RISK-BASED DESIGN OF COASTAL FLOOD DEFENCES: A SUGGESTION FOR A CONCEPTUAL FRAMEWORK

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Abstract: A conceptual framework based on probabilistic risk analysis (PRA) is proposed for the design of coastal flood defences which meets the sustainability requirements. The overall framework includes the management of the remaining risk as an integral part of the design process. The implementation of the risk analysis requires (i) the prediction of the flood risk, (ii) the evaluation of the acceptable flood risk and (iii) the evaluation of the flood risk level which is obtained through comparison of the predicted and acceptable flood risk.

NECESSITY OF NEW DESIGN APPROACH FOR COASTAL FLOOD DEFENCES

Coastal areas are among the most densely populated areas worldwide so that there is a large and increasing demand for housing, recreation and further socio-economic activities in these areas. Today almost 40% of the world population are living within a 100 km wide coastal strip and almost 70 % of the large cities with more than 2.5 million inhabitants are located in coastal areas (Fig. 1).

Generally, this tendency implies more infrastructure to be provided and more coastal defence structures to be built in this area. In fact, this development has already resulted in a dramatic conversion of the natural coastal zones to a built (artificial) environment protected by an almost artificial defence line.

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Width of Coastal Zone	Number and Percentage of Inhabitants of Coastal Zone as Related to World Population (5.62 10^9 in 1994)	
100 km	**$2.07\cdot10^9$**	**37 % (**)**
200 km	**$2.75\cdot10^9$**	**49 %**
300 km	**$3.71\cdot10^9$**	**66 %**

(*) based on figures by *Cohen et al.* (1997)

(**) include 65% of large cities with more than 2.5 million inhabitants

Fig. 1: Coastal population worldwide (after Cohen et al., 1997)

On the other hand, the most valuable ecosystems are located in the coastal zones. An approach to evaluate ecosystems in the world has been put together by Constanza et al. (1997). The results in Figure 2 have shown that (i) the services of all ecosystems of our planet have been evaluated to a total of about 33.000 billion US $ / year, that is almost twice the Gross National Product of the world population, which is about 18.000 billions $ / year; (ii) although the coastal zones world-wide occupy only 6 % of the total surface of our planet, they represent almost 40 % of the value of all marine and terrestrial ecosystems (this means 12.500 billion US $ / year form a total of 33.000 billion US%$ / year).

	Marine Ecosystems		**Terrestrial Ecosystems**			**Ecosystems of Planet Earth Total**
	Open Sea	**Coast**	**Forest**	**Wetlands**	**Others**	
Area [Million ha]	33 200 (64 %)	3 102 (6 %)	4 855 (9.4%)	330 (0.6 %)	10 138 (20%)	51 625 (100 %)
	36 302 (70 %)		15 323 (30 %)			
Yearly value per area [US$/a/ha]	252	4 052	969	14 785	-	-
Yearly total value [Billion US$/a]	8 381 (25 %)	12 568 (38 %)	4 706 (14.1 %)	4 879 (14.7 %)	2 743 (8.2 %)	33 268(*) (100 %)
	20 040 (63 %)		12 319 (37 %)			
Gross National Product of Earth Inhabitants: US$ 18 000 Billion/a						
Ecosystems of Planet Earth / Gross National Product: $\frac{33\,268}{18\,000}=1.84$						

(*) adapted from figures given by *Constanza et al.* 1997

(**) with variation range of US$ 16 000 - 54 000 Billion. Due to these uncertainties the mean value of US$ 33 268 billion is rather underestimated than overestimated

Fig. 2: Valuation of terrestrial and marine ecosystems (after Constanza et al., 1997)

These rather surprising result suggest that conservation and preservation of the coastal ecosystems should have the highest priority which is contradictory to the need of more coastal defences and infrastructure which was required by increasing population in coastal areas which was highlighted before.

