RISK ASSESSMENT AND RISK COMMUNICATION IN CIVIL ENGINEERING

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Public Perception of Safety and Risks In Civil Engineering

Risk Assessment and Risk Communication in Civil Engineering

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Preface

The design of buildings and civil engineering structures involves a consideration of safety, lifetime performance and environmental aspects. The risks may be related to structural collapse, collisions explosions and fires in buildings and in tunnels, flooding, accidents at industrial or nuclear plants, and so on. In this fundamental area of decision making about the safety, engineers have to communicate with their clients and the general public or, more usually, the politicians on its behalf. Communication between engineers themselves and between engineers and authorities, their clients or the general public is often difficult. Further the perception of some actual failure and the over-reaction to it, by both the public and the authorities, frequently prevents a rational treatment of similar structures in the future. In this report, the various aspects of this challenging subject are addressed. Both the risk evaluation and the decision making process will be treated. The fundamental question is "How much safety does society really need and what is it prepared to pay for that level or for a higher level is it insists"? Applications may be in all fields of building and civil engineering or in other fields where similar decisions are integral to the design process.

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Gratefully use as been made of comments given by the Joint Committee on Structural Safety.

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LIST OF SYMBOLS

A	parameter, (imaginary acceptable probability for n=1)
C_o	investment in a safety measure
C_j	damage costs in year j
D	damage
$E(..\|..)$	conditional expectation
$f(..)$	probability density function
F	failure event
$F(n)$	F-n-curve
g(..)	limit state function
j	number of the year
k	slope of the F-n-curve in a log-log-diagram
N_d	number people being killed in one year in one accident
$P(...)$	probability of some event
$P(d)$	annual death probability
$P(e_i)$	probability of event i
$P(d\|e_i)$	probability of being killed if accident event e_i occurs
$P(target\ i)$	the target value for activity i
P_F	failure probability
P_{Fj}	probability of failure in year j
r	real rate of interest
R	risk
R_{rep}	representative value of the capacity
S_{rep}	representative value of the sollicitation
X_d	value of the basic variable X at the design point
X_i	random variable
X_{rep}	representative value of the basic variable
y	decision parameter
γ_R	partial factor for the capacity
γ_S	partial factor for sollicitations
γ_X	partial factor for X

1. INTRODUCTION

The design of building structures and civil engineering works structures involves the consideration of safety, lifetime performance, environmental aspects and economics. To an engineer, the “risk” associated with a hazard is a combination of the probability that that hazard will occur *and* the consequences of that hazard (the “threat”). Consequences to be taken into account include:

- Injury, or loss of life, due to structural collapse;
- Reconstruction costs;
- Loss of economic activity
- Environmental losses

In all cases, the safety issue has to be addressed either *explicitly* or *implicitly.*

- When explicitly addressed, a risk analysis is carried out and the result is compared with safety targets set in terms of the *maximum acceptable risks.* The most appropriate level for the maximum acceptable risk, of course, may depend on the cost associated with providing that level.
- When implicitly addressed, the designer makes a *design-judgement,* based on experience, which is deemed reasonable for the type of structure concerned but without quantifying the risk.

The first of these is the more scientific, and gives a rationale for decision-making. This report is primarily aimed at improving that aspect. However, in chapter 3.4 the relation between the implicit and explicit methods will be discussed.

The fundamental problem to be addressed is that of deciding the "maximum acceptable risk". Here, the use of the term "acceptable" raises immediately the question "Acceptable to whom?" And the second question is to actually assess the opinion of those involved about what is acceptable or not. Whatever way this problem is addressed, one thing is clear: fundamental levels of safety have to be acceptable to society as a whole, for it is on their behalf that engineers make such decisions.

In practice, the views of the society or the public will often be represented by those of their elected politicians. These can normally be expected to be at a very general level of attitude-setting, and are very unlikely to involve precise figures. Politicians will rightly set the Agenda, in terms of basic attitudes. But when it comes to quantifying the details of "maximum acceptable risk" then it is, in theory, necessary to turn also to the public in order to assess their opinions. The fundamental problem with this is that the public apparently do not usually interpret “Risk” in the same way as do engineers. It seems that the everyday, layman’s concept of “Risk” is a very complex concept which is very difficult to identify but which can sometimes be closely associated with "Threat", so that Hazards with high consequences are then highly ranked despite having extremely low probabilities of occurrence.

Two examples from the UK will serve to show the differing attitudes that the public can take.

- **Ronan Point collapse, 1968. 5 deaths.**
  This occupied the news media for several days, and had ramifications not only in the UK but throughout the world generally. Consequences included the modification of building codes & regulations and contributed to a fundamental change in the public's attitude towards high-rise accommodation.
- **Traffic accidents, every year 1000 deaths.**
  Very approximately, 1,000 or more people a year are killed in the UK in traffic accidents. An accident involving 5 fatalities usually makes the local news but not normally the national news other than in a relatively minor way.

Why should two incidents, involving the same number of fatalities, cause such differing reactions? Is it, for example, that the public are used to traffic accidents, but are not used to having buildings fall down? If so, then it might be possible to gauge the public's reaction to an adverse event by looking at frequency of occurrence. Or is it due to a feeling of lack of control? Or is it due to the way that incidents are reported (an important factor, here, is the role of the media in shaping public opinion)? Or something else? Questions such as these need to be asked, and answered, if the engineering profession is to make informed judgements about the acceptable levels of risk which they should adopt.

It is this which the work of WG 32 has addressed, and which is the subject of this report. The key to a good communication about risk is a set of proper definitions and clear procedures. This is the topic of the Chapters 2 and 3. Chapter 4 deals with acceptance criteria as commonly formulated. Standardisation in this field may also contribute to a better communication about risks and their acceptance. Finally, in Chapter 5 the item of communication with the general public will be addressed in more detail.

This document contains two Annexes: Annex A summarises the system of definitions that have been used in this document. Annex B presents four cases of structural failures that have lead to extensive communications between the engineers and the outside world.

2. RISK ASSESSMENT - A General Overview

2.1 Introduction

The general procedure of the risk assessment of civil engineering systems outlined here, follows the basic concepts presented in documents [2.1 to 2.6]. The risk assessment of a system is an important part of entire risk management schematically indicated in *Figure 2.1*, which is adapted mainly from [2.2].

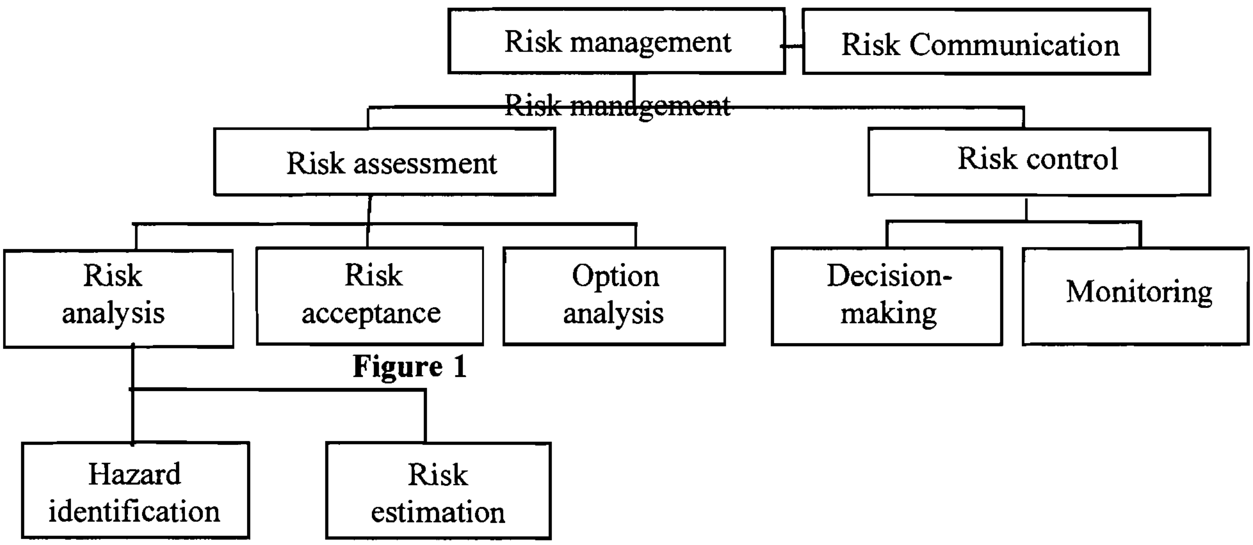


Figure. 2.1 A framework for risk management (inspired by [2.2])

According to Figure (2.1) risk management is considered as the highest level when dealing with risky activities and systems. It comprises the assessment procedures , the daily monitoring and control part and, last but not least, the communication between all parties involved. This report will deal primarily with assessment and communication.

The system is understood [2.2] as a bounded group of interrelated, interdependent or interacting elements forming an entity that achieves in its environment a defined objective through interaction of its parts. In case of technological hazards related to civil engineering works, a system is normally formed from physical subsystem, human subsystem, their management, and environment. Note that, similarly as in most systems, risk analysis of civil engineering systems usually involves several interdependent components (e.g. human life, injuries, economic lose).

2.2 Hazard identification

The risk assessment of a system consists of the use of all available information to estimate the risk to individuals or populations, property or the environment, from identified hazards, the comparison with targets and the search for optimal solutions. The first step in the analysis involves the context (scope) definition related to the system and subsequent identification of hazards. It is also referred to as the Qualitative Risk Analysis, as opposed to the Quantitative Risk Analysis where consequences, probabilities and risks are quantified.

A hazard is defined here as a set of circumstances, possibly occurring within a given system, with the potential for causing events with undesirable consequences. For instance the hazard of a civil engineering system may be a set of circumstances with the potential to an abnormal action (e.g. fire, explosion) or environmental influence (flooding, tornado) and/or insufficient strength or resistance or excessive deviation from intended dimensions. In the case of a chemical substance, the hazard may be a set of circumstances likely to cause its exposure [2.2].

Hazard identification and modelling is a process to recognise the hazard and to define its characteristics in time and space. In case of civil engineering systems the hazards H_i may be linked to various design situations of the building (as defined in [2.7]) including persistent, transient and accidental design situation. As a rule H_i are mutually exclusive situations (e.g. persistent and accidental design situation of a building). Then if the situation H_i occurs with the probability $P\{H_i\}$ it holds $\sum P\{H_i\} = 1$. If the situations H_i are not mutually exclusive, then the analysis becomes more complicated.

Note that in some documents (for example in the recent draft of EN 1990 [2.7]) the hazard is defined as an event, while in risk analysis [2.2] it is usually considered as a condition with the potential for causing event, thus as a synonym to danger.

A Hazard scenario is a sequence of possible events for a given hazard leading to undesired consequences. To identify what might go wrong with the system or its subsystem is crucial task to a risk analysis. It requires detail examination and understanding of the system [2.6]. Nevertheless, a given system is often a part of a larger system. Consequently, modelling and subsequent analysis of the system is a conditional analysis.

The modelling of relevant scenarios may be dependent on specific characteristics of the system. For this reason a variety of methodologies have been developed for identification of hazards (e.g. FMEA, PHA, HAZOP) and for modelling of relevant scenarios (fault tree, event tree/decision trees, causal networks). Detailed descriptions of these methodologies is beyond the scope of this document, but may be however found in [2.6,2.9] and other literature.

2.3 Risk estimation

Probabilities

Probability is, generally speaking, the likelihood or degree of certainty of a particular event occurring during a specified period of time. In particular, reliability of a structure is often expressed as probability related to a specific requirement and a given period of time, for example 50 years [2.3 - 2.7]. If the probability is give for a unit period of time (e.g. a year) one might alternatively (or even better) use terms like occurrence rate of frequency. We will stick here however to the term probability

Assuming that a system may be found in mutually exclusive situations H_i, and the failure F of the system (e.g. of the structure or its element) given a particular situation H_i occurs with the conditional probability $\mathrm{P}\{F|H_i\}$, then the total probability of failure p_F is given by the law of total probability (see for example [2.9]) as:

$$p_F = \sum_i \mathrm{P}\{H_i\}\mathrm{P}\{F \mid H_i\} \tag{2.1}$$

Note that the failure event F in itself may be a compound event, for instance of the type:

$$F = \cup \cap F_{\mathrm{ij}}$$

Equation (2.1) can be used to modify partial probabilities $\mathrm{P}\{H_i\}\mathrm{P}\{F|H_i\}$ (appropriate to the situations H_i) with the aim to comply with the design condition $p_F < p_\mathrm{t}$, where p_t is a specified target probability of failure. The target value p_t may be determined using probabilistic optimisation of an objective function describing, for example, the total cost.

The conditional probabilities $\mathrm{P}\{F|H_i\}$must be determined by a detailed probabilistic analysis of the respective situations H_i under relevant scenarios. The classiscal reliability methods [2.8] assume, that the failure F of the system can be well defined in the domain of the vector of basic variables $\boldsymbol{X}$. For example, it is assumed that the failure domain of a system may be defined by the inequality $\mathrm{g}(\boldsymbol{x}) < 0$, where $\mathrm{g}(\boldsymbol{x})$ is so called failure boundary or limit state function, where $\boldsymbol{x}$ is a realisation of the vector $\boldsymbol{X}$. Note that $\mathrm{g}(\boldsymbol{x}) = 0$ describes the limit state itself and inequality $\mathrm{g}(\boldsymbol{x}) > 0$ the non failure domain of a structure.

If the joint probability density $\mathrm{f}_{\boldsymbol{X}}(\boldsymbol{x}|H_i)$ of basic variables $\boldsymbol{X}$ given situation H_i is known, the conditional probability of failure $\mathrm{P}\{F|H_i\}$ can be then determined [2.8] using the integral

$$\mathrm{P}\{F|H_i\} = \frac{\int\limits_{g(x)<0 \text{ and} H(i)} f_X(x \mid H_i)\,dx}{\int\limits_{H(i)} f_X(x \mid H_i)\,dx} \tag{2.2}$$

It should be mentioned that the probability $\mathrm{P}\{F|H_i\}$ calculated using equation (2.2) suffer generally from two essential deficiencies:

- uncertainty in the definition of the limit state function $g(\boldsymbol{x})$,
- uncertainty in the theoretical model for the density function $f_X(\boldsymbol{x}|H_i)$ of basic variables $\boldsymbol{X}$ [2.8].

These deficiencies are most likely significant causes of observed discrepancy between determined probability p_F and actual frequency of failures. That is why the probability of failure p_F is often regarded to as notional probability that may be, however, disturbing in practical interpretation of obtained results [2.10]. Yet, the probability requirement $p_F < p_t$ is generally accepted as a basic criterion for design of structures.

In a risk analysis we need to know not only probability of the structural failure F but probabilities of all events having unfavourable consequences. In general, the situations H_i may cause a number of events e_{ij} (e.g. excessive deformations, full development of the fire). The required conditional probabilities $\mathrm{P}\{e_{ij}|H_i\}$ may be estimated by a separate analysis using various methods, for example fault tree method or causal networks.

Consequences

Consequences are possible outcomes of a desired or undesired event that may be expressed verbally or numerically to define the extent of human fatalities and injuries or environmental damage and economic loss [2.1]. A systematic procedure to describe and/or calculate consequence is called consequence analysis. Obviously consequences are generally not one-dimensional. However in specific case they may be simplified and described by several components only, e.g. by human fatalities, environmental damages and costs. At present frequently various costs are usually included only. It is assumed that adverse consequences of the events E_{ij} can be normally expressed by several components $C_{ij,k}$, where the subscript k denotes the individual components (for example number of lost lives, number of human injuries and damage expressed in a certain currency).

Risks

Risk is a measure of the danger that undesired events represent for humans, environment or economic values. Risk is commonly expressed in the probability and consequences of the undesired events. Often it is estimated by the mathematical expectation of the consequences of an undesired event. Then it is the product "probability $\times$ consequences". However, a more general interpretation of risk involves probability and consequences in a non-product form. This presentation is sometimes useful, particularly when a spectrum of consequences, with each magnitude having its own probability of occurrence, is considered [2.2].

As already stated above the risk estimation is based on hazard identification and generally contains the following steps: scope definition, frequency analysis, consequence analysis, and their integration [2.2]. If there is one-to-one mapping between the consequences $D_{ij,k}$ and the events e_{ij}, then the total risk R_k related to the considered situations H_i is the sum

$$R_k = \sum_{ij} D_{ij,k} \mathrm{P}\{e_{ij} \mid H_i\} \mathrm{P}\{H_i\} \tag{2.3}$$

If the dependence of consequences on events is more complicated than just one-to-one mapping, then equation (2.3) will have to be modified. A practical example of equation (2.3) can be found in [2.10], where an attempt to estimate risk due to persistent fire design situation is presented.

In some cases it is possible to deal with one-component risk R only. Then the subscript k in equation (2.3) may be omitted. Moreover, probability of undesired events may depend on vector of basic variables $\boldsymbol{X}$. Then the total risk R may be formally written as

$$R = \int D(\mathbf{x}) \mathrm{f}_{\mathbf{X}}(\mathbf{x}) \mathrm{d}\mathbf{x} \tag{2.4}$$

where $R(\boldsymbol{x})$ denotes degree of risk as a function of basic variables $\boldsymbol{X}$, and $\mathrm{f}_{\boldsymbol{X}}(\boldsymbol{x})$ denotes joint probability density function $\boldsymbol{X}$. In many cases the following alternative formulation is more convenient:

$$R = P_F\, E(D|F) \tag{2.5}$$

where P_F is a failure probability and $E(D|F)$ the expectation of the damage given that a failure has occurred. The failure probability can then be calculated by efficient procedures as FORM and SORM [2.x], and the damage expectation may be based on a suitable approximation. This point will be further discussed in chapter 3.

2.4 Risk assessment, decision-making and optimization

Decision-making is generally based on the process of risk acceptance and option analysis (see *Figure. 2.1*) that is sometimes referred to as risk assessment. Risk acceptance is based on various criteria of risk that are reference points against which the results of the risk analysis are to be assessed. Criteria are generally based on regulations, standards, experience, and/or theoretical knowledge used as a basis for decision about acceptable risk. Acceptance criteria and criteria of risk may be sometimes distinguished [2.1]. Various aspects may be considered, including cultural, social, psychological, economical and other aspect [2.6]. Generally acceptance criteria may be expressed verbally or numerically [2.6].

Assuming for example that the acceptance limits $C_{k,\mathrm{d}}$ for the components C_k are specified, then it is possible to design the structure on the basis of acceptable risks using the criterion $C_k < C_{k,\mathrm{d}}$, which may supplement the probability requirement $p_F < p_t$. For more details: see chapter 4.

It should be noted that various levels of risk might be recognised, for example acceptable risk, tolerable risk, and objective risk (see definition of theses terms) [6]. It is remarkable fact that the public seems to be generally better prepared to accept certain risks than to stand for specified probabilities of failure [2.8]. See also chapter 5.

If risks are considered as too large for direct acceptance, one should look for adequate counter measures. When planning counter measures, the mentioned techniques for the recognition of possible hazards are very helpful. The aim is to detect those events or processes, where with a small effort an important effect can be obtained. Possible measures can be technical or administrative, and can fall in the following strategies:

- *Reduce* the cause of the risk.
- *Avoid* the risk by changing the concept or the objectives.
- *Control* the risks by using suitable alarm systems, vigilance, inspections, etc.
- *Overcome* the risks by providing an adequate capacity.

The possible measures can and should refer to all phases of the realization, use and demolition of the engineering facility. The further analysis should mainly be concerned to find out whether or not certain countermeasures should be taken or not. In general an economic balance between the counter measures and risk reduction should be achieved. In cases one simply has to accept the (remaining) risk. This topic will be re-addressed in chapter 4.

2.5 Concluding remarks

Risk is commonly estimated by the mathematical expectation of the consequences of an undesired event that often leads to the product "probability × consequences". As a rule risk of civil engineering systems is multidimensional quantity having several components.

Risk analysis is based on hazard identification and generally contains the following steps: scope definition, hazard identification, definition and modelling of hazard scenarios, estimation of probabilities, estimation of consequences, estimation of risk and decision-making.

3. APPROACHES FOR RISK ASSESSMENT

3. RISK ASSESSMENT

3.1 Hazard scenarios

Any technical system is exposed to a multitude of possible hazards. In the case of civil engineering installations or facilities, these hazards include both, those from the environment (wind, temperature, snow, avalanches, rock falls, ground effects, water and ground water, chemical or physical attacks, etc.) and those from human activities (usage, chemical or physical attacks, fire, explosion, etc.). Furthermore, the importance of hazards due to human errors can be decisive.

Usually, different hazards occur together in space and time. Such situations may lead to higher risks than those corresponding to the individual hazards. The recognition of these situations is the first step of the so-called *scenario approach* (see also section 2.3). Further steps are the evaluation of these hazards (including determination of the risks corresponding to the different scenarios), and the planning of preventive measures (section 2.4). The qualitative identification of hazards is possibly the most important step of the approach. Indeed, once the potential hazards and combination of hazards are recognized, usually it is relatively simple to adopt appropriate measures to overcome their consequences. Due to their importance, some hazard-identification techniques are presented in section 3.2. The second major step in risk analysis, the estimation of probabilities and consequences, is treated with in sections 3.3 and 3.4 where an overview of advanced and simplified risk analysis techniques is given.

3.2 Identification techniques

Various techniques exist that may help the engineer to recognize possible hazards. These techniques present some common characteristics in the sense that they are all based on asking questions. Once the right questions are asked, the identification of potential hazards is relatively easy. Therefore, all the mentioned techniques require imagination and creativity.

When searching for possible hazards, it is essential that already at the concept stage of a new engineering facility the whole process of its construction, use, repair and/or its future replacement or demolition is taken into account. To do so, not only the application of creative techniques or strategies is helpful. Extensive use should also be made of experience, e.g. by referring to specialized literature related to the problem at hand.

Hazard and Operability Study

Different strategies of thinking with a view to identifying possible hazards and hazard scenarios are known under various names, e.g. Hazard and Operability Study (HAZOP), What-if Analysis, or Failure Mode and Effect Analysis (FMEA) [3.1]. In daily practice, the goal is to recognise all possible hazards related to a particular problem. In order to reach this goal, a combination of different of these strategies, which are listed below, is to be applied.

- In a *chronological analysis*, the whole process, step by step, has to be established in mind. Typical questions to be asked are: What will occur, where and when?
- In a *utilization analysis* questions concerning the planned use of the future engineering facility are to be raised: What equipment or machines will be used? What influence do they have? What could go wrong?
- In an *influence analysis* it is looked at influences from the natural environment and from human activities. New situations have to be anticipated, which could make initially harmless influences dangerous. Furthermore, it must be looked at individual hazards that alone would be negligible, but in combination become dangerous.
- *Energy analysis*: Where and in what circumstances potentials due to different energies (gravity, kinetic, chemical, thermal, electrical, etc.) could lead to a hazardous situation? The failure of an energy supply can also constitute a danger.
- In a *material analysis* it has to be looked, for example, at the durability, combustibility, toxicity, or explosiveness of the used raw materials or end products.
- *Examining interfaces*, hazards can be anticipated where different materials are in contact, or where information has to be transmitted, or where responsibilities are not clearly defined.

Morphological thinking is a method developed in [3.2] that is aimed at identifying *all* possible problems and their solutions. In a further step, these theoretically possible problems are then reduced to the really important ones which are to be tackled in the further analysis.

Logic trees

The application of logic trees (fault tree, event tree, cause-consequence chart) contributes to introduce some order, completeness and clarity into the engineering work. The use of this kind of tool is very widespread in risk analysis and implies some important advantages. Influences from the environment and from human activities can easily be considered simultaneously. Logic trees also can contribute to detect the most effective countermeasures. Furthermore, they are easy to understand and therefore very helpful for communication purposes with non-experts.

A *fault tree* can be defined as a logical diagram for the representation of combinations of influences that can lead to an undesired event. Simple examples are represented by the figures 3.1 and 3.2, belonging to the fields of fire and structural engineering, respectively. When establishing a fault tree, the undesired event constitutes the starting point. Going out from this event, the possible causes are to be identified. Possible causes and consequences are to be linked in a logic way, without introducing any loops. Every event that is not a consequence of a previous event has to be considered as an independent variable [3.3].

After a failure event, fault trees can be used in order to clarify the causes in case that they should be unknown. The most common application, however, consists in detecting possible causes of undesirable events before they can occur. Since fault trees also show the possible consequences of events, they are very useful for the establishment of the most accurate measures for prevention from these events.

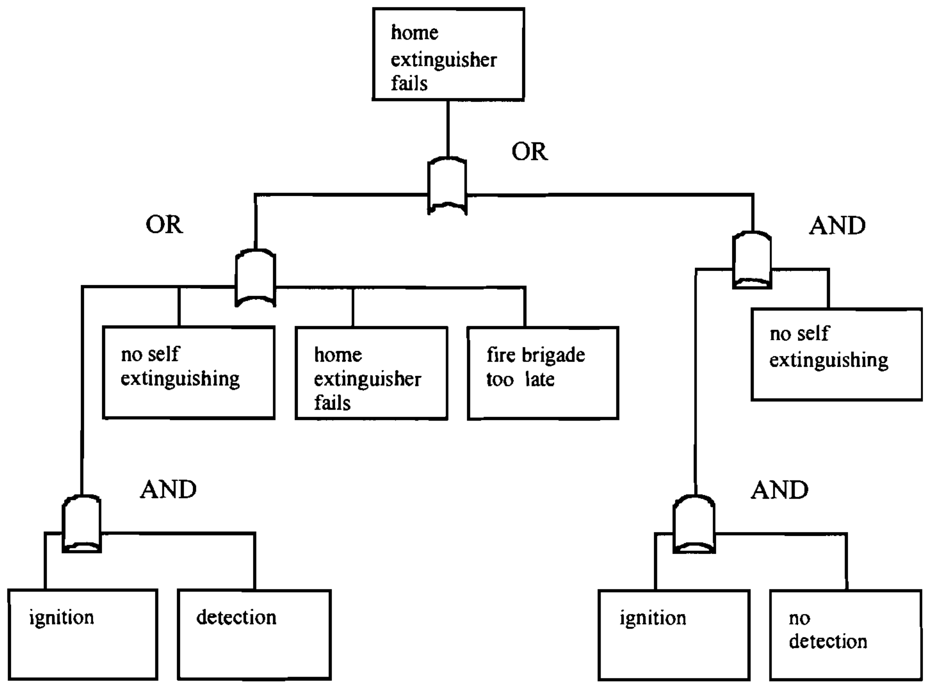


Figure 3.1: Fault tree for fire risk analysis

Going out from an initial event, an *event tree* identifies the possible subsequent events. Each path consists of a sequence of events and ends up at the consequence level (Figure 3.3). The aim is therefore the establishment of possible consequences of an initial event. In a second step, the event tree also can be used for the calculation of probabilities of occurrence of these consequences.

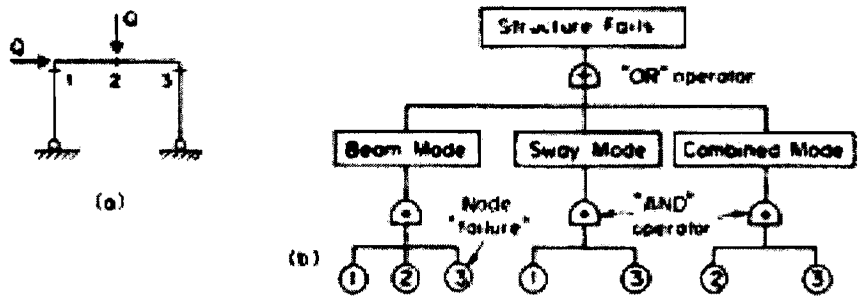


Figure 3.2: Fault tree representation of the failure mechanisms for a frame (according to [3.4])

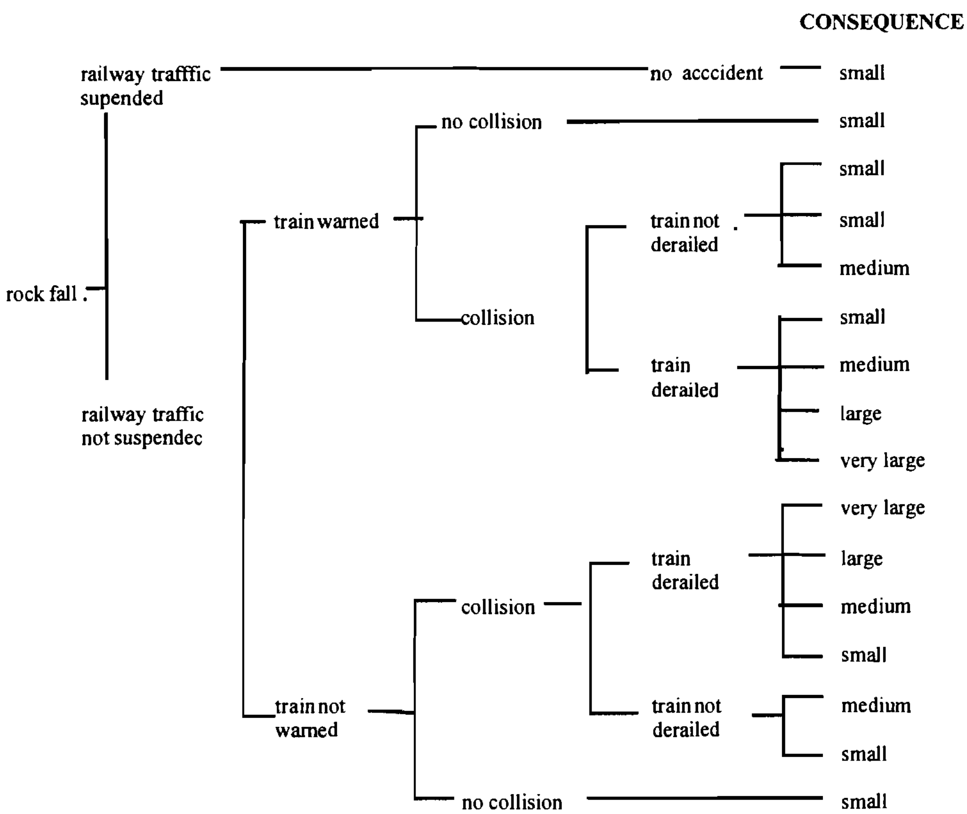


Figure 3.3: Event tree for the Rock-fall on railway line (adapted from [3.5])

The aforementioned logic trees can also be combined. To this end, a special representation is used, containing as well the causes as the consequences (*cause/consequence-chart*). The part with the causes corresponds basically to a fault tree. However, if necessary different undesired events can be introduced as starting points. The consequence part, on the other hand, corresponds to an event tree with a slightly different representation. The questions are formulated in a way that the answer only can be "yes" or "no". In this way, a very compact representation of complex problems can be obtained.

3.3 Methods of reliability and risk evaluation

Risk formulation

In many fields of engineering the failure of a system or element in the system is often governed by the difference between two quantities: the intensity of an action on a component or system and a corresponding capacity or limit value. Examples are:

Intensity of action (S)	**Capacity or resistance (R)**
Applied bending moment	Bending resistance
Intensity of traffic	Traffic capacity of a road
Water flow	Flow capacity of a river bed
Number of passengers	Capacity of a transportation system
Number of persons / fire load	Capacity emergency exits

Table 3.1: Examples for intensities of actions and the corresponding capacities of engineering systems [3.1]

Normally, the quantity representing the intensity of an action should be smaller than the quantity representing the corresponding capacity or resistance. In that case no failure occurs. However, both R and S are random variables, and there exists a certain probability that S is larger than R. So the failure event can be written as:

$$R\text{-}S < 0 \tag{3.1}$$

As a more general expression this failure event can be represented as:

$$g(\mathbf{x}) = g(X_1, X_2, \ldots X_n) < 0 \tag{3.2}$$

where g(..) is the limit state condition and the X_i represent the random variables. So for values of g less than zero, the technical system does not reach the corresponding requirement and we are talking about failure. In the present context we are interested in the so-called *probability of failure* p_f.

$$p_f = p\{ g(X_1, X_2, \ldots X_n) < 0 \} \tag{3.3}$$

The failure probability should always be defined for a predefined period of time. Formally, the failure probability can be represented by the relation (2.2) where $f_x(\mathbf{x})$ is the joint probability density function of the basic random variables $X_1 \ldots X_n$. Furthermore, $g(\mathbf{x})<0$ in relation (2.2) represents the integration domain or failure domain (see also figure 3.5).

The risk associated with a hazard is a combination of the probability of occurrence of this hazard and the consequences in case that it occurs. Therefore, the most sophisticated methods for risk analysis take all consequences of a failure directly into account. The basic relation for this kind of risk calculation is given by equation (2.4), which can also be represented as:

$$R = \int\!\!\int\!..\!\int \; D(X_1, X_2, \ldots X_n)\, f(X_1, X_2, \ldots X_n)\; dX_1\, dX_2, \ldots dX_n \tag{3.4}$$

where R is the risk (not resistance), D is the damage and $f\,(..)$ the joint probability density function of the basic random variables. Of course, this integral is not easy to solve. Therefore, the simplest function relating the two constituents of risk (section 2.6) is often used by multiplying the probability of failure, p_f, by the damage should the failure event occur, D:

$$R = p_f D \tag{3.5}$$

The damage may be expressed in monetary units or in terms of injured or dead per event, or by some other indicator. Since fixed or deterministic values are used for considering the consequences of a possible failure, the application of definition (3.5) is formally very simple. The problem lies in the adoption of reasonable quantities for the constituents of risk, particularly also for the possible damage. However, as long as the results are interpreted in a comparative way, extremely useful information is obtained, e.g. for optimisation problems.

An intermediate level of sophistication for the representation of risk can be achieved if the randomness of the expected damage is also taken into account. Formally, the risk associated with a hazard can then be represented as:

$$R = p_f E(D|F) \tag{3.6}$$

where $E(D|F)$ is the expectation of the damage should the failure event take place.

Note: it is sometimes tempting to use in (3.6) a conservative estimate for the Damage, modeling some kind of risk aversion. This, however, is not the proper way. The correct way in the decision theoretical sense is to use a nonlinear utility function for large benefits and damages. The problem of very small probabilities and large consequences will be further discussed in chapters 4 and 5.

Finally, it is to be mentioned that probabilistic methods as referred to in the present section are possibly not aimed at the practising engineer for everyday use. There exist mainly two reasons for that. Firstly, they require a considerable knowledge about probability concepts and, secondly, very often there is a lack of information concerning the parameters of the different variables entering a problem, and in daily practice the time needed for gathering the lacking data is usually not available. Therefore, simplified methods have been developed in different fields of engineering. The aim is to verify that equation (3.1) is satisfied by carrying out simple deterministic analysis for selected hazard scenarios. Further information on this approach to risk analysis can be found in section 3.4.

Integration and simulation methods

Figure 3.4 illustrates the joint probability distribution of R and S. The volume of the hump is 1 and the contour are concentric curves. The limit state equation $G=R-S=0$ separates the failure domain from the non failure domain, dividing the volume into two parts. The aim of the integration defined by equation (2.2) is to calculate the volume of the failure zone in order to determine the probability of failure. Figure 3.4 shows the failure zone with respect to the joint probability distribution of R and S. It also illustrates the design point [S*, R*], which is defined as the most probable failure point on the limit state surface. The design point constitutes the key to many reliability methods for estimating the probability of failure.

The design point is illustrated in two dimensions in figure 3.5, which also shows the reliability index, β. This index is a measure of the distance of the design point [S*, R*] from the point [μ_S, μ_R], measured in standard deviations. Safety with respect to a limit state function can be represented by either the probability of failure or the reliability index. It is clear, however, that the design point does not represent the failure probability exactly since more than one limit state function may share the same design point (figure 3.5 illustrates a linear failure surface). Although the design point and thus the reliability index can be the same, the probability of failure is lower for a convex failure surface than for a concave surface. The practical calculation of the failure probability can be achieved through the use of reliability methods, which are presented below.

As indicated already in equation (3.2), a limit state function usually is more complex than equation (3.1) since both, the R and S variable normally are functions of other basic variables. Probability calculations for a technical system involves therefore the determination of probability distributions that represent the uncertainty associated with the basic variables. Based on these distributions, the practical calculation of the failure probability can be achieved through the use of reliability methods, which are either analytical or numerical. Some methods estimate reliability using a point estimator of the limit state surface. In this way the precise shape of the limit state surface, and thus the volume of the failure zone, is not considered. Examples of these methods are the ***First Order Reliability Method (FORM)*** [3.6] and the ***Second Order Reliability Method (SORM)*** [3.7]. For the reasons mentioned earlier, FORM does not represent the failure probability exactly since failure functions may be curves or more than one limit state function may be active. The magnitude of the error will depend on the non-linearity of the limit state surface.

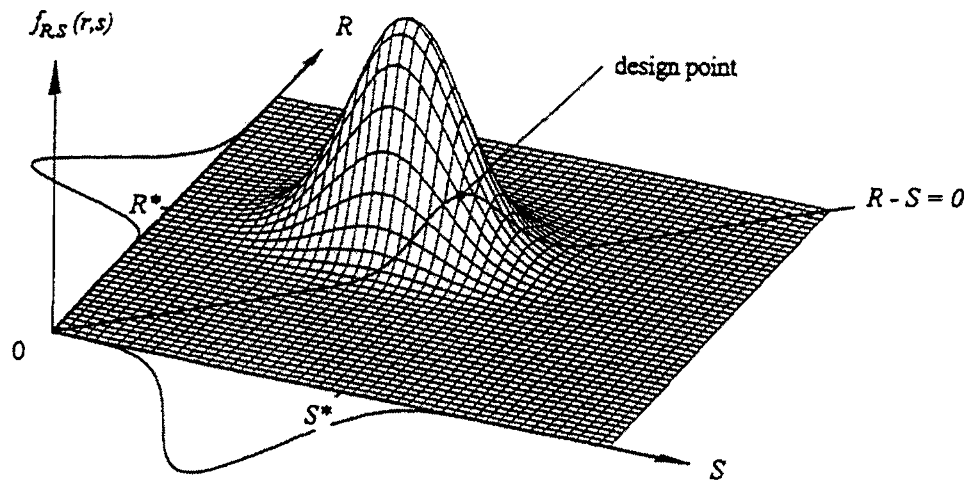


Figure 3.4: Failure zone with respect to the joint probability distribution of R and S

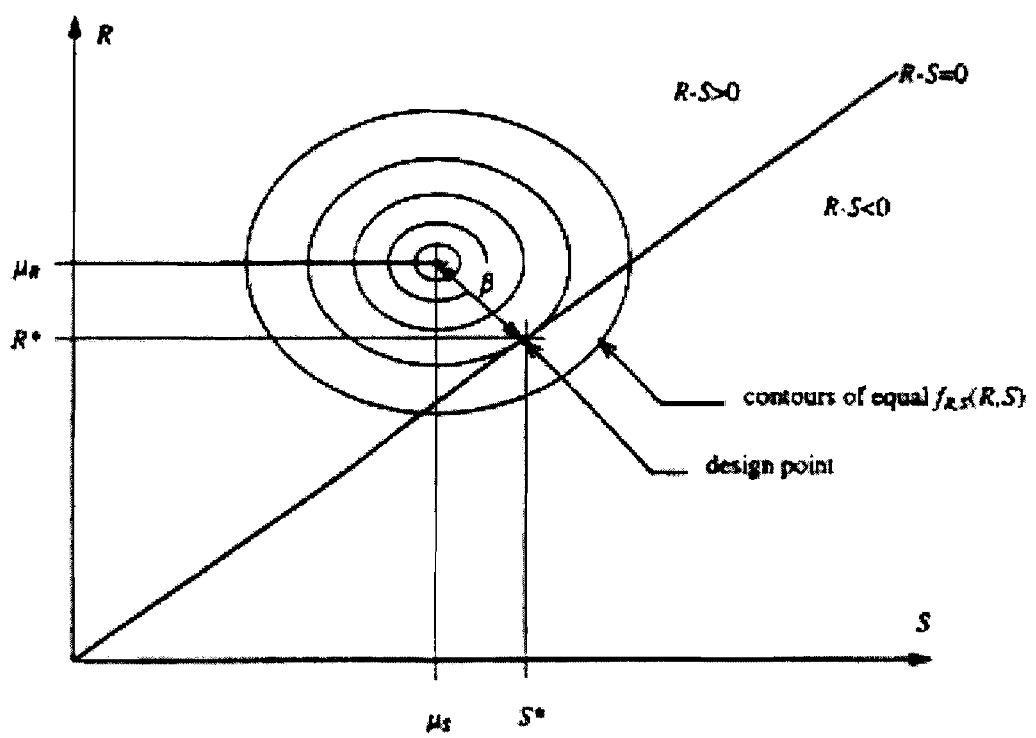


Figure 3.5: Two dimensional representation of the design point

The most easily understandable numerical method is the ***Monte Carlo*** simulation [3.8]. The exact or approximate calculation of the probability density and of the parameters of a limit state function is replaced by statistically analyzing a large number of individual evaluations of the function using random realizations x_{ik} of the corresponding distributions X_i. Each set of the k realizations gives a value g_k. The limit state function is then checked. If the limit state condition is violated, $g_k < 0$, the system has failed in the artificial experiment. The experiment is repeated many times, and the number n of failures is counted. Knowing the number of trials conducted, N, and the number of counted failures, n, the probability of failure, p_f, can be estimated. Obviously, the number of trials required is related to the desired accuracy for p_f.

The technique sketched above is the simplest Monte Carlo approach for reliability problems. Although it is possibly the most widely used approach, it is not the most efficient one. Its slow convergence has been a severe penalty for direct sampling techniques until the emergence of powerful computers in the last decade. This disadvantage has led to so-called variance reduction techniques. A good overview of the various strategies for variance reduction is given in [3.9]. More efficiency in the sense that, for a given level of confidence, fewer sample points are required is also obtained by the so-called importance sampling.

When performing a Risk Analysis, an advantage of Monte Carlo methods is that they can deal directly with formulation (3.4) including gradual loss functions, where FORM/SORM is primarily developed for calculating the p_f in formulation (3.5).

Quantitative Logic tree analysis

After the qualitative establishment of a logic tree (section 3.2), the calculation of the probability of occurrence of the undesirable top event (fault tree) or the probability of occurrence of the consequences of a given initiation event (event tree) should be performed. In the following, only some basic ideas are introduced about the estimation of probabilities by using logic trees.

In the case of an *event tree*, the possible subsequent events following a previous event exclude each other. Therefore, the sum of the probabilities at a gate of an event tree must be the unity. The calculation of the probability of occurrence of a consequence is very simple since it is obtained by multiplying the probabilities of the different events constituting the path that leads to the considered consequence (Figure 3.3). The difficulty lies in the establishment of the probabilities of the different events, and very often numerical values are based on subjective estimations.

In the case of a *fault tree*, the probabilities are to be calculated depending on the type of the logic gate. If the different components must fail at the same time (the first and the second and...), they constitute a parallel system represented by an AND-Gate. Therefore, the corresponding probability is obtained according to the multiplication rule, by multiplying the probabilities of the different components (Figure 3.2). On the other hand, if only one component must fail (either the first, or the second, or...), they represent a series system. In that case we are talking about an OR-gate and the probability of failure is obtained by adding the probabilities of the different components.

The aforementioned rules are valid for uncorrelated events. Unfortunately these rules become more complex if the events in the fault tree are correlated. However, in order to deal with correlations, the previously mentioned calculation rules can be extended by means of transformation methods. Correlations can both, increase and reduce the probability of failure. If a car is properly maintained, then probably the engine will be in a good condition, as well as the breaks, the wheels, etc. All these forms of good maintenance may be correlated to one factor, the responsible owner of the car. Therefore, all of them may act in the same direction reducing the probabilities of failure. The opposite, of course, might also occur. Finally, there also exist correlations with approximately balanced effects.

Time dependency

In the foregoing the factor of time has not been considered. In almost all cases, however, time is an important issue. Many random variables, in fact should be treated as random processes. Some random processes are continuous by nature, as for instance wind or traffic loading. Other random processes may have a completely different nature: a phenomenon is absent for most of the time, but may pop up at certain irregular time intervals. One may refer to these processes as pulse processes. Examples are earthquakes, collisions, fires etc. The arrivals of these events are usually modelled as Poisson processes. The magnitude of the phenomenon itself may be random again. Figure 3.6 gives some clarification

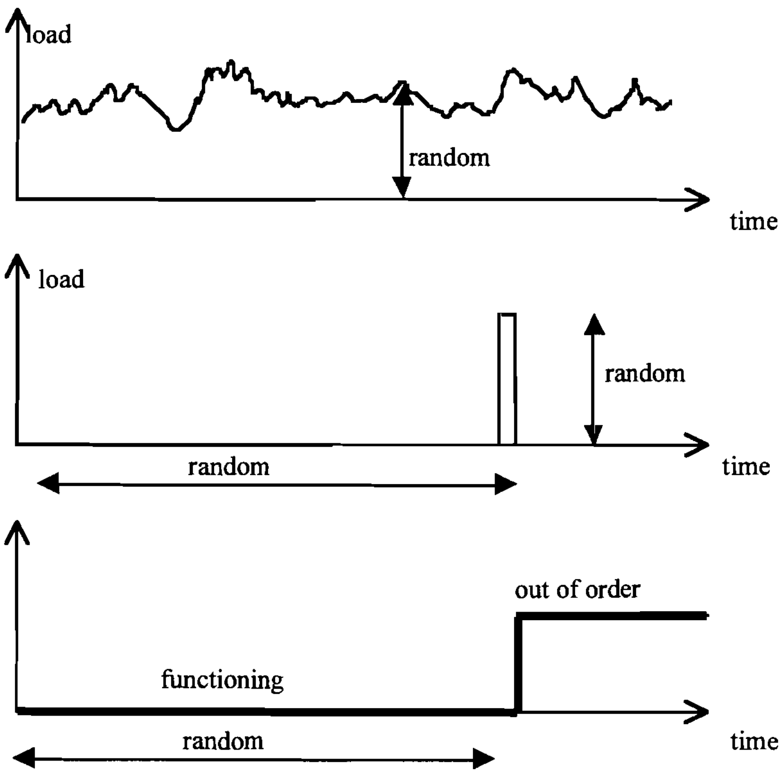
The Poisson process may also be used to model the binary status ("working-failed" or "present–absent") of many electronic or mechanical devices. Warning systems like the ones in the rock fall example of figure 3.2 may have this nature. Another example is a sprinkler systems in buildings: if there is a fire, the probability of large consequences is considerably reduced if the sprinkler system works. However, there is a certain probability that the sprinkler system is out of work just during a fire event. Details of this are, however, outside the scope of this document.

3.4 Approaches to risk analysis

Explicit probabilistic approach

As mentioned in section 3.3, risk analysis implies the quantification of the probability or frequency of damaging events and expected damages, based on available statistics, tools such as fault or event trees, or detailed knowledge from investigated events. It has also been mentioned that risk analysis according to explicit probabilistic approaches can

be used as a tool for decision making. The evaluation of risks according to decision methods is based on optimisation strategies for the chosen damage indicator. The design of a technical system or facility can therefore be carried out in a way that for example the overall cost accumulated throughout its life, including the cost of a possible failure, is minimal. The formal procedure will be treated in the next chapter.
Optimisations of this type rely on a great number of arbitrary assumptions. Particularly, it should be bared in mind that probabilities of failure are usually very small and that



Figuur 3.6: Upper: continuous type of load process; middle: pulse type of load process; lower: binary type of process for electrical of mechanical type of device

for this reason numerical values depend very strongly on the assumptions made. Therefore, decision methods based on probabilistic analysis should only be used for classification purposes (from good to less good), for example for different possible solutions to the same problem. In other words, the values obtained should not be misinterpreted as absolute values, but if they are interpreted in a comparative way, decision methods supply extremely useful information.

Implicit probabilistic approach

In an implicit probabilistic verification of safety of a technical system one verifies a set of requirements by using simple deterministic hazard scenarios and deterministic values for the basic variables. The models may be the same for both, probabilistic and deterministic approaches. Although users of these methods often claim to be fully deterministic, this is hardly to believe. In most cases in the choice of the requirements, the scenarios and the values, some notion on consequences of events and occurrence frequencies enter the process. No one is going to make calculations on hazard scenarios that either happen too often or never at all.

In structural analysis a formal link has been derived between probabilistic and deterministic methods. This link is the FORM design point. The relationship between this point, the partial factor and the representative value is given by the following expression:

$$X_d = \gamma_X X_{rep} \tag{3.7}$$

X_d value of the basic variable X at the design point in a reliability analysis
γ_X partial factor
X_{rep} representative value of the basic variable

The requirement for safety in its simplest form can be derived from condition (3.1) and is
expressed by

$$\gamma_S S_{rep} = R_{rep} / \gamma_R \tag{3.8}$$

γ_S partial factor for sollicitations in a deterministic analysis
γ_R partial factor for the capacity in a deterministic analysis
S_{rep} representative value of the sollicitation
R_{rep} representative value of the corresponding capacity

Partial factors are determined according to relation (3.7), using probabilistic analysis. As mentioned, in this way safety differentiation can be incorporated in the Partial Factor Method in order to take implicitly into account the consequences of a possible failure.

4 RISK ACCEPTANCE –SAFETY CRITERIA

4.1 Introduction

Criteria for accepting or rejecting the assessed risks include two related entities: the frequency of an undesired event and the consequences (casualties, monetary values, environmental values). In general one may state that the higher the consequences, the lower the accepted probabilities are. In more detail, the acceptance limits for a given disaster may originate from three different angles:

1. comparison with other risks related to individual safety
2. societal aversion of big disasters, especially when many casualties are involved.
3. economic considerations

Of course, in a specific situation , the three aspects should be integrated and/or prioritised. In general one may state that one strives at an economic optimum, but that the society (emotionally) and the authorities (formally) put some limits to the individual and group risks to human lives. In this chapter all three criteria will be discussed one by one. In a chapter 4.5 we will come back to the problem of the combination of the criteria.

Implicitly, in the above paragraph, already a large simplification of reality has been made: the results of a disaster have been reduced to death and money. Many other aspects, of course, play a role. Many (material) losses cannot easily be expressed in money, like destruction of pieces of art and pollution of the environments. Also people may get hurt, disabled, suffer from post traumatic depressions, live long fears, forced to relocate housing or work. In other words: risk is multidimensional and one could speak of a risk profile rather than risk [4.1]. It is extremely difficult to include all these items in the risk analysis. If one does, one needs in the end weighing factors for all risk dimensions in order to make them comparable to each other and to relate them to the measures that must be taken for possible risk reduction. [4.2] [4.3] [4.4] [4.10].

A practical problem in risk acceptance decisions is that the group which has to pay for the safety measures and the group that profits from there, are often not the same. Groups that do not have pay directly for the measures generally want very tight rules and vice versa. The groups exposed to hazards also are not identical to the groups that profit from the risk related activity. Together with the emotional reactions to dangerous situations this may lead to an unwillingness to accept so called objective criteria. Nevertheless, the existence of objective criteria as to be presented in this chapter may make the multi party process of acceptance, negotiation and decision more easy [4.5][4.6]. This item will be further discussed in section 5.

4.2 Individual acceptable level of risk

Table 4.1 gives an overview of personal risks in developed countries. In column (b) the risk is presented as the probability per time unit of being killed when actually doing the activity mentionend in columnn (a). Such a frequency is called a fatal accident rate or *FAR*. Following [4.7] and [4.8] the *FAR* is expressed as the number of fatalities per 100 million hours (= 11,500 ≈ 10,000 years). In column (d) the frequency is presented as the fatality probability per time unit averaged out over the hours doing and not doing the activity. It is expressed as a annual probability. The link between the two risk measures, of course, is the part of time spent on the activity. Formally the relation is given by:

$$P(\text{A person being killed in one year}) = (FAR/10000) * \text{part of time}$$

The estimated part of the time spend on the activity is mentioned in column (c). It is assumed that workers spend 20 percent of the time doing their job, while travelling is only done during 1 to 5 percent of the time. Also dangerous hobbies like climbing mountains or driving motor cycles are assumed to be done only during a small portion of the time. Some activities, like being a person between 30 and 40 years old, of course, have a time participation of 100 percent. As an example, consider the first activity, rock climbing. The $FAR = 4000\ /10^8$ hours $= 4000\ /\ 10000$ years = 0.4 /year. The part of the time a climber is really in the mountains is estimated as 1/200, or say about 2 full days per year. This leads to:

$$P(\text{An active rock climber being killed in one year}) = 0.4 * 0.005 = 2\ 10^{-3} = 1/500$$

It should be noted that in some tables (not here) the risks are further averaged out over all persons in a country, involved in some activity or not. This number, however, is not so much a measure of personal risk as well a measure of a social risk. A dangerous activity is a morepronounced social problem if more people are involved.

Let us now have a look at the details of Table 4.1. An almost unavoidable risk is the probability of dying from natural causes. In the developed countries this probability for a person under 50 years of age is about 10^{-3} per year. The probability of losing one's life in normal daily activities, such as car driving or working in a factory, is in general one or two orders of magnitude lower than the normal probability of dying. Activities such as mountaineering entails a much higher risk. These numbers may be reflected as an implicit risk acceptance model by the public. Of course, people do not have those numbers actually in mind, but there seems to be a pattern that for activities considered as attractive and done voluntary much higher risks are accepted as for non-voluntary activities. Another point is how much one benefits from the activity: for a well paid job one also accepts higher risks. The lowest acceptance level can be found for activities which are involuntary and of little or no profit for the person at risk. This, however, is not an uncommon situation for the risks involved many engineering works like transport systems and industrial areas. So, in this respect for the same activity, it may be useful to distinguish between the "internal risks" and the "external risks", referring respectively to the people using the facility and profiting therefrom and the group that only experiences the risks related to the activity.

(a)	(b)	(c)	(d)
Cause of Death	**During activity [/10^8 hrs]**	**Part of time (average)**	**Annual probability [1/year]**
Rock climbing	4000	0.005	1 / 500
Motorcycle accidents	300	0.01	1 / 3000
Skiing	130	0.01	1 / 8000
Workers in high rise building industry	70	0.2	1 / 700
Deep sea fishing	50	0.2	1 / 1000
Workers on offshore oil – and gas-rigs	20	0.2	1 / 2500
Disease average for 40-44 age group	17	1	1 / 600
Travel by air	15	0.01	1 / 70000
Travel by car	15	0.05	1 / 13000
Disease average for 30-40 age group	8	1	1 / 1200
Coal Mining	8	0.2	1 / 6000
Travel by train	5	0.05	1 / 40000
Construction industry	5	0.2	1 / 10000
Agriculture (employees)	4	0.2	1 / 12000
Accidents in the home	1.5	0.8	1 / 9000
Travel by local bus	1	0.05	1 / 200000
Chemical industry	1	0.2	1 / 50000
California earthquake	0.2	1	1 / 50000

Table 4.1 Fatal Accident Rates [4/7], expressed as
in column (b): the number of fatalities per 100 million hours spent on an activity
in column (d): the number of fatalities per year for people involved in the activity

Anyhow, inspired on the numbers given in Table 4.1 one may define acceptance limits for the individual risk. The UK Health and Safety Executive (HSE) has defined a maximum level of individual risk which is just tolerable and a minimal level below which further action to reduce risks may not be required. The values are collected in table 4.2. Between these levels, it is required to reduce risks to levels "as low as reasonably practicable" (ALARP) that is, until the costs of further measures would be grossly disproportionate to the benefit gained.

	Per hour activity [$*10^{-8}$]	**Per year per person**
Workers, all occupations (upper limit)	50	1 / 1000
Public at risk from industrial operations	1	1 / 10000
Public at risk from nuclear industry operations	0,1	1 / 100000

Table 4.2 Maximum acceptable FAR values for individual risk according to the Health and Safety Executive in the UK.

Written as a formula one might state the individual risk requirement as follows:

$$P(d_i) = P(e_i) * P(d|e_i) < P(target\ i) \qquad (4.1)$$

where

$P(d)$	= annual death probability
$P(e_i)$	= probability of accident event i
$P(d\|e_i)$	= probability of being killed if accident event E_i occurs
$P(target\ i)$	= the target value for activity i, depending on the type of activity

The target probability for one year should be 10^{-4} for "normal cases" as this is what society nowadays seems to accept or is unavoidable anyway. For voluntary activities, involving economic benefits or other profits a higher value may be considered as acceptable. However, if somebody is involuntary put to an unnatural risk form which he has no benefits at all, the target must be substantially lower as 10^{-4} per year. Given the above discussion one and also looking at Table 4.2, one might set the targets as indicated in Table 4.3:

	Type of risk	P(target)
1	Voluntary risks / profitable or attractive activity	10^{-3} /year
2	Natural hazards	10^{-4} / year
3	Unnatural hazards / involuntary and unavoidable risk	10^{-5} / year

Table 4.3 Target values for individual yearly risk

Most important of course is type 3 where people are exposed to riskful activities by others but have no profit from it whatsoever. One might think of people living close to a plant or near a transport route of dangerous materials who have no economical bond with those activities. For this category the 10^{-5} per year target is set as an upper limit.

In the above targets, the limits are set for a single and isolated i-th activity. What really counts for an individual is the summed up risk over all activities. Based on this idea one might deduce that the acceptable probability of the set of undesired event during one year is limited by:

$$P(d) = \Sigma\, P(e_i) * P(d|e_i) / P(target\ i) < 1 \qquad (4.2)$$

The summing up is of course theoretically correct, but difficult to handle in practice. If for some individuals total risk is too high, which risk contribution should then be blamed and reduced? And do we include the dangerous hobbies? So in the end it is more use (4.1):

4.3 Socially acceptable level of risk

The social acceptance of risk to human life is often presented as a so called F-n-curve. The F-n-curve indicates the border between "acceptable" and "unacceptable" in a diagram with probability on one axis and number of casualties on the other. Formally written:

$$P(N_d \geq n) < F(n) \qquad \text{(for all } n\text{)} \tag{4.3}$$

Here N_d is the number people being killed *in one year in one accident*. The *probability* $P(N_d \geq n)$ depends on the probability of failure of the system under consideration and on the factors that determine the number of fatalities in case of a failure. The criterion is not applicable to frequent small scale accidents like car accidents (see later comment). It is quite customary to have two *F(n)*-curves as indicated in Figure 4.1:

- one curve representing an upper limit above which activities or situations are not acceptable
- another one representing a lower limit below which no further risk reductions are necessary

In the area in between risk reducing measures should be considered and judged on an economical basis. This is again the ALARP-approach (as low as reasonably practicable, see also the section on individual risk).

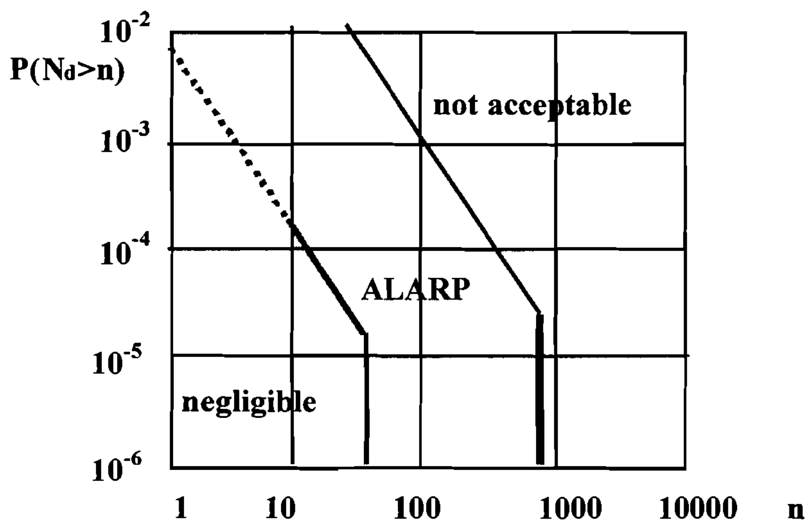


Figure 4.1 F-n-curves, where $F(n) = P(N_d > n$ in one year), and the ALARP region; the curve is dotted for small n as it is not applicable in this region.

A mathematical expression in the case of a straight F-n-curve (on the log-log-scale) is often presented as: (see for instance ISO 2394):

$$F(n) = P(N_d \geq n) < A\, n^{-k} \tag{4.4}$$

The parameter A is the (say imaginary) acceptable probability for n=1 and k determines the slope of the F-n-curve in a log-log-diagram. The value k=1 gives a line under 45°. The value of A may range from 0.001 to 1 and the value of k from 1 to 2. For relatively weak and stringent values of A and k example F-n-curves are presented in Figure 4.2. Some examples form chosen target reliabilities have been included

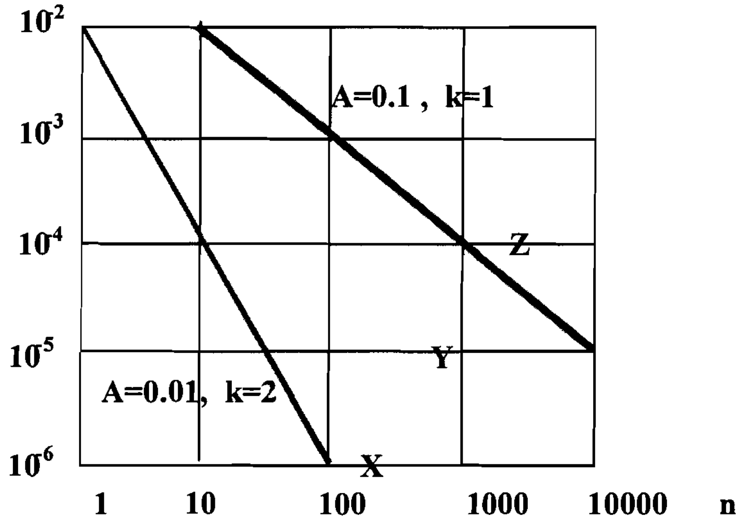


Figure 4.2 The $F(n) = P(N_d > n) < A\, n^{-k}$ requirement for one year (see ISO 2394).
Examples: X = the Storebelt requirement, Y = Delta works in Holland
Z = Channel Tunnel design

We shall discuss some issues related to this criterion in more detail.

The Choice of the F-n-curve

The choice of the F-n-curves and the ALARP region is a matter of Safety Policy of the company or the country involved. Many types of reasoning are followed in this respect. For instance, for the Channel Tunnel the policy was that the tunnel itself should be at least as safe as the (much longer) open railway part. It is questionable whether this is reasonable. May be it is better to have the same safety as for an open air track section of the same length. Maybe the safety could even be less as it may be expensive to increase the safety in the tunnel and the advantages of a tunnel are great anyway. But this statement may be difficult from the psychological point of view. See also chapter 5.

The value of k

High values of k express the social aversion to large disasters. Explanations for a more than proportional decrease in the failure probability (that is k>1) may be:

1. Economy of scale in the protection of a larger number of people. Exercises based on the econometric calculation method likewise lead to lower failure probabilities for more important consequences.
2. The effect of the social channels of communications is more intense in response to 100

deaths all at once than to 100 x 1 death. The cause lies in economy of scale in politics and the press.

3. The social disruption in more than proportional to $P(d|e_i)$. If an accident results in the deaths of 1% of a social entity, its further functioning remains possible. But if, say, 50% of the persons concerned lose their lives, the social structure is disrupted and the continued existence of the organisation as a whole becomes doubtful, even though half the number of individuals survived the accident.

The value of A.

A point of discussion, of course, is the choice of A. One should keep in mind that a country does not suffer from just a single riskful activity, but from series of hazardous activities, each one giving a contribution to the probability of having a large accident. So, from a theoretical point of view, the discussion on the socially acceptable level should start on a national level, incorporating all dangerous activities. For a single activity one may then derive a part of the total as an acceptance limit. Next, for each location where the activity is performed a share may be determined. The choice of A (and k) on the national level should reflect the national safety policy. Of course, large countries will have (for all hazardous activities together) larger A values then smaller countries for reasons of consistency. A country might also decide that some maximum should hold for each region, in order to prevent that one region gets all the risks and other regions have nothing.

Line elements.

A particular problem in this field is the acceptance criterion for line elements like railways, waterways, roads, pipelines, etc, intended for the transport of dangerous materials. In those cases one might for instance be interested in the acceptable failure probability per kilometre. One should, however, keep in mind that the failure event for one part of the line element may be correlated to another part. In those cases it may be more rational to find the integrated probability of having a disastrous event over the whole system and compare this to the corresponding acceptance limit. .

Frequent small accidents

Society of course also has an aversion to frequently occurring small accidents. The most important example is the car accident. Limits to these types of accidents, however are more to be found in the individual risk criterion. The (4.4) criterion in any cases is not relevant. In most countries the number of accidents is about 10^{+3} to 10^{+4} with n = 1 to 4. In Figure 4.1 this would indicate a point far above the line given by A=0.1 and k=1. We even have to interpret the probability as a frequency. For this reason (4.4) is often considered only to be valid for n>10.

Relation between social and individual risk

It is interesting to point out that there is a relation between the individual risk and the probability of exceeding a number of casualties for some particular activity. Consider a plant where there is some danger of explosion. In the neighbourhood of this plant people are living. Let $\nu(xy)$ be the number of people per unit area living at location (x,y) and let P(x,y) be the probability of a person being killed in one year if being on location (x,y). The expected number of casualties per year may then be calculated from:

$$E(N_d) = \iint P(xy)\ \nu(xy)\ dxdy \qquad (4.5a)$$

So this is the expected number of casualties based on the individual risk. Based on the group risk notion, we may define the same number as:

$$E(N_d) = \int P(N_d>n)\ dn \qquad (4.5b)$$

This relation makes clear that the social or group risk requires the same information as is needed for evaluating the individual risk plus the information on the population densities.

An inconsistency in the criterion for k=1

A theoretical difficulty in applying the requirement (4.4) is the following. Consider two activities A and B, where activity A has an occurrence probability of 10^{-3} per year and results in exactly 100 fatalities; activity B is characterised exactly by $P(N_d>n) = 0.1\ n^{-1}$ for $n \geq 1$. Both activities fulfil the social safety requirement with A=0.1 and k=2. However, the expected number of fatalities per year for activity A is 0.1 while, as can easily be shown, for activity B the expectation is infinitely large. It is difficult to accept such a big difference in expectation where the criterion considers both situations as "just on the limit".

Some criteria have additionally to the A n^{-k} line a limit to the maximum number of fatalities N_{max}, for example $N_{max} = 5000$. In that case the expected number of fatalities per year can be found to be:

$$E(N_d) = \Sigma\ n\ P(N_d=n) \approx {}_1\!\int^{N_{max}} n\ f(n)\ dn + N_{max}\ F(N_{max}) = A\ \ln(n)\ |_1^{N_{max}} + A \approx A\ \ln(N_{max}) = 0.8.$$

The sum has been approximated by an integral expression running from n=1 to $n=N_{max}$., where $F(n) = P(N_d>n)$ and $f(n) = -dF(n)/dn$. For k>1 we have in a similar way:

$$E(N_d) = A\ \frac{k}{k-1}\ [1 - (1/k)\ N_{max}^{-k+1}]$$

So in this case the expectations are final. Fortunately the expectation is not very sensitive to N_{max}.

4.4 Economic criteria

In the third acceptance criterion the problem is schematised as a mathematical-economic decision problem by expressing all consequences of the disaster in terms of money (assuming a given period of time):

$$C_{tot} = C_o(y) + \Sigma\ \frac{P_{Fj}(y) C_j}{(1+r)^j} \qquad (4.5)$$

$C_o\,(y)$ = investment in a safety measure
j = number of the year
r = real rate of interest
C_j = damage costs in year j
y = decision parameter
$P_{Fj}(y)$ = probability of failure in year j

One should realise that $P_{Fj}(y)$ denotes the failure exactly in year j, that is not in any year before or later. The term C_j includes all costs after failure: it includes direct damage, cost of repair, but also all future failure costs of the repaired structure (if any). So in fact it is a quite complex term, but most contributions other then direct damage and repair may be small in most cases. The failure cost C may or may not involve a term related to a monetary value of human lives. We will come back to this issue in the next paragraph.

If P_F is considered as being constant in time and the relevant period of time may be taken as an infinitely long period of time, then the optimum yearly failure probability can be found by to be:

$$P_{Fj}\ (optimum) = \frac{r\,I'\,b}{C_j} \tag{4.6}$$

I' = first derivative of I to the decision parameter x
$b = P_F\ /(P_F\ /\ dy)$ (for example $P = exp(-\ (y\text{-}A)\ /\ B)$, then $b = B$)

According to (4.6) a higher damage leads to smaller optimum failure rate as might be expected. Obviously one also has to check whether this optimum is better than present situation. So we should additionally to (4.6) also fulfil:

$$C_o(y) + \Sigma\ \frac{P_{Fj}(optimum)C_j}{(1+r)^j} < \Sigma\ \frac{P_{Fj}(present)C_j}{(1+r)^j} \tag{4.7}$$

The point is that the present situation may be close to the optimum in which case the C_o-investment is not worthwhile to do. In this comparison it is important that C_o does not only include all costs but also all profits from the activity or the system.

Of course, in the general case, more then one hazard may be present and one may want to consider the optimum for all integrated safety measures.

4.5 Combination of the criteria

Most decision makers prefer to treat the economic and human safety criteria ompletely separated. It means that we take the most economical solution from all alternatives that are allowable from the human safety point of view. Mathematically that comes down to:

minimise: $$C_{tot} = C_o(y) + \Sigma \frac{P_{Fj}(y)C_j}{(1+r)^j} \tag{4.8a}$$

conditional upon: $$P(d) = P(E) * P(d|E) < P(target) \tag{4.8b}$$

$$P(N_d > n) < A\, n^{-k} \tag{4.8c}$$

In (4.8a) the parameter C_j represents the material losses only. This approach looks fine but may not be correct from a decision making point of view. It would be better to assess some amount of money to the event of death or injury. It would create a mechanism where more safe solutions are chosen if there are more people at risk. If, despite ethical objections to such an approach, a human life is rated at an amount s, an insight into the effect of this upon the optimal failure probability is obtained. For this purpose the amount for material damage is increased from C_j to $E(N_d)\ c + C_j$ where $E(N_d) = P(d|e_i)\ N_p$, is the expected number of casualties and c is the “monetary value per casualty”. The optimum failure probability then becomes:

minimise: $$C_{tot} = C_o(y) + \Sigma \frac{P_{Fj}(y)\{C_j + c\,E(N_d \mid F)\}}{(1+r)^j} \tag{4.9a}$$

conditional upon: $$P(d) = P(E) * P(d|E) < P(target) \tag{4.9b}$$

$$P(N_d > n) < A\, n^{-k} \tag{4.9c}$$

So the two constraints resulting from the individual and the social acceptance limits are still present. The requirements (4.9) together, in fact, is representation the ALARP principle, that is measures may follow form an economic criterion but some risks are simply not accepted. Only the negligible lower bound is not defined here. A numerical example of the application of the criteria in this section can be found in Annex B.2.

Note further that for c=0 the criterion is fully compatible to the first approach mentioned in this paragraph. This of course can hardly be called an attractive proposal. However, if not zero, the difficult problem of choosing a certain value for a human life has been introduced. Numerous approximations for this are to be found in the literature. One may for instance take the cash value of the net national product per inhabitant. Another approach is to determine what people are willing to pay for reductions in risk, either from what they say or from the choices they make in practice [4.11]. For example, a sample of individuals can be asked what they would be prepared to pay for a 1 or 10 per cent reduction in the risk of being killed in a road accident; alternatively the extra wages required in occupation deemed to be dangerous can be evaluated. Finally one may look into amounts of money that are used in medical practice. The values have been summarised in Table 4.3. As one might expect, such exercises result in a wide range of values, from a few hundred thousand to few million Euro; a reasonable median value seems to be 1.0 million Euro. Another method, based on the so called Life Quality Index (LQI) may be found in [4.12] and [4.13].

Theoretical Evaluations	**Value for c [Euro per person]**
Human capital calculations	300.000
Willingness to pay (hypothetical)	1.600.000
Road Safety (UK, 1987)	500.000
Costs of medical procedures for comparison (real)	2.000 – 300.000

Table 4.3 Investment in Risk Reduction, per nominal life saved [University of East Anglia in 1998]

Whatever rule is followed, one should of course always keep in mind that ensuring a design that meets the safety targets is only the first step towards achieving a safe plant, though an indispensable one [4.9]. Safety can be delivered only by good management. The best designed plant can be compromised by poor maintenance and sloppy operational discipline.

5. RISK COMMUNICATION

5.1 Why communicate about risks?

A risk assessment as described in the previous chapters, even if technically perfect, is in general it is not sufficient to reach a decision. The risk assessment is a tool to help the decision making process, not the decision maker itself. Both the risk analysis as the acceptance criteria may be subject to debate. In general it is necessary to reach consensus about the various options available between the various parties involved. This process is referred to as risk communication. More formal definitions may be found in annex A.

Possible parties involved in a decision process on risk acceptance are:

- politicians
- civil servants, officials
- companies (producers)
- insurance companies
- lawyers
- the news media
- the public
- experts

It will rarely be the case that any one of these will fill the role of being just a communicator or just the audience. In practice, the inherent exchange of information means that all will fill both roles at different times, and to different extents. In any case, someone who talks but does not listen can hardly claim to be involved in *communication.* As a consequence, communications about risks will normally be complex and -because of the need to bear in mind the perceptions and understandings of the differing audiences- difficult.

It is not to say that communications are always directly aimed at decision-makers only. The general public as a whole, for example, are rarely in the position to make decisions involving risk, since professionals or politicians normally make such decisions on their behalf; but they will nonetheless often be affected by those decisions. Since the public's opinions do (at least, in a democracy) matter, decision-makers will usually need to keep them informed as much as is possible. The public *have an interest in* risk, even though they might not always *be interested in* it.

Although the overall aim might be thought to be better decision-making, "better" is a multi-dimensional, qualitative concept -so it cannot be assumed that minimisation of risk must always be the overall objective. "Risk" is simply one factor that needs to be taken into account. A clearer objective would be to give *better-informed* decision-making. But here, too, "better informed" should not be thought of as referring only to the decision-makers themselves: the term does also cover those who would be affected.

5.2 Perceptions and understandings

How does communication take place? The easy answer to this is "in any and every way". In practice, though, some ways are more common than others. A few communication forms will be discussed and the perceptions and understandings characterized.

Communications by Experts

Professionals and experts are the main group of people who might normally be expected to be trained, albeit sometimes at an elementary level, in risk identification/analysis. As such, they are more amenable to a mathematical means of communication than other groups -although even this may depend to a certain extent on the profession involved.

Methods of communication tend towards formalized approaches:

- Within a profession, the emphasis is on professional journals, seminars, reports, committees etc.
- When communicating with clients, the communication is usually by written report, often with verbal backup, e.g. at face-to-face meetings.
- Communications with politicians are rarely direct, instead being via some other means such as reports to officials, by giving evidence at public enquiries etc.
- Contact with the public media is normally at a very minimal level, presumably because journalists do not view risks and risk-analysis as being "sexy", i.e. as being attractive and eye-catching to their readership.

The difficulty faced by the professional is that nearly all other parties no not think in teh same terms about risk. The concept of risk as the (integrated) product of consequences and probabilities is far from common in most other parties, with possible exceptions of specialised officials and company experts. However, even then communication may be hampered by relatively small differences in interpretation. Especially the high impact low probability (HILP) events, in particular when subject to large subjective uncertainty estimations, may cause deeply philosophical debates among experts themselves.

The most difficult communication, however, may be the communication with the public. The point is that the public in general has had no training in thinking of terms of risk as probability times consequence. The perception of risk may therefor be complete different. Risks are considered as unacceptably great if the consequences are large and the cause of events leading to it can be vividly imagined. This is the reason that recent catastrophes, broadly presented by the news media, always call for strong measures (see the examples in the introduction and Annex B. On the other hand, is something has never happened before or only a relatively long time ago (more than ten or twenty years) the risk in the view of the people is not so serious.

The engineer usually sees it as his task to warn against this over- and under-estimation. However, the difficulties may be large, especially as "the public" does not exist but is a mixture of individuals all having a different understandings from and attitudes towards risk. We will now discuss the various communications from and by the public in more detail.

Communications from the public

The form that the public's communications might take varies according to the circumstances. It is, however, commonly aimed at politicians and usually attempts to make use of the news media.

Immediate, one-off hazards, such as the planned construction of a chemical works in the local neighbourhood; the routing of a train carrying hazardous material or the introduction of a major road system nearby, typically give rise to protest meetings, marches, petitions, organised letters to politicians. The collection of signatures for a petition, and the organising of letters, might themselves involve people in going from door-to-door or in setting up a stand in some public place such as a market: both of which give opportunity for the handing-out of leaflets and for individual discussion. Expressed concerns normally concentrate on hazards and threats rather than risk.

Long-term, continuing hazards such as the general levels of traffic accidents and pollution can give rise to all of the forms of communications as in the immediate, one-off case. An additional mechanism of communication, commonly associated with this type of hazard, is the setting up of a recognised pressure group with formal representation on committees, working groups etc. Because the interest is in general levels (which are basically long term expectations confirmed on a regular basis), there is a natural tendency here to be more concerned with risks than threats.

Communications to the public

Communications to the public are rarely about risk per se but usually about various threats or hazards and -sometimes- their probabilities.

Communications can take place at a very personal level, such as between doctor and patient about the probabilities of the various outcomes associated with an illness or operation. In the building industry, there might be personal discussion between a surveyor/consultant etc and home-owner about the hazards associated with not carrying out some form of remedial action.

In public domains, there can be -but usually is not- some very basic discussion of probabilities in the immediate aftermath of a major incident such as an explosion or rail crash. More commonly, however, any discussion about long-term threats, such as those from smoking or from traffic levels, is a mixture of qualitative and quantitative information.

Role of the news media

The news media are usually viewed as being central to communications generally, and Risk is no exception.

The media play two essentially different roles: as a **passive** transmitter of someone else's message (as when they repeat a press release), or as an **active** producer, or interpreter, of a message. They will often use several sources of information, and are by no means limited to official sources. Their messages often reflect the concerns of the public and other sectors of society, but are not necessarily unbiased.

Professional journals and magazines are rarely published at even weekly intervals, more usually being monthly or quarterly. These long publication dates can combine with the the nature of professional discussion to place the emphasis on long-term probabilities and risk rather than immediate happenings.

The demands acting on the daily media, however, mean that they must inevitably tend to emphasize the short-term and so want to report immediate events such as large-scale accidents or just-published reports into areas perceived as being of public concern. Discussion about longer-term implications can [5.4] find their way into Editorials, the weekly press and discussion programmes.

5.3 The basic rules of Risk Communication to the public

Unfortunately, there is (at least, in english-speaking countries) the common expression "you can prove anything with statistics". As a result of such beliefs, the public tends to judge a message about risk not so much in terms of any information that it contains but, rather, in terms of their view of the communicator.

In addition, from the formal point of view, “information” is a measure of the surprise contained in a message. A message whose content could be completely predicted in advance contains no surprises and so carries no information, but one whose content could not be predicted at all is highly surprising and has a correspondingly high information content.

From either point of view, the information that a communication contains depends on what the audience would expect it to contain. This does depend, to a very large extent, on their view of the communicator.

For example, if a tobacco company were to say that smoking carried no risks, then the public would be unlikely to take much notice since that is what they would expect them to say, so there would be no surprise in hearing it. But if an anti-smoking pressure group were to say exactly the same thing then the surprise would be very great, and the information conveyed would be that much higher and have correspondingly greater impact and effect.

A major factor, here, is the public's view of the *credibility* and *trustworthiness* of the communicator. These are qualitative terms which are very difficult to define, but include other concepts such as [5.3] *factual*, *knowledgeable*, *expert*, *public welfare*, *responsible*, *truthful*, and good "*track record*".

It is generally accepted that credibility and trust can take a long while to build up, but can be quickly and easily destroyed by ineffective or inappropriate communication. Factors which can destroy trust in a communicator include *omissions*, *exagerations*, *distortions*, *self-serving statements*.

Covello and Allen [5.5], in a widely-quoted paper, took seven basic rules of good communications, and interpreted them in the context of risk communication, as follows:

- *Accept and involve the public as a legitimate partner.* A basic tenet of risk communication in a democracy is that people and communities have a right to participate in decisions that affect their lives, their property, and the things they value.
- *Plan carefully and evaluate performance.* Risk communication will be successful only if carefully planned.
- *Listen to the public's specific concerns.* If you do not listen to people, you cannot expect them to listen to you. Communication is a two-way activity.
- *Be honest, frank and open.* In communicating risk information, trust and credibility are your most precious assets.
- *Co-ordinate and collaborate with other credible sources.* Allies, if believed to be independent, can be effective in helping you communicate risk information.
- *Meet the needs of the media.* The media are a prime transmitter of information on risks; they play a critical role in setting agendas and in determining outcomes
- *Speak clearly and with compassion.* Technical language and jargon are useful as professional shorthand. But they are barriers to successful communication with the public.

5.4 Closure

Risk Communication:

- Is a very complex subject involving highly technical information, psychology, presentational skills etc.
- Is about involving all partners in an open and honest way. Any attempt to dissemble will almost certainly defeat the objective.
- Involves sending messages about complex concepts to a wide range of people and organisations with differing levels of skills and understanding, and listening to their responses: which will often be contradictory, and use apparently technical words in a non-technical sense.
- Requires flexibility.

6 CONCLUSIONS AND RECOMMENDATIONS

Risk is commonly estimated by the mathematical expectation of the consequences of an undesired event that often leads to the product "probability × consequences". As a rule risk of civil engineering systems is multidimensional quantity having several components.

A Risk analysis is generally contains the following steps:

- scope definition,
- hazard identification,
- modelling of hazard scenarios
- estimation of consequences
- estimation of probabilities
- estimation of risks

The first three steps are the Qualitative Part, the last three steps the Quantitative Part. In many cases only the Qualitative part is carried out and measures are taken on an intuitive basis. Although not complete, such an analysis is certainly not without value. Better however is to include the last three steps and perform a full Quantitative Risk Analysis.

An intermediate procedure is to define a number of design hazard scenarios on the basis of step 3 and check the systems abilities to cope with them. Such an approach is often referred to as a "deterministic risk analysis". This of course is not a correct term as the selection procedure involves some implicit judgement about the probabilities and the consequences of the hazard scenarios selected. No one would select design scenarios that are expected to occur either too often or never at all. If somehow the probabilities enter the selection procedure in an explicit way, one may speak of the "semi-probabilistic" approach. Anyway, the existing gap between "probabilistic" and "deterministic" methods in Risk Analysis should be narrowed.

However, the theoretically best way to proceed is an explicit full probabilistic estimate of all the events and corresponding consequences. The next step is then to think of and evaluate measures for reducing the risks. The commonly accepted approach is to define two levels: Above the upper level the risk is considered as being not acceptable and below the lower level the risk is considered s being negligible. For the area between the limits economic considerations may govern the decision. This is considered as the ALARP-principle (As Low As Reasonably Practicable)

The upper limits may be inspired by the ethical maximum acceptable risk of individual persons or by the risk aversion of society to large disasters, usually expresses as F-n-curves. The cost optimisation may or may not include some "value of the human lives lost". This document advocates to include some value for casualties, as neglecting them is the same as choosing a value of zero.

From an objective point of view the decision process seems to end when an economic solution has been reached falling within the bounds permitted by the individual and group risk criteria. However, in practice life may be completely different. In many civil engineering applications decisions for are not made by the engineers but by others: clients, public, politicians. In other cases people may react in a different way as expected: a tunnel or bridge may be avoided if ti is considered as unsafe, true or not. It is not sufficient to ask them simply for the proper F-n-curve. The other parties involved may even fail to understand what an F-n-curve exactly is or what a cost-benefit analysis in the case of uncertainty stands for. The notions of probability, consequence and risk may have completely different meanings depending on the background and education of people. I addition to that we have to face in this discussion the High Impact Low Probability event, the subjective probability estimates, the differences in profits for the various parties involved and so on. This all makes the risk communication process a very critical, not to say random process in itself.

Some recommendations in this field may be:

- Accept all parties as legitimate partners and listen to the public's specific concerns.
- Co-ordinate and collaborate with other independent and credible sources.
- Make at first sight unlikely looking but dangerous events more believable using visualisation in order to avoid under-reaction by public and authorities
- Accept emotional overreaction to large disasters as a fact of life, in particular shortly after a catastrophe and try to get more rational reactions in a later stage.

It should be kept in mind that public and political reactions to disasters often lead to worthwhile measures and procedures in the world of engineering that could not be reached before.

Closure

The present report presents an overview of the state of the art in Risk Assessment and Risk Communication in Civil Engineering. It is clear that this is a topic of increasing interest. Many decisions related to buildings, civil engineering structures and major civil engineering planning affect the safety of many people in a variety of ways. It is important that all concerned speak the same language and can understand each other. A good step forward might be to develop an extensive ISO document in this field, not only standardizing the terminology, but also describing methods, interpretations and procedures for fruitful communication between the various parties involved.. Additionally, worked examples and reports of cases on the basis of such a standard would be extremely helpful.

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ANNEX A DEFINITIONS

The following definitions are provided in order to assure a consistent understanding of selected terms within the scope of CIB TG 32, which aims at achieving consensus amongst expert concerning guide lines for assessing public perception of safety and risk related to civil engineering works.

Acceptable risk: A level of risk, which is generally not seriously perceived by an individual or society, and which may be considered as a reference point in criteria of risk.

> Note. It is expectable that various aspects including cultural, social, psychological, economical and other aspects will influence society risk perception (see also definition of criteria of risk).

Causal analysis: A systematic procedure for describing and/or calculating the probability of causes for desired or undesired events.

Consequence: A possible outcome of a desired or undesired event.

> Note. Consequence may be expressed verbally or numerically to define the extent of human fatalities and injuries or environmental damage and economic losses [1].

Consequence analysis: A systematic procedure to describe and/or calculate consequence.

Criteria of risk: Reference points against which the results of the risk analysis are to be assessed. Criteria are generally based on regulations, standards, experience, and/or theoretical knowledge used as a basis for decision about acceptable risk.

> Note. Acceptance criteria and criteria of risk may be distinguished [1]. Various aspects may be considered, including cultural, social, psychological, economical and other aspects [6]. Acceptance criteria may be expressed verbally or numerically [6].

Frequency: number of times an event occurs per unit of time

Hazard: A set of circumstance with the potential for causing events with undesirable consequence.

> Note 1. For instance a set of circumstances with the potential to an abnormal action or environmental influence and/or insufficient strength or resistance or excessive deviation from intended dimensions, in the case of a chemical, the potential that the substance has for causing adverse effects at various levels of exposure. [2].
> Note 2. In some documents (for example in the recent draft of EN 1990 [7]) the hazard

is defined as the event, while in risk analysis [2] it is considered as a condition with the potential for causing event. Thus, in risk analysis the hazard is a synonym to danger.

Hazard identification: A process to recognize the hazard and to define its characteristics.

Hazard scenarios: Sequence of possible events for a given hazard leading to undesired consequences.

Note. To identify what might go wrong with the system or its subsystem is crucial to a risk analysis. It requires the system to be examined and understood in considerable detail [6].

Objective probability: Probability determined using theoretical arguments or adequate statistical data.

Objective risk: An estimate of system risk obtained using theoretical arguments or adequate statistical data (for example annual expected fatalities from car accident) or from quantified risk analysis methods (QRA, PRA).

Option analysis: The process used to identify a range of possible alternatives for managing the risk.

Probability: The likelihood or degree of certainty of a particular event occurring, on a given occasion or during a specified period of time.

Note. Probability may significantly depend on a time period during which a particular event may occur.

Reliability: Ability of a system or part thereof to fulfil the specified requirements during a given period of time (e.g. design life).

Note 1. Reliability is often expressed as probability related to a specific requirement and period of time [3,4,5].
Note 2. Reliability with respect to ultimate limit states is often referred to as safety, reliability with respect to the serviceability limit states is often referred to as serviceability [3,4,5].

Risk: A measure of the danger that undesired events represent for humans, environment or economic values. Risk is expressed in the probability and consequences of the undesired events.

Note 1. Risk is often estimated by the mathematical expectation of the consequences of an undesired event. Then it is the product "probability $\times$ consequences". However,

a more general interpretation of risk involves probability and consequences in a non-product form. This presentation is sometimes useful, particularly when a spectrum of consequences, with each magnitude having its own corresponding probability of occurrence, is considered [2].
Note 2. Various levels of risk may be recognized, for example acceptable risk, tolerable risk, objective risk (see definition of theses terms) [6].

Risk analysis: The use of available information to estimate the risk to individuals or populations, property or the environment, from hazards.

Note. Risk analysis generally involves the context (scope) definition, hazard identification, and risk estimation [2].

Risk assessment: The process of risk analysis, risk acceptance and option analysis.

Note. In some documents [2] risk assessment is defined as risk analysis and risk evaluation, where risk evaluation covers risk acceptance and option analysis (see definition of risk evaluation).

Risk communication: the exchange of information and opinions concerning risk and risk-related factors among risk assessors, risk managers, consumers and other interested parties.

Note: This definition is from [5.3]; alternatives may be found in [5.1] and [5.2]. Important is that "risk communication" is not the mere communication of technical information about risk but also involves wider concepts concerning people's opinions, reactions etc.

Risk estimation: The process used to produce an estimate of a measure of risk.

Note. Risk estimation is based on hazard identification and generally contains the following steps: scope definition, frequency analysis, consequence analysis, and their integration [2].

Risk evaluation: The process of risk acceptance and option analysis.

Risk management: The complete process of risk assessment and risk control.

Note. Entire risk management is schematically indicated in Figure 1 (adapted from [2]).

Safety: The state of being adequately protected against hurt or injury, freedom from serious danger or hazard.

Note. In structural reliability safety is often understood as reliability with respect to ultimate limit state (see definition of Reliability).

Safety management: Systematic process undertaken by an organization in order to attain and maintain a level of safety that complies with the defined objectives.

Sensitivity analysis: A systematic procedure to describe and/or calculate the effect of variations in the input data on the final result.

Subjective probability: Probability determined using intuition and relevant experience.

System: A bounded group of interrelated, interdependent or interacting elements forming an entity that achieves in its environment a defined objective through interaction of its parts.

Note 1. This definition implies that the system is identifiable, is made up of interacting elements or subsystems, all elements are identifiable, and the boundary of the system can be identified [2].
Note 2. In terms of technological hazards, a system is normally formed from physical subsystem, human subsystem, their management, and environment [2].

Tolerable risk: A level of risk, which an individual or society is willing to live with to secure certain benefits in the confidence that the risk will be properly controlled.

Note. The tolerable risk may not be negligible but it should be kept under review and permanent control [6].

Undesired event: The event, which can cause human fatalities and injuries or environmental damage and economic losses.

References for Annex 1

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ANNEX B CASES

ANNEX B.1 Performance Deficiency of Department store

Introduction

Load bearing structure of the department store consists of a flat reinforced concrete slabs supported directly by columns within span distances 12 × 12 m (see *Fig.1*). Slim slabs (height of 450 mm) above the first and second storey cantilever out by 3 m beyond the edge columns. Shortly after its completion, several structural defects concerning cladding elements, interior partitions and other secondary elements (cracking of walls, deflections of horizontal elements, malfunctioning of sliding doors, etc.) have been observed (see *Fig. 2* and *3*).

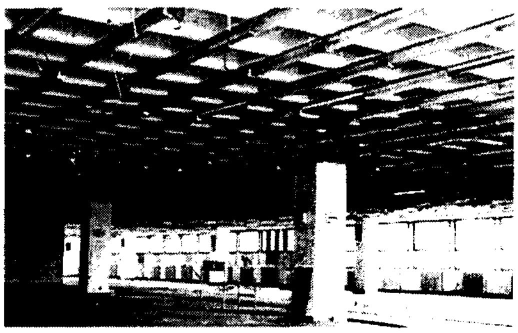

Fig. 1 Load bearing structure

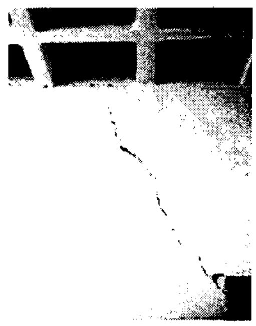

Fig. 2 Crack in a partition

Fig. 3 Damaged partition

Assessment

The detail analysis and assessment of the building has shown that the structure had sufficient bearing capacity and was safe with respect to the ultimate limit states. The main reason for development of observed defects was clearly insufficient stiffness of large span cantilevered slabs. Observed deformations and other unfavourable effects (caused mainly by permanent load and shrinkage) have been slightly enhanced due minor construction faults. Nevertheless, due to unfavourable public perception and uncertainty in expert assessments (generally analysed in [1]), three years after its completion the department store was closed and thoroughly reconstructed.

Public perception

New department store became soon the building closely watched by a large population of users and local authorities. Incidentally, at the same time another department store suffered from construction faults and this was partly the reason why all the performance deficiencies have been carefully recorded (similar experience is notified in [1]). Observed defects were often exaggerated and regarded to as indicators of insufficient structural safety. Widespread public perception of defects and discrepancies in experts assessments were reported in newspapers and finally resulted in a strong communal pressure on strengthening of the whole building.

Theoretical model for public perception

Evaluation of public as well as experts assessments has indicated that there is no distinct point in any performance indicator x (e.g. deflection, crack width) that would separate acceptable and unacceptable structures. Rather there seemed to be a transition region <a, b> in which the structure gradually becomes unserviceable and the degree of caused damage $\nu(x)$ increases [2]. A conceivable model for $\nu(x)$ is indicated in *Fig.4*. Obviously, at any damage level $\nu(x)$ there may be a perception scatter expressed by distribution function $\Phi_P(x,\mu_P,\sigma_P)$, for which lognormal distribution having the mean $\mu_P = x$ and standard deviation $\sigma_P = s \times a$ is accepted here. Taking into account all levels $\nu(x)$, the cumulative damage $\Phi_D(x)$ is [2]

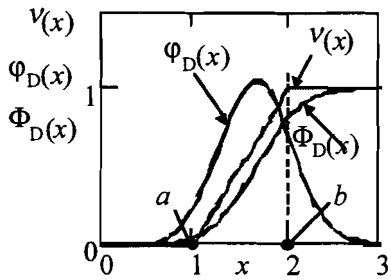

Fig. 4 Perception model

$$\Phi_D(x) = K\int_a^b \nu(\xi)\,\Phi_P(x,\xi,\sigma_P)\,d\xi \tag{1}$$

where K is the normalising factor. Cumulative damage $\Phi_D(x)$ and corresponding density function $\varphi_D(x)$, shown in *Fig.4* for $a = 1$, $b = 2$ and $s = 0.3$, can be considered as generalised probabilistic models (involving economic aspects) [2]. Considering appropriate load effect E (e.g. deflection, crack width) expected perception level π can be defined as

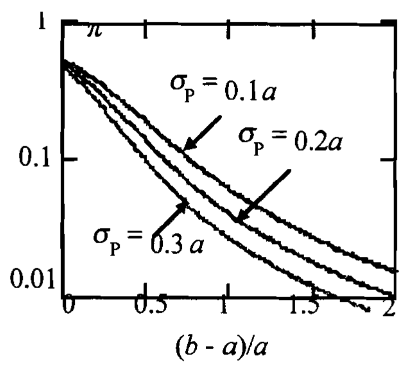

Fig. 5 Expected perception level π

$$\pi = \int_{-\infty}^{+\infty} \varphi_E(x)\,\Phi_D(x)\,dx \tag{2}$$

Here $\varphi_E(x)$ is the probability density function of E; gamma distribution having the mean equal to the lower limit of the transition region a and coefficient of variation 0.2 is assumed in in *Fig. 5*, where expected perception level π is indicated as a function of the ratio $(b-a)/a$ and σ_P. It appears that the expected perception level π is strongly dependent on the width b-a, which may further depend on sensitivity or experience of an observer. This finding explains observed differences in public perception and discrepancy in expert assessment.

Conclusions

- Serviceability failure of the department store was primarily caused by lack of consideration in design of deflection due to permanent load and shrinkage.
- Current engineering climate seems to play an important role in the public perception of performance deficiencies and subsequent structural assessment.
- Disturbing variance in public perception and in expert assessment of structural defects may be well explained using proposed theoretical model for public perception.

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ANNEX B.2 Flood protection in The Netherlands

The situation

The Netherlands are situated in the delta of three of Europe's biggest rivers: the Rhine, the Meuse and the Scheldt. Large parts of the country lie below the water levels that may occur on the North Sea, the large rivers and the IJsselmeer. Consequently, most of the country is protected by flood defences. Along the coast, protection from flooding is provided by a combination of dunes and sea dikes. Along the entire Rhine and along parts of the Meuse, river dikes offer protection from flooding by the rivers.

The 1953 incident and the reaction

In 1953 a large number of dikes failed during a strong North Western storm and over 1800 people living in the Western part of the country drowned. After this disaster a thorough investigation was carried out by a special task committee, the Delta Committee, which was installed by the government. The committee produced safety standards on the basis of a cost benefit approach. The analysis did not include casualties and other imponderables. The resulting optimal safety level for the central part of the country corresponded to a return period of about 10^5 year.

Measures taken

Given the technical capabilities at that time, this safety concept was not implemented directly. By way of simplification a design sea level was chosen with a return period of 10^4 year. For economically less vital areas lower values were derived. Additionally it was required that the failure probability of the dikes should be small, given the design conditions. The probability of a dike actually collapsing (and flooding) was not calculated.

Present situation

In 1995 the present safety standards have been laid down in the Flood Protection Act. The purpose of the Flood Protection Act includes maintaining safety, which is being achieved by the dike strengthening process instituted after the floods of 1953. In the Flood Protection Act the opportunity is given to change, in due time, to a more advanced safety concept based on flooding probabilities for so called dike-ring areas. A dike-ring area is the area that is surrounded by a continuous system of flood defences. The new safety concept requires the calculation of the flooding probabilities. The method to do so are now under development. The method includes the stochastic modelling of both loads (sea levels, wind speeds, river charges) and resistances for a set of failure mechanisms. Statistical dependency between the failure modes and between the various dike sections is taken into account. Additionally there is a tendency to make estimates of the inundation consequences in order to arrive at a full risk base design.

The process of changing from the old system (based on return periods for design water levels) to a new system (based on inundation probabilities and risk) involves not only a discussion within the group of civil engineers, but also between engineers on the one hand and authorities and public on the other. Most people in Holland think that all dikes have been designed in such a way that flooding is to be expected only once in 10000 years (for central Holland) or 1 - 4000 years for the other parts. The probability of exceeding the design conditions is mixed up with the probability of inundation. Present day calculations show that the return period of inundation may be shorter than the return period of the design condition. It may be a problem to pass this message.

Anyway the new methods of analysis as well as the new results enforce a renewed thinking on the target reliabilities. The Dutch TAW-committee (which advises the minister of public works on affairs related to flood defence matters) uses the ideas presented in chapter 4, that is, targets are derived on the basis of individual and group risk criteria as well as economical considerations. By way of example, consider a (non-existing) dike ring area in The Netherlands with the following properties:

Np	number of inhabitants	100000	-
C	nominal monetary value of material loss	1000	M Euro
b	standard deviation of water height	0.33	m
I'	investment per m dike height	180	M Euro/m
P(d|F)	probability of drowning during inundation	0.01	-

Let us further assume:

r	discount rate	0.02	/year
c	nominal monetary value of human life	1	M Euro
P(target)	weight factor for inundation (involuntary risk)	10^{-5}	-
A	constant in social acceptable risk value	10	/year
k	risk aversion factor	2	-

Using the formula of chapter 4 we find as limits for the failure probability of the flood defence system:

(i) based on the individual risk criterion (4.2):

$$P_F < P(\text{target}) \;/\; P(d|F) = \quad 10^{-5}/0.01 = 0.001\ 00\ /\text{year}$$

(ii) based on the group risk criterion (4.3):

$$P_F < A\ \{P(d|F)\ N_p\}^{-k} = \quad 0.000\ 03\ /\text{year}$$

(iii) based on the economic criterion (4.6):

$$P_f = b\ r\ I' \;/\; [\ P(d|F)\ N_p\ c + C_i\ ] = \qquad 0.000$$

60 /year

If we put c=0 in the last equation we find 0.0012. So including a monetary value for the human lives gives a two times stronger requirement.

It can be seen that the social risk criterion, based on risk aversion against large numbers of fatalities, leads to the lowest value for the acceptable inundation probability for the flood defence system.

Lessons learnt
The disaster in 1953 gave the clearance for an ambitious flood protection plan, where risk analysis was used as far as the techniques at that time allowed to go. There was a common agreement between engineers, authorities and public about the cause of actin and the levels of safety. Half a century later, however, it is extremely difficult to re-open this discussion and to arrive at more advanced methods of verification. The new targets often seem to be stronger and the dike qualities lower than was expected.

ANNEX B.3 Ronan Point Tower (1968)

The incident

The need to provide replacement housing for that destroyed in the 1939-45 war prompted the development in Europe of innovative prefabricated construction techniques in the decades following. One such scheme involved the erection of high rise apartment buildings using factory made concrete components. The structural system comprised load bearing walls, with each level of apartments stacked directly on the one below. Floor on wall and wall on floor joints were grouted bearing surfaces.

On May 16, 1968 an undetected gas leak resulted in an explosion in the kitchen of a unit on the eighteenth floor when the occupant attempted to light the stove. The corner walls of this unit blew out, causing the wall above to collapse. These in turn impacted on the floors below and destroyed the whole corner of the building. Fourteen people were injured, three fatally.

Analysis of the event revelled the disadvantage of no alternative load paths being present when one part of an external wall at one level was removed. Demolition of the building also confirmed that deficiencies existed in the quality of the grouted joints between the prefabricated components.

The outcome of the Ronan Point Tower episode was that doubt was cast on the safety of other apartment towers using similar structural systems. Many were demolished well in advance of their aspected life expectancy. Progressive collaps, in which local failure is followed by a chain reaction producing widespread collapse, certainly was not unknown prior to the Ronan Point Event. Structures are particularly susceptible to this domino effect in the course of the construction process. What was unusual in the case of the Ronan Point was that a relatively minor gas explosiontriggered the collapse of a significant portion of a completed building.

Lesson Learnt:

The experience of Ronan Point re-emphasised the need to be ware of the possibility of progressive collapse of constructed facilities, the desirability of providing redundancy – or fail safe possibilities – in structural systems and the necessity of ensuring quality control in the construction process.

As a result of the Ronan Point tower collapse, other projects in the United Kingdom deemed successtible to progressive collapse were demolished. In 1970, England strengthened its building standards to provide an alternative means of support, even if a main structural member were to be removed or to fail. Steel bracing with floor-to-wall connectors was mandated, along with a minimum tensile strength of 44 kN/m (3000 lb/ft) across the length and width of floors (ENR 1970).

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ANNEX B.4 The piper alpha oil platform disaster

The Incident

Piper Alpha was an offshore oil platform situated in the UK's North Sea. On July 8, 1988 a catastrophic fire destroyed the installation, leading to the death of 165 out of 226 persons on board and of two rescuers. The financial loss itself was said to be US $ 3 billion.
The explosions were caused by a vapour release through a flange. The resulting pool of fire created by this spread into many areas, including the important control room and the radio room which were, thus, destroyed at the early stages of the accident. Due to the first explosion many essential items such as electric power, public address systems, general alarm, and fire protection systems failed at the initial stages.
The failures that led to the disaster and its consequences are mainly attributed to 'human error' in design/expansion, production decisions, personnel and crisis management, and inspection/maintenance. Most of the questionable or bad decisions and practices had been given rise to by a bad management system. During the fire, many human errors such as the non-ordering of evacuation, blocking of evacuation routes, and inaccessible life boats helped to further increase the casualties. This was exacerbated by inoperable fire fighting equipment and poor fire fighting command procedure.

The Inquiry

On 13th July 1988, the UK government appointed Lord Cullen to investigate the disaster. The public inquiry, which lasted over a period of 13 months, consisted of two parts: the first on the actual events of the disaster, and the second on the lessons to be learnt. The inquiry report was presented to the Parliament in November 1990.

Resulting Actions

As a result of the disaster and the subsequent public inquiry, in 1991 the Government decided to increase spending on offshore safety by 150% - from il3m to E35m over four years. The Offshore Safety Division was transferred from the Department of Energy to the Government's safety regulator Health and Safety Commission (HSC).
Following the Cullent Report, the Government introduced the Offshore Installation (Safety Case) Regulations of 1992. This required the owner or operator of every offshore installation to submit a safety case for the approval of the HSC2. In addition, an updated safety case was required to be submitted every three years or whenever modifications were carried out to the operating system. The safety case needed to show that all operations have been fully risk-assessed, with systems in place to deal with any emergency. At that time, this meant the submission of safety cases for 272 fixed and mobile installations before 1993 for acceptance by 1995.
Further regulations which implemented more recommendations of Lord Cullen were introduced as Offshore Installations (Prevention of Fire and Explosion, and Emergency Response) Regulations 1995 and the Offshore Installations and Pipeline Works (Management and Administration) Regulations 1995.

Lessons Learnt

Due to the Piper Alpha disaster many lessons were learnt and relevant new safety related measures were put into place in the UK. For example,

For the 'extractive' industries, reporting requirements were made to include measures taken to prevent any repetitions of fatal and serious occupational accidents and dangerous occurrences.

- The employers were required to carry out formal safety assessments and demonstrate that the Safety Management Systems are adequate, and that major hazards are identified and suitable controls are in place.
- Every workplace was made to have competent qualified persons who are responsible for supervision.
- Moves were made towards more risk analysis based approaches to evaluate and design safety systems.
- Extensive reviews and scrutiny of all safety systems, especially passive fire proofing, were undertaken.
- The owners/operators of oil platforms were required to devise comprehensive risk management strategies and to promote a safety culture. This was to replace their previous strategy of providing the minimal requirements to satisfy the governing regulations.

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TG27 Human-Machine Technologies for Construction Sites
TG28 Dissemination of Indoor Air Sciences (joint CIB-ISIAQ Task Group)
TG29 Construction in Developing Countries
TG31 Macro-Economic Data for the Construction Industry
TG32 Public Perception of Safety and Risks in Civil Engineering (joint CIB-IABSE Group)
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TG43 Megacities
TG44 Performance Evaluation of Buildings with Responsive Control Devices
TG45 Performance Indicators for Urban Development (Joint FIG – CIB Task Group)
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TG47 Innovation Brokerage in Construction

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W018 Timber Structures
W023 Wall Structures
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W055 Building Economics
W056 Sandwich Panels (joint CIB - ECCS Commission)
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W067 Energy Conservation in the Built Environment
W069 Housing Sociology
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W078 Information Technology for Construction

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(as at 1st January 2001)

W080 Prediction of Service Life of Building Materials and Components (also RILEM SLM)
W082 Future Studies in Construction
W083 Roofing Materials and Systems (also RILEM MRS)
W084 Building Non-Handicapping Environments
W085 Structural Serviceability
W086 Building Pathology
W087 Post-Construction Liability and Insurance
W089 Building Research and Education
W092 Procurement Systems
W094 Design for Durability
W096 Architectural Management
W098 Intelligent and Responsive Buildings
W099 Safety and Health on Construction Sites
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2. Newsletter
3. Databases

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