of parallel computers, one of them serving as master, the other ones (say about a hundred) being slaves. Each slave computer gets its own set of random variables and starts a simulation. If there is no failure, this result is passed on directly to the master and a new run may be started. If, however, there is a failure, all data will be stored for the third phase. The data consist our of the location of the failure, the failure mechanism, upstream discharge time functions, wind direction and velocity and resistance parameters for all potential second, third etc breach locations, breach properties, including possible random quantities

The above scheme holds for some relatively short tie span, one year or a part of it. The results need to be expanded to a period of say 50 years. If there are no time depending loads or deteriorating effects, we may use a transformation of the standard out crossing method to the risk domain:

$$R(T)= R(1)+(T-1)\,(R(2)- R(1)) \tag{12}$$

where $R$(T) is the risk for a period T (in years) and $R$(1) and $R$(2) are risks for 1 and 2 year periods respectively. Additionally corrections for discounting, deterioration and climate changes should be included.

## 6. Decision making and risk acceptance

The aim of a risk analysis is to judge whether the risk is acceptable, and if not, to decide on the measures to be taken. The acceptability of risks is usually judged against costs for reduction. Of course, one may argue that not all matters can be expressed in terms of money. It is indeed difficult to express the value of a human life as an amount of euros, but useful attempts have been made (Rackwitz, 2001, De Blaije, 2003). On the other hand, one should keep in mind that this amount is nothing more or less than help in making consistent decisions. If one does not accept those explicit considerations one is forced to make such decisions implicitly, leading to a result which probably is much less consistent and optimal.

In addition to the economic criterion often individual and societal risk criteria for human safety are considered. The individual criterion may be important when economic acceptable risks for a whole system lead to very high mortality rates for an identifiable small group of people. The societal risk limit is because society has a great aversion against accidents that lead to many casualties at once. The limits are usually presented in the form of so-called F-N-criteria.

At present Dutch dikes are designed according to load levels that are fixed in the law. The elements of flood protection should be designed in such a way that they can withstand safely hydraulic circumstances with return periods varying from 1000 year to 10000 year. To some extent, this is an easy criterion. At present we want to change this criterion to an explicitly risk based cost benefit criterion within a legal system. This is not an easy task. On the one hand, the notion of risk seems easier to communicate than the notion of reliability. Showing simulations of floods makes politicians and people very much aware of what might happen and they are in principle prepared to pay a price for protection. But it is difficult to find a legal basis for optimal decisions. Note for instance that they interact with may interact with other issues like urban planning or sail ability of the river. Maybe again a two step approach is necessary and a risk based translation into minimum reliability requirements is unavoidable.

## Closure

Based on principles like described in the paper, one may try to find optimal decisions for flood protection. What is better? Higher dikes, wider rivers, retention areas, evacuation or some balanced combination? Note that also this is a difficult decision problem as design parameters like the dike crest height may influence both the probability of inundation and also the consequences. Higher crest heights may lead to the later breach forming, less water, less damage and more successful evacuation.

Even if we succeed to find a mathematical optimum, this is an optimum for a certain individual or a certain group with common interest. Decision-making becomes more complex when the stakeholders with a variety of preferences or interests are present. Not everybody has the same view on the value of masterpieces of art or areas of a great importance for wild life. Even in a purely economic context, people will have different opinions, depending on how they may profit from certain mitigating measures. Finally, apart from "objective items" like probability and consequence, many more psychological matters may play an important role like the degree of voluntariness, the way the authorities are believed to control and assist in case of a disaster, the simple feeling of something being safe. The point is that a citizen is not only interested in "objective safety", but also or even more in a comfortable feeling of being safe. The conclusion is that the final decision about the safety measures is not the outcome of some mathematical calculation, but of a democratic process where many parties with conflicting interests may be involved, and emotions are judged to be at least equally important to arguments, based upon rational technical-, and decision theory.

One of the main difficulties in the communication about this topic is the divergence of perception for the keywords and numbers between the various partners. Among experts it may be reasonably clear what the definition is of words like probability, consequence and risk and how to deal with them in a rational decision making context. Other people, however, may have completely different opinions and are usually not easily inclined to follow the experts in this very sensitive topic. Especially if experts do not agree on all points, which may easily be the case for small probability large consequence events, there is a legitimate excuse to neglect the expert views completely. In those cases a non-expert is inclined to consider an imaginable event as likely and the other way around. In particular, recent disasters will increase the imaginability of related events. Events of long ago will generally be considered as being not very likely to happen in the present time area.

The final decision is the outcome of a political process where many emotional and psychological influences of individuals and groups may play a role. It is important to pay attention also to this part of the game as in the end only the decisions made in the politics are relevant. In the Netherlands this game has been played during the last 50 years, partly induced by incidents, partly based on special cases. However, the final design method was always to build dikes on the basis of design loads (with prescribed probability levels), given the river system and dike ring use as it was. Now, it is intended to develop risk based and cost benefit criteria, leaving open all options for optimization. For sure it will take some time before a new, operational and generally accepted method has been developed.

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