Solving this “coastal conundrum” is only possible by following a sustainability approach as for example suggested by Oumeraci & Kortenhaus (2001). These and further considerations suggest that a design approach - based on the failure probability of flood defence structures, associated flood probabilities and risks - must be developed. Further reasons pleading for a probabilistic risk analysis (PRA) as the sole candidate framework are: (i) the large variety of the involved aspects, together with their uncertainties which have to be addressed explicitly in the analyses, (ii) the integrated nature and the high complexity of the design problem, as well as (iii) the necessity to harmonise design and safety standards in various fields (coastal engineering, dam engineering, transportation, nuclear power plants, etc.).

Moreover, the new direction forward should provide a detailed scientific and technical integrated framework which will (i) explicitly address the uncertainties through a comprehensive reliability based approach, (ii) help to bridge the gap between technical and non technical decision makers through the introduction of the risk concept and a new risk scale and (iii) build a sound basis for a broader and a more general framework for the management of coastal flood risks, including strategies for monitoring, inspection, maintenance, repair, review and safety evaluation updates as well as for emergency measures.

A BRIEF OUTLINE OF THE NEW CONCEPTUAL PRA-BASED FRAMEWORK

A conceptual PRA-based framework as shown in Figure 3 (Oumeraci & Kortenhaus, 2001) has been developed for the design of coastal flood defences: (i) prediction of flood risk, (ii) evaluation of acceptable flood risk, (iii) evaluation of the remaining risk/risk level through comparison of predicted and acceptable risk and (iv) management of the remaining risk. One of the key features of this design framework is the incorporation of the risk management as an integral part of the design process. In fact, no design optimisation would be possible without the knowledge of the remaining risk and its management.

The main sources and types of uncertainties which must be explicitly considered in the PRA framework have been already summarised in Oumeraci & Kortenhaus (2001). Some methods on how to assess and consider these uncertainties in PRA have been used for vertical breakwaters (Oumeraci et al. 2001), but further sophisticated methods such as fuzzy sets, elicitation of expert opinions etc. are getting more and more operational and must also be applied (Cooke 1991).

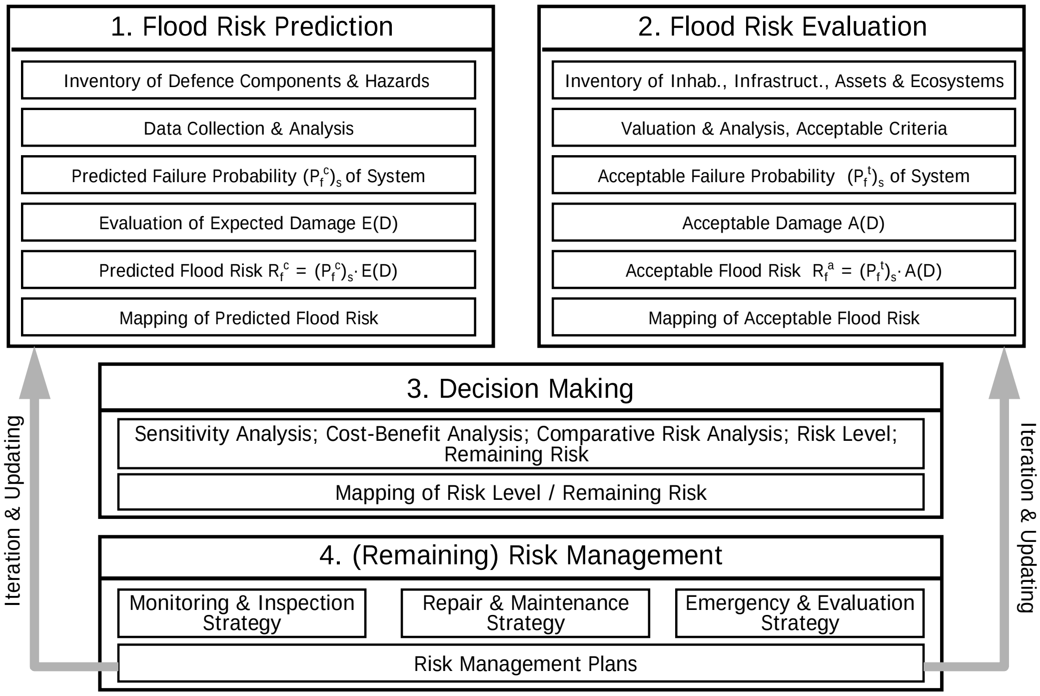


Fig. 3. Probabilistic Risk Analysis Based Framework for the Design of Coastal Flood Defences (Oumeraci & Kortenhaus, 2001)

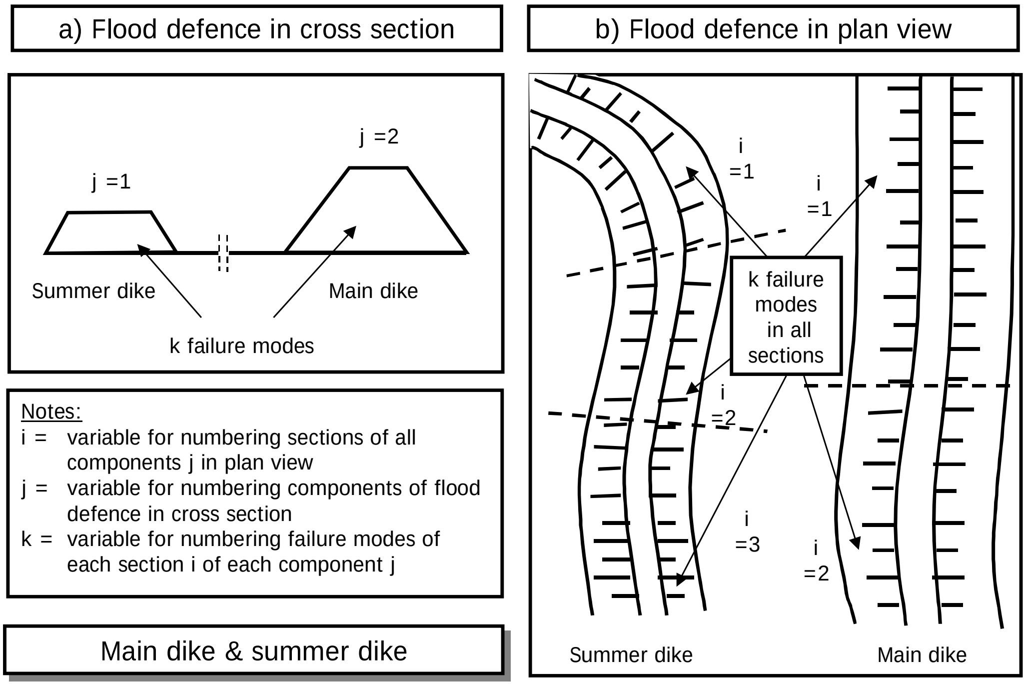
In the following sections particular focus will be put on the methodologies related to three aspects illustrated by Figure 3, including (i) the prediction of flood risk, (ii) the evaluation of acceptable risk and (iii) the calculation of the flood risk level (remaining risk).

PREDICTION OF FLOOD RISK

The prediction of the flood risk requires the knowledge and associated uncertainties of (i) the morphological, topographic, hydraulic and other boundary conditions, (ii) the failure modes of the defence components, their interactions and related limit state equations and (iii) the breaching of the defence structures as well as the flood wave propagation and the subsequent damages which would result in the protected area. The first two issues will be discussed in more detail in the following.

Topographic, Hydraulic and Further Boundary Conditions

First, the flood defence scheme, including the foreshore topography, the entire chain of flood defence structures must be described, together with the protected areas, facilities and infrastructures (socio-economic aspects). The description must be performed at different scales and levels of detail, depending on the purpose under consideration. Basically, both a cross sectional representation (Figure 4a) and a plan view representation (Figure 4b) are needed. The former is particularly important for the analysis of the hydraulic boundary conditions (water levels and waves) and the effect of the interaction between the various failures of the components (high foreshores, dikes, dunes etc.) of the defence chain on the flooding probability. The plan view representation is relevant for the analysis of the overall failure of defence components (spatial correlation), the subsequent flood wave propagation and its damaging effects in the protected area.



Notes:
i = variable for numbering sections of all components j in plan view
j = variable for numbering components of flood defence in cross section
k = variable for numbering failure modes of each section i of each component j

Fig. 4: Flood defence system in cross section and plan view (example: summer dike and main dike)

From the view point of safety and risk classes, some fundamental cases must be distinguished. Depending on the source of the hazards there are two typical cases: (i) threat from both sea and river and (ii) threat only from the sea. Depending on the conditions in the protected areas, typical situations with short or long propagation time of the flood wave as well as situations with high and low urbanisation level may be encountered, thus requiring different scales and detail levels of description and mapping (GIS).

Second, the hydraulic boundary conditions must be reliably assessed. This particularly includes (i) the joint probability of water levels and waves and (ii) transformations of waves propagating over the shallow foreshore to obtain the design waves at the defence structures. In fact, both water levels and associated wave conditions at the structure belong to the input parameters which are vital for any design. Small errors in these inputs may lead to much larger errors for outputs such as wave loads, overtopping and structure stability.

One of the key findings of the PROVERBS project was that (i) the uncertainties of the wave loads still represent the major uncertainty in the entire design process and (ii) these uncertainties essentially originate from the errors in predicting wave transformation from deep water towards and over shallow foreshores (Oumeraci et al., 2001). However, the most important source of uncertainty is due to the lack of knowledge and appropriate data on the joint probability of water levels and waves.

For this reason and because the joint occurrence of water level and waves provide the input data required for the prediction of wave transformation propagating into shallow foreshores, these problems are discussed first. Second, the problems associated with wave transformation and the uncertainties in predicting waves over shallow foreshores are addressed.

Joint Probability of Storm Water Levels and Waves

Disastrous damages to sea defences are often caused by unfavourable combinations of water levels and waves during storms. Therefore, the development of more appropriate and practical approaches to predict such extreme conditions becomes a key issue in any PRA-based design of coastal flood protection. To obtain homogeneous data sets for water levels it is essential to distinguish between (i) astronomical tidal components which are deterministic and which may change due to human interference (dredging, closure of estuaries etc.), and (ii) the meteorological forcing components which represent the stochastic surge part of the actually measured water levels.

The yet available attempts to describe the joint probability of extreme water levels and waves do not explicitly include the distribution of wave periods. In some circumstances however, wave periods can be as important as wave heights in predicting structure responses such as wave overtopping, especially when waves are limited by depth.

Moreover, the future prediction methods should also enable (i) an explicit consideration of additional non-simultaneous data and information, (ii) an easy assessment of uncertainties and of their combined effect on the result, (iii) a long-term simulation to produce extreme values of water levels, of wave heights with their associated periods and of their combination. Research towards the development of such methods is underway (e.g. Owen et al. 1997).

Uncertainties in Predicting Waves Over Shallow Foreshores

Coastal defences are generally attacked by waves which have propagated over shallow foreshores with complex morphological features before reaching the main defence line.

Therefore, the waves approaching the defence line are subject to a variety of transformation processes including depth-limited wave breaking, wave refraction, etc. These processes and the subsequent changes in the wave height distribution have to be simulated in order to obtain the distribution just in front of the defence line. Generally, wave models such as SWAN (Wood et al. 2000), Boussinesq models (Bayram & Larson, 2000) and Volume of Fluid (VOF) models (Wu et al. 1994) are used for this purpose. The difficulty, however, consists in assessing the associated uncertainties which are required for the implementation of any PRA-based design of coastal flood defences. It should also be kept in mind that large uncertainties already occur in assessing the waves in deep water.

For details on uncertainties of waves refer to Goda (1994) which probably represents the most detailed reference yet available on uncertainties of design wave heights. In fact, the various sources of uncertainties have been systematically identified. For some classes of uncertainties, orders of magnitudes and even formulae are proposed to assess e.g. the coefficient of variation. Nevertheless, much remains to be done in this respect.

Analysis of Failure Modes, Breach Initiation and Flood Wave Propagation

Once the topographic, hydraulic, structural and socio-economic boundary conditions have been determined, the next step consists in the systematic identification and analysis of all relevant failure modes likely to lead to flooding, including the associated hydraulic loading.

In the case of a dike for instance, flooding may be induced as a result of a dike breaching which can be initiated

- from the seaward side through repeated wave impacts progressively eroding the structure, through wave uplift displacing revetment elements and through shear stresses induced by run up/down velocity,
- from the landward side through infiltration, overflow, wave overtopping or a combination of both which may lead to piping, sliding of the rear slope revetment and sliding failure.

Most of the dike breaches which occurred during the catastrophic surges of 1953 in the Netherlands and of 1962 in Germany were initiated from the landward side - essentially by wave overtopping. (Oumeraci & Schüttrumpf, 1999). In fact, only the knowledge of the detailed flow field associated with wave overtopping will enable to derive any type of loading (pressure, flow velocity and shear stress at any location) relevant for breach initiation (Schüttrumpf & Oumeraci, 1999). However, for modern seadikes which have been heightened and strengthened over the last forty years probabilistic calculations using most recent failure mode descriptions indicate that there is a higher probability of failure from the seaward side of the dike by erosion of the dike cover (Kortenhaus et al., 2002).

A further important research issue is the effect of shallow foreshore on wave loading of sloping coastal structures. Very often the natural wave spectra in such shallow foreshores are double or multi-peaked, so that the question arises on which characteristic wave heights and wave periods of the multi-peaked-spectra are most suitable to describe wave loading.

When simulating flood wave propagation and its devastating effects in the protected area, one of the major uncertainties arises from assessing the initial conditions of the flood wave which are essentially governed by the development of the dike breach. The large experience available in dam engineering with dam-break flood wave models cannot be simply extrapolated to coastal flood defences, due to several reasons such as (i) the initial conditions of the flood wave which interacts with the breach growth, (ii) the limited breach width along the defence line and (iii) the 3D-character of the flood wave in a coastal plain. Therefore, substantially new knowledge towards the physical understanding and proper modelling of the breaching process must be generated before embarking into the numerical modelling of flood wave propagation and its effects on typical obstacles in the protected areas.

Since the growth of a breach initiated from the seaward side and that initiated from the landward side may differ, both cases must be experimentally examined. Based on the experimental results, numerical models to simulate both cases must be developed which are essential to obtain the initial conditions for the simulation of the flood wave propagation in the protected area. Once these initial conditions are properly determined, suitable numerical models exist which can be used for the simulation of the flood wave propagation. However, further research is also needed to incorporate in these models the destructive effects of the flood wave propagating in the protected area.

Integration Methodology for Flood Risk Prediction

The existing methods for the evaluation of the most relevant failure probabilities of individual components of a flood defence system must be further developed. Much more work remains to be done with respect to the flooding probability due to the failure of the entire defence systems. The same applies for the assessment of the expected damages in the protected area. Therefore, a general methodology is proposed for this purpose (Oumeraci & Kortenhaus, 2001). It integrates all the data and information resulting from the analysis of failures and their interactions, as well as from the subsequent flood wave propagation and its damaging effects in the protected area.

The methodology requires the use of component reliability models as well as models for the reliability of the entire flood defence scheme which consists of components with given material, cross sections and lengths. Links between the flood defence scheme components and between the protected areas with various vulnerability levels must be taken into account.

The effect of spatial correlation to account for the effect of influencing factors such as the longshore segmentation of the defence components is also important. The segmentation of the defence may become a crucial step. The degree of spatial correlation between components will depend upon the respective distance along and across shore between the defence components and on how they are tied to each other in plan view (links, bonds, etc.). Therefore, due consideration of both cross sectional representation and along shore representation of components are necessary to formulate an appropriate correlation function. As an overall result of the first step shown in Figure 3, the predicted flood risk associated with the area protected by a given flood defence scheme is obtained. The next step, i.e. the evaluation of the acceptable flood risk, is addressed in the following section.

EVALUATION OF ACCEPTABLE FLOOD RISK

General Methodology and Framework for Acceptable Flood Risks

Since the ALARP principle (**A**s **L**ow **A**s **R**easonably **P**racticable) is a widely accepted concept across most disciplines for the evaluation of acceptable risk, it is also recommended for the design and safety assessment of flood defence systems. However, further developments and extensions are necessary to overcome the disadvantages of the conventional ALARP approach. Candidate issues for such extensions and further developments are for example:

(i) *introduction of uncertainty:* a high uncertainty of the risk may be caused by a high uncertainty of the probability of the event under consideration of/and by a high uncertainty in the consequences of that event. A high uncertainty in a very low risk is more acceptable than a comparably lower uncertainty in a very high risk;

(ii) *introduction of weight factors:* to account for differences in the acceptance/penalisation of certain risks as compared to others and to achieve a better consensus on the acceptable risk across many disciplines (car traffic risk more accepted than the risk with the same value for a dike breach and 1000 hazard events with 1 fatality/event are more accepted than 1 hazard event with 1000 fatalities).

Evaluation of Tangible and Intangible Losses

In order to achieve a wide consensus on the acceptable flood risk in accordance with acceptable risks in other disciplines (e.g. dam engineering, offshore engineering, transportation, nuclear power plants), it is indispensable that the various methods, rules and tools to be developed in the advanced ALARP framework are robust and transparent. To increase this transparency and to enable a better comparison with the acceptable risks in other disciplines, the acceptable (target) flood risk R_f^t is defined as a product of the acceptable (target) flooding probability P_f^t and the acceptable (target) damages or losses A(D).

If the damages are expressed in monetary terms (tangible losses) the target flooding probability P_f^t may be formulated as a cost optimisation problem (Voortman, 2002). In addition, however, the uncertainties resulting from the assumptions and cost calculations must explicitly be taken into account within the overall probabilities framework.

Most of the difficulties arise when trying to evaluate the so-called intangible losses such as human injury, loss of life, environmental and cultural losses caused by flooding.

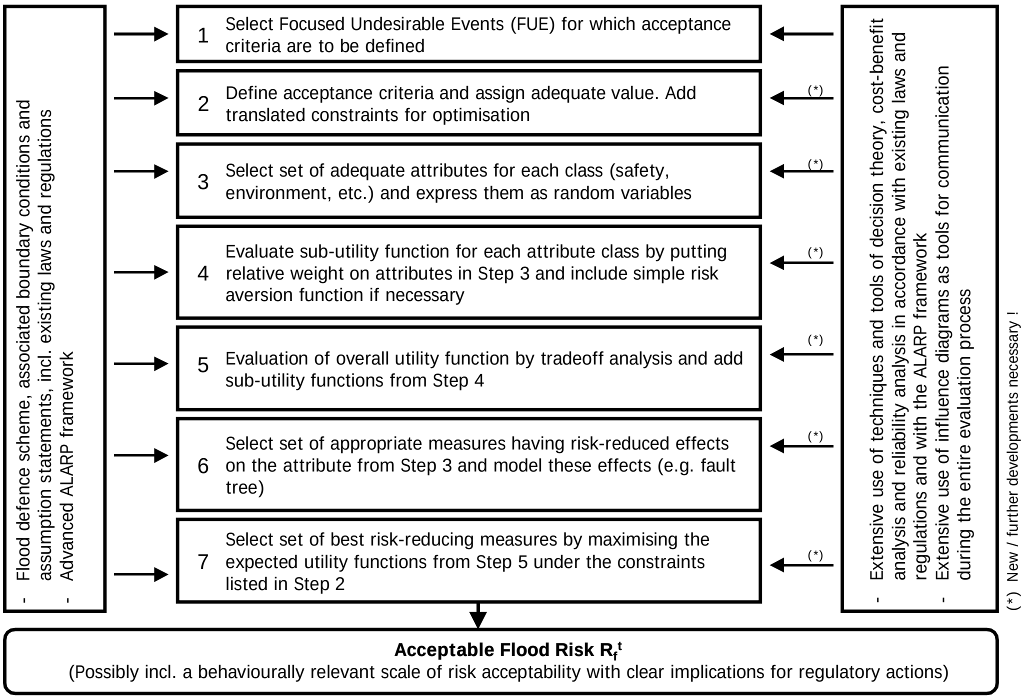
Although the valuation of human life is questionable from the ethical view point, the problem is often formulated in terms of the amount society is willing to pay for saving life. Values between 1 to 10 million US$, depending on considerations associated with aversion of risk, have been reported.

Various methods to evaluate intangible losses are available in the literature which can systematically be analