

Safe dams and dikes, how safe ?

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Abstract

Historically human civilisations have striven to protect themselves against natural and manmade hazards. The degree of protection is a matter of political choice. Today this choice should be expressed in terms of risk and acceptable probability of failure to form the basis of the probabilistic design of the protection. It is additionally argued that the choice for a certain technology and the connected risk is made in a cost-benefit framework. The benefits and the costs including risk are weighed in the decision process. A set of rules for the evaluation of risk is proposed and tested in cases. The set of rules leads to a technical advice in a question that has to be decided politically.

Keywords: Design, acceptable risk, risk aversion, hazards, dams, failure, flood .

1 INTRODUCTION

Over the centuries all human civilisations have been threatened by natural hazards like hurricanes, floods, droughts, earthquakes, etc, that claimed the lives of individuals or entire groups bound by their residence or profession. Many activities have been deployed to protect man against these hazards. Even today money is spent to avoid or prevent natural hazards, because the consequences in developed societies have increased considerably. Other more recent hazards are man-made and result from the technological progress in transport, civil, chemical and energy engineering. One of the tasks of human civilisations is to protect individual members and groups against natural and man-made hazards to a certain extent. The extent of the protection was in historic cases mostly decided after the occurrence of the hazard had shown the consequences. The modern approach aims to give protection when the risks are felt to be high. This gives rise to the rather novel idea of acceptable risk.

As long as the modern approach is not firmly embedded in society, the idea of acceptable risk or safety may, just as in the old days, be quite suddenly influenced by a single spectacular accident as the catastrophe at Chernobyl, the plane crash at Schiphol airport in 1992, or even by non-calamitous threats like the Dutch river floods of 1993 and 1995. Here the political process is at work and public opinion is influenced not only by the accident itself, but also by the attention paid to it by the media and the politicians.

However according to the modern approach the politicians in an advanced technological society should not base their decisions to provide protection fully upon the above mentioned subjective and historical ideas of acceptable risk, but also use the outcome of risk analyses and probabilistic computations as a more objective basis. As the notion of probability of failure and the consequent risk forms the basis for the design of many technological systems, from simple river levees via multi-purpose dams to advanced jumbo-passenger-jets, that contribute to the welfare of modern nations, politicians should have an objective set of rules for the evaluation of risk. This paper proposes of a possible set of ideas that may serve as a rational and more objective basis for technological design.

2 HISTORICAL DEVELOPMENT OF DIKES AND DAMS

Although many contemporary academics would like to let us believe otherwise, the construction and the maintenance of dikes and dams has in most cases greatly benefitted mankind. This cannot be refuted by pointing to the few cases where the engineering predictions have not become completely true or where unforeseen natural effects have reduced the benefits.

A short sketch of the historical development will show why mankind built dikes and dams and still intends to maintain and construct them in future to some considerable extent.

Around 0 A.D. the people in the delta of the Meuse and the Rhine lived on fertile but marshy soil that was regularly flooded by river floods and during winter storms by sea water. Especially the salty and unexpectedly rising storm surges threatened not only the fertility of the land but also human lives, livestock and housing. To protect their families, their cattle and their houses the people started to erect clay mounds to live on. This proved to be a beneficial solution. However the growing population and the secular rise of the sealevel made the more frequent flooding of land and the consequent damage less acceptable. The far reaching invention was to connect the mounds with dikes as flood protection for the cultivated areas. The wealth of the people grew after this considerable investment in technology. It is however frequently forgotten by engineers that this innovation could flourish only because governmental structures were established simultaneously. Where the erection and the maintenance of terps could be organised within one family, the management of a dike system required the orderly and reliable cooperation of a group of families. To share the burden of investment and maintenance democratic waterboards were erected, that still exist today..

In the course of time the sea level kept rising and the land that was now gravity drained settled more than before. This forced the waterboards, after a period of implementing ever more sophisticated methods of draining by gravity, to install windmills.. The necessity of this new investment was clear as increasing numbers of the population had started to live beside the mounds. The effectiveness of this rather costly new technological step forward showed itself in an increasing wealth of the ever growing population. The improved artificial drainage increased however not only the agricultural yields, but also the settlement of the soil as is shown in Fig 1.

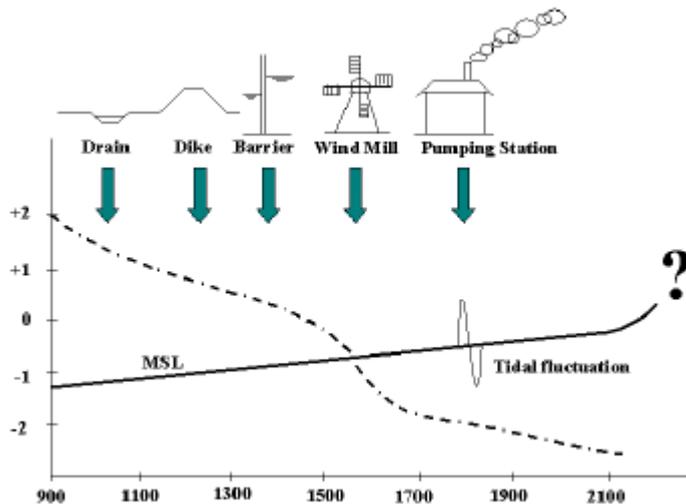


Figure 1: Rising sea and sinking land.

The solution came with the advent of fossil fuels. The limits of windpower were overcome by installing coal and oil fired pumping stations, that could be operated more precisely with respect time and level. The

improved living conditions induced once again an increase of population numbers. The inhabitants of the polders showed their trust in the technology of dikes and drainage systems by building the required new towns preferably in the deepest parts of the polders.

Even today only engineers ponder about the growing risk, that results from the increased number of inhabitants of the deepest parts of the polders. The safety of the dikes is no matter of public discussion, also the incredible wealth and welfare is taken for granted, only the damage to “nature” caused by dike maintenance is severely criticised

For dams in rivers a similar history can be painted. A natural river flowing down a valley could sustain the living of a few people. The hydrological cycle of the river limited the population. The river threatened their livelihood by increased water levels and discharges during the wet season and by lack of water during the hot season. The first problem could be reduced by choosing higher grounds to settle, weighing the cost of transporting water against the risk of flooding. The second was less easily solved.

Damming the river and storing the water behind the dam for use during dry periods was a great invention, assuming that floods could be passed over or through the dam when needed.. The increased reliability of the water supply over a longer part of the year improved agricultural yields considerably. Investments in irrigation systems could be defended on the basis of the more stable water supply. The healthy and growing population required and could afford to increase the capacity of the dam and the related storage. This was especially true, because the higher head improved the efficiency of power generation. The continuous availability of water and power formed the basis of growing wealth which stimulated a further increase in the number of people living downstream of the dam.

Moreover the increased capacity of the dam had also reduced the probability of flooding of the downstream area, thus adding to the availability of safe living space. In recent times the recreational possibilities of the reservoir may certainly have enhanced the attractiveness of living in the neighbourhood of an existing dam. So for various reasons the population down stream of a dam has grown in living memory. These people seldom think of or discuss the remote possibility that the dam may fail, but enjoy it's benefits. The remote prospect of failure, is what makes some engineers in the ICOLD community nervous. This is caused by the enormous havoc that the flood wave will make in the densely populated valley downstream of the dam, not by their lack of trust in the safety of the dam. They know from engineering education and from the experience of many years of dam operation , that the probability of failure is less than 1./10,000 dam years. The ensuing catastrophe could however be beyond human imagination. The dam engineers would like to share the responsibility for the choice which risk is acceptable with the general public.

3 RISK OF FLOOD

Although the probability of failure of well designed and constructed dams and dikes is very remote, the consequences can be extremely varied and large. Considerable numbers of people could lose their lives, most of the property in the threatened area will be damaged, income in the immediate future will be lost due to the incredible loss and disturbance, heritage and works of art will vanish and the environment will be threatened directly by the force of the water and indirectly by the release of toxic substances from chemical installations destroyed by the flood waters.

The risk consists of two components that together indicate the level of risk. The first is the probability of failure of the dam or dike. Failure may be caused by technical causes that are more or less familiar to dam- and dike engineers like overtopping, sliding, piping, etc. as sketched in the faulttree of Fig 2

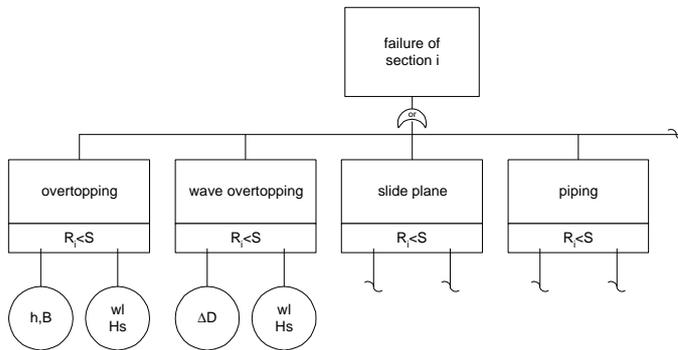


Figure 2: A section of a dam or dike as a series system of failure modes.

Less obvious to classical engineers is however that management mistakes may also lead to failure. A small example for a sluice or a spill way gate is given in Fig 3. One should realise that generally the probability of human failure is larger than of technical failure. The total failure probability of the dike or dam system is found by combining all failure modes of all elements as shown in the table 1

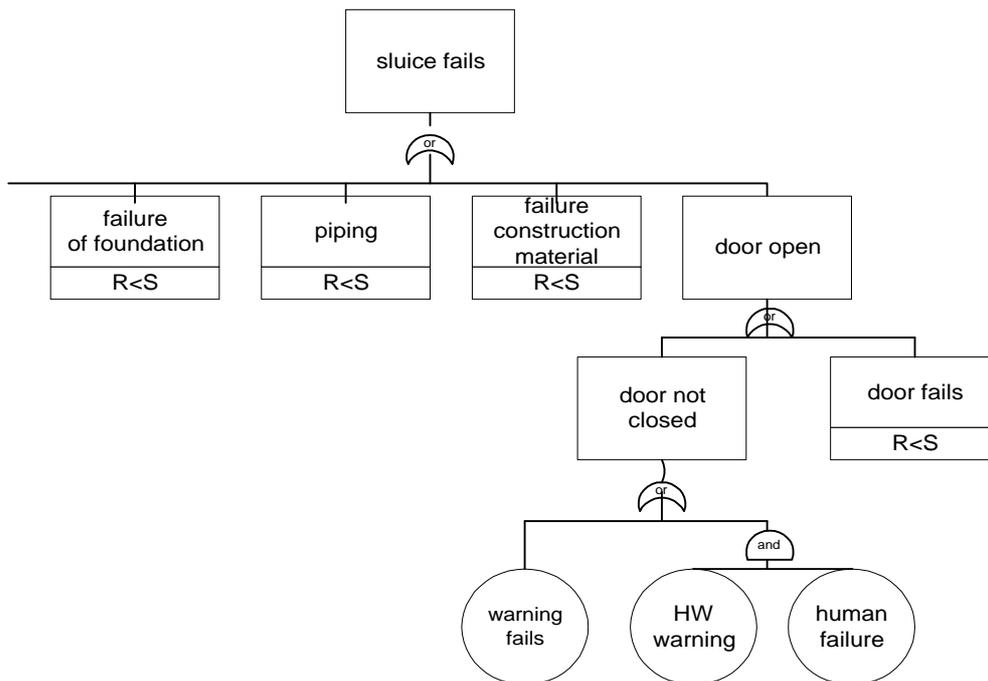


Figure 3: The failure of a sluice caused by technical or human failure. A spillway gate could fail to open due to similar causes.

| section | Overtopping | Piping | etc. | total |
|------------------|---------------------------------------|------------------------------------|----------------------------------|---------------------------------|
| dike section 1.1 | $p_{1.1}(\text{overtopp.})$ | $p_{1.1}(\text{piping})$ | $p_{1.1}(\text{etc.})$ | $p_{1.1}(\text{all})$ |
| dike section 1.2 | $p_{1.2}(\text{overtopp.})$ | $p_{1.2}(\text{piping})$ | $p_{1.2}(\text{etc.})$ | $p_{1.2}(\text{all})$ |
| etc. | .. | .. | .. | .. |
| Dune | $p_{\text{dune}}(\text{overtopp.})$ | $p_{\text{dune}}(\text{piping})$ | $p_{\text{dune}}(\text{etc.})$ | $p_{\text{dune}}(\text{all})$ |
| Sluice | $p_{\text{sluice}}(\text{overtopp.})$ | $p_{\text{sluice}}(\text{piping})$ | $p_{\text{sluice}}(\text{etc.})$ | $p_{\text{sluice}}(\text{all})$ |
| Total | $p_{\text{all}}(\text{overtopp.})$ | $p_{\text{all}}(\text{piping})$ | $p_{\text{all}}(\text{etc.})$ | $p_{\text{all}}(\text{all})$ |

Table 1: Calculation table for the overall probability of flooding of a polder defended by dikes, a dune and a sluice (Vrijling, 2001)

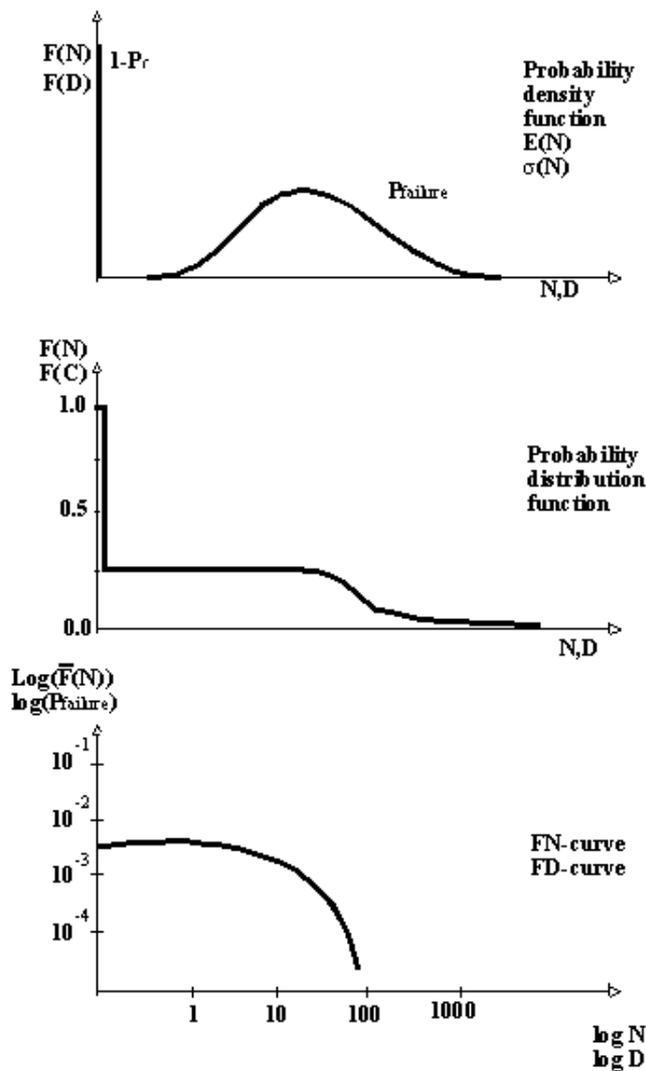


Figure 4: Risk of flooding.

As pointed out the consequences of a flood are varied and large. To simplify this complicated picture of the consequence of such a disaster and to make it countable and open to quantitative analysis the losses are mostly schematised. In many practical cases the specified level of harm is limited exclusively to the loss of life N . In other cases (Dantzig et al. 1956) the description of the damage is reduced to the counting of the material loss D in monetary units, in order to avoid the embarrassing discussion of the number of threatened population that might not survive a major failure. Either schematisation is not necessarily representative. Most probably society will look to the *total* damage caused by the occurrence of a hazard. This comprises the number of wounded as well as casualties, the material and economic damage as well as the loss of or harm to immaterial values. It is important to realise this fact when one discusses safety issues with the general public.

The consequences in case of the flooding of polders or valleys will be estimated from two points of view. First an estimate of the probability to die for an individual residing at some place in the polder or valley will be given. The most practical form of presentation might be a contour plot of the risk as a function of the place in the polder or valley.

Secondly the total number of people that will drown in a flood must be estimated. If the specified level of harm is limited to the number of casualties the risk may be modelled by the probability density function (pdf) of the number of deaths. As the chance of failure of dams and dikes is generally very remote the pdf will show a large mass of $1 - p_f$ at the origin exemplifying the normal safe functioning without any problems. However to the right on the x-axis a part of the pdf with mass p_f will show the range of possible outcomes in terms of deaths if the dam or dike fails. Here p_f is the probability of failure. The performance of an integration from the right will produce the probability of exceedance curve of the number of deaths. This curve starts at 1 at the vertical axis and drops immediately to p_f also called the FN-curve due to a specific hazard. The FN-curve is commonly depicted on double-log axes as shown in the graph at the bottom of Fig 4. Thirdly the consequence part of a risk may also be limited to the total material damage expressed in monetary terms. The graphical presentation could be the same as indicated in Fig 4 exchanging N for D at the horizontal axis. As pointed out by Vrijling (1997) it is useful and illustrative to calculate the expected value and the standard deviation of N and D beside the graphical representation by the pdf or the FN/D-curve.

In many practical cases the FN-curve is calculated numerically, leading to a stepwise decreasing function as given in Fig 5. In this graph the effect of two categories of measures to reduce the risk can be indicated. If the safety of the dam or the dike is increased, the graph will be lowered. To narrow the FN/D-curve the maximal consequences of a breach must be reduced. This seems only possible by spatial planning measures like the restriction of new settlements to relatively higher grounds. A difficult proposition as any planner knows.

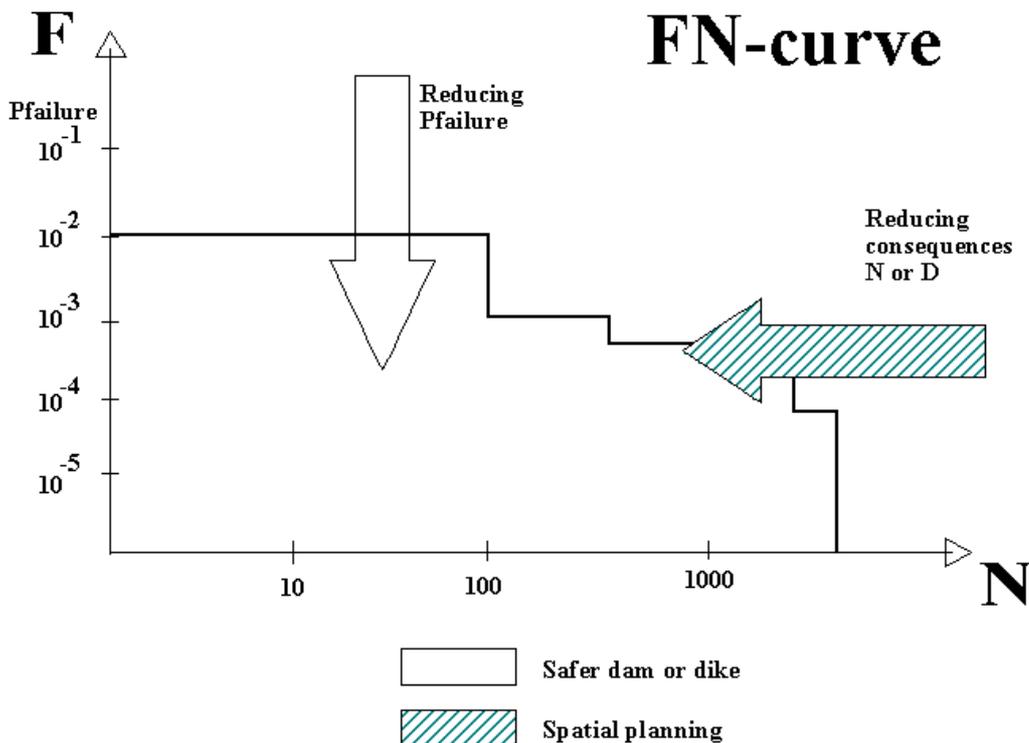


Figure 5: A numerically calculated FN-Curve.

It should be stressed again, however, that the reduction of the consequences of an accident to the number of casualties or the economic damage may not adequately model the public's perception of the potential loss. The aim of the schematisation is to clarify the reasoning at the cost of accuracy.

4 HOW SAFE SHOULD THE DAM OR THE DIKE BE ?

The most complex, controversial and sensitive issue that highly matters to society is the relation between classical engineering safety as guided by experience and codes on the one hand and the philosophies about acceptable risk levels, that have been evolving in some societies in recent years. The first ideas were developed for certain industrial activities sited in the neighbourhood of housing and offices (HSE, 1989 and VROM 1988).

The question of acceptable risk is sometimes explicitly but mostly implicitly at the basis of every engineering design decision. The popular request for absolute safety is unattainable, because it would require the spending of an unlimited amount of society's resources. In the design of dams and dikes all uncertainties have to be exposed and included to ensure that the trade off between reduced uncertainty i.e. extra safety and the required increased use of society's resources is explicitly made.

Clearly this involves a careful balancing of the costs to society of

1. the planning and design activities
 2. the construction of the dam or dike
 3. the area occupied by the structure
 4. the reduction (or the increase) of environmental values
- against the benefits
1. reliable water supply or living area safe from flooding
 2. reduced probability of loss of life
 3. reduced probability of material loss
 4. reduced probability of damage to the environment by toxic or other releases
 5. increased economic development and welfare

The well informed and scientifically based decision making that properly takes account of all uncertainties, costs and benefits is crucial in the process. Here guidance to arrive at a credible defensible and transparent risk analysis could be given, but the formulation of a standard for e.g. acceptable risk, is judged to be too difficult as it would require a generalisation of the cost/benefit decision for a range of hazardous activities. These decisions are related to the geographical situation, the economical development, the cultural values and the political system of each country.

Here an exposition will be given of the current thinking in the Netherlands and some neighbouring countries.

In most treatises of acceptable risk two positions are discerned. The point of view of the individual, who decides to undertake an activity weighing the risks against the direct and indirect personal benefits. And secondly the point of view of the society, considering if an activity is acceptable in terms of the risk-benefit trade off for the total population.

The first point of view leads to the personally acceptable level of risk or the acceptable individual risk, defined in ICE as "the frequency at which an individual may be expected to sustain a given level of harm from the realisation of specified hazards". It was explained above that in many practical cases the specified level of harm is limited exclusively to the loss of life.

Similarly the notion of risk in a societal context is reduced to total number of casualties using a definition as in ICE: "the relation between frequency and the number of people suffering from a specified level of harm in a given population from the realisation of specified hazards". If the specified level of harm is limited in this way the societal risk may be modelled by the FN-curve due to a specific hazard.

As stated above the consequence part of a risk may also be limited to the total material damage expressed as a FD-curve in monetary terms.

The smallest component of the social acceptance of risk is the assessment by the individual. Attempts to model this are not feasible, therefore it is proposed to look to the preferences revealed in the accident

statistics. The fact, that the actual personal risk levels connected to various activities show statistical stability over the years and are approximately equal for the Western countries, indicates a consistent pattern of preferences. The probability of losing one's life in normal daily activities such as driving a car or working in a factory appears to be one or two orders of magnitude lower than the overall probability of dying. Only a purely voluntary activity such as mountaineering entails a higher risk (Fig. 6).

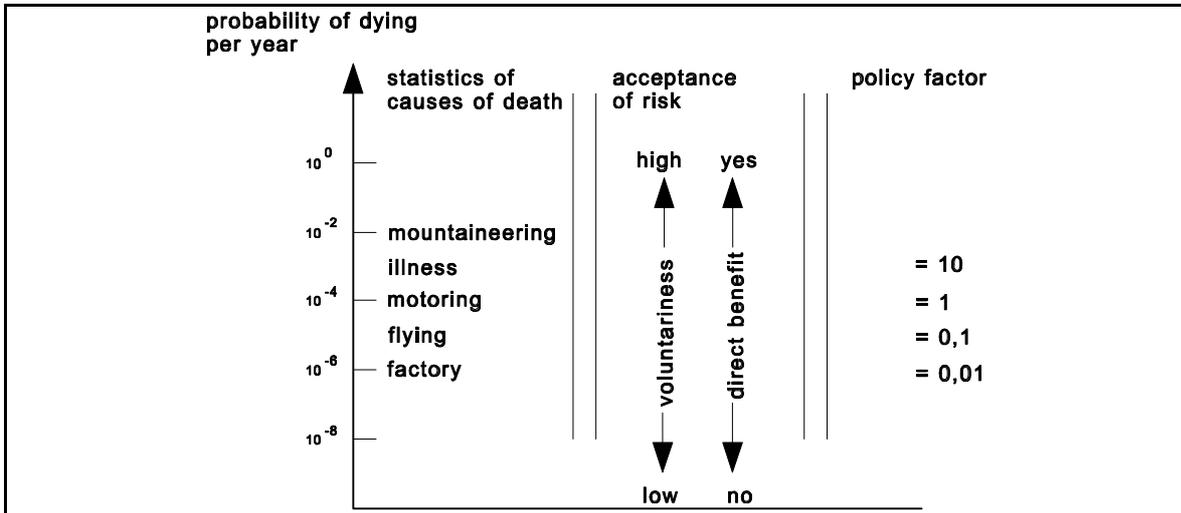


Figure 6: Personal risks in Western countries, deduced from the statistics of causes of death and the number of participants per activity

If one neglects a secular downward trend of the death risks due to technical progress, it seems permissible to use them as a basis for decisions with regard to the personally acceptable probability of failure of activity i in the following way:

$$P_{fi} = \frac{b_i \cdot 10^{-4}}{P_{d|fi}}$$

where $P_{d|fi}$ denotes the probability of being killed in the event of a failure. In this expression the policy factor β_i varies with the degree of voluntariness with which an activity i is undertaken and with the benefits perceived. This factor ranges from 100 in the case of complete freedom of choice like mountaineering, to 0.01 in case of an imposed risk without any perceived direct benefit, like the siting of a hazardous installation near a housing area. A proposal for the choice of the value of the policy factor β_i as a function of voluntariness and benefit is given in the table below:

| β_i | Voluntariness | Direct benefit | Example |
|-----------|---------------|----------------|----------------|
| 100 | Voluntary | Direct benefit | Mountaineering |
| 10 | Voluntary | Direct benefit | Motorbiking |
| 1.0 | Neutral | Direct benefit | car driving |
| 0.1 | Involuntary | Some benefit | Factory |
| 0.01 | Involuntary | no benefit | LPG-station |

Table 2: The value of the policy factor β_i as a function of voluntariness and benefit.

For the safety of dikes and dams a β_i -value of 1.0 to 0.1 is thought to be applicable.

The judgement of societal risk due to a certain activity should be made on a national level. The risk on a national level is the aggregate of the risks of local reservoirs or polders. Starting with a risk criterion on a national level one should evaluate the acceptable local risk level, in view of the actual number of reservoirs or polders, the cost/benefit aspects of the activity and the general progress in safety, in an iterative process with say a twenty to fifty year cycle.

The determination of the socially acceptable level of risk assumes also that the accident statistics reflect the result of a social process of risk appraisal and that a standard can be derived from them. The formula should account for well known risk aversion in society. Relatively frequent small accidents are easily accepted, while one single rare accident with considerable consequences like a flood (or more recently the fireworks disaster in Enschede and the pub-fire in Volendam) fills the newspapers for days, although the expected number of casualties is equal for both cases. The standard deviation of the number of casualties, that is much larger for the second case, reflects this difference to some extent.

Risk aversion can be represented mathematically by adding the desired multiple k of the standard deviation to the mathematical expectation of the total number of deaths, $E(N_{di})$ before the situation is tested against the norm of $\beta_i \cdot 100$ casualties for the Netherlands:

$$E(N_{di}) + k \cdot s(N_{di}) < b_i \cdot 100$$

where: $k = 3$ risk aversion index

To determine the mathematical expectation and the standard deviation of the total number of deaths occurring annually in the context of activity i , it is necessary to take into account the number of independent places N_{Ai} where the activity under consideration is carried out.

The translation of the nationally acceptable level of risk to a risk criterion for one single installation or polder where an activity takes place depends on the of the number of casualties for accidents of the activity under consideration. In order to relate the new local risk criterion to the FN-curve, the following type is preferred:

$$1 - F_{N_{di}}(x) < \frac{C_i}{x^2} \text{ for all } x \geq 10$$

The principle of the societal risk criterion limiting the risk of a single local installation is given in Fig 7.

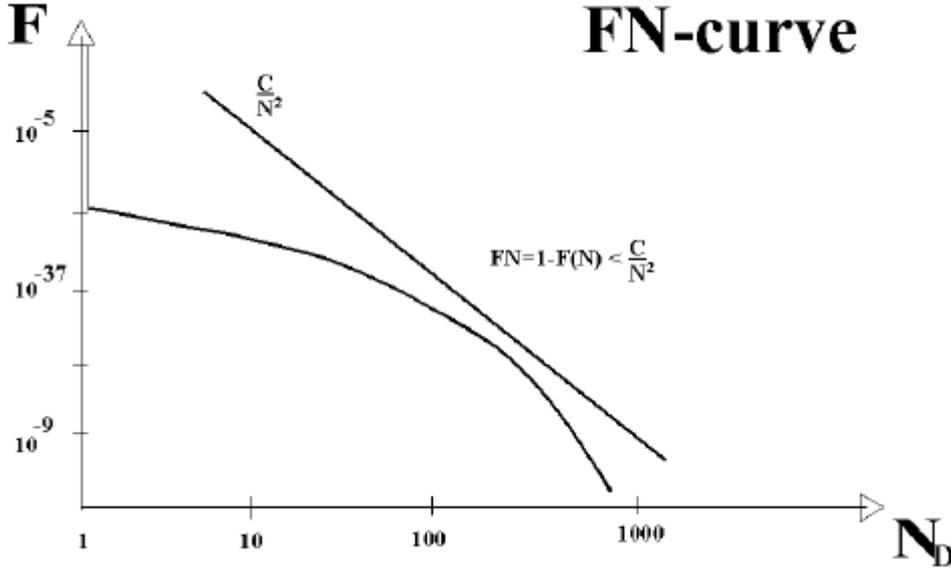


Figure 7: Societal risk criterion for the FN-curve at local level.

If the expected value of the number of deaths is much smaller than its standard deviation, which is often true for the rare calamities studied here, the value of C_i reduces to:

$$C_i = \left[\frac{b_i \cdot 100}{k \cdot \sqrt{N_{A_i}}} \right]^2$$

The problem of the acceptable level of risk can be also formulated as an economic decision problem as explained earlier. The expenditure I for a safer system is equated with the gain made by the decreasing present value of the risk (Fig. 8). The optimal level of safety indicated by P_f corresponds to the point of minimal cost.

$$\min(Q) = \min(I(P_f) + PV(P_f \cdot S))$$

where :
 Q = total cost
 PV = present value operator
 S = total damage in case of failure

If despite ethical objections, the value of a human life is rated at s , the amount of damage is increased to:

$$P_{d/fi} \cdot N_{pi} \cdot s + S$$

where N_{pi} = number of inhabitants in polder i .

This extension makes the optimal failure probability a decreasing function of the expected number of deaths. The valuation of human life is chosen as the present value of the nett national product per inhabitant. The advantage of taking the possible loss of lives into account in economic terms is that the safety measures are affordable in the context of the national income.

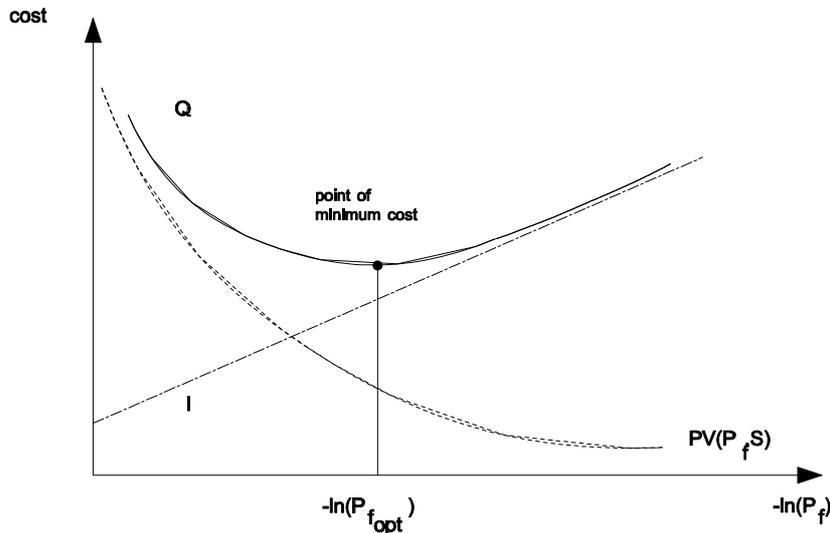


Figure 8: The economically optimal probability of failure of a dam or dike.

In assessing the required safety of a dike system the three approaches described above should all be investigated and presented. The most stringent of the three criteria should be adopted as a basis for the "technical" advice to the political decision process. However all information of the risk assessment should be available in the political process.

5 CONCLUSIONS

It is shown that contrary to what many contemporary academics would like to let us believe, the construction and the maintenance of dikes and dams has in most cases greatly benefitted mankind. This cannot be refuted by pointing to the few cases where the engineering predictions have not become completely true or where unforeseen natural effects have reduced the benefits.

A short sketch of the historical development showed that mankind built dikes and dams to improve living conditions, wealth and welfare. A consequence was the continuous growth of the population in polders and down stream valleys. It is reasonable to expect that mankind, especially in less developed areas, still intends to maintain and construct dams and dikes in future to some considerable extent.

The probabilistic approach has great advantages compared with the present classical engineering approach. The event that the dam or dike is meant to prevent (flooding), comes at the center of the analysis. The contribution of all elements of the system and of all failure mechanisms of each element to the probability of flooding is calculated and presented. The possibility to include the probability of human failure in the analysis of the management of the structures is especially attractive and useful.

Finally an approach is sketched to define the level of acceptable risk. The decision on the level of acceptable risk is a cost/benefit judgement, that must be made from individual as well as from societal point of view. A system of three rules is developed to support the decision how safe the dikes should be. The

individual acceptable risk criterium, the societal acceptable risk criterium and the economical optimal societal risk should all be calculated for a specific project.

The most stringent of the three criteria should be adopted as a basis for the "technical" advice to the political decision process. However all information of the risk assessment should also be made available to the political process. A decision that is political in nature, must be made open and democratically, because many differing values have to be weighed. The economic optimisation may however show that the economic activity in the polders and the areas down stream of dams has grown so much since the start of the 20-th century that a fundamental reassessment of the acceptability of the flood risks is justified. Moreover the image of the polders and valleys down stream dams as a safe areas to live, work, and invest in is an important factor to consider especially when the population continues to grow and ever more ambitious private and public investments are planned.

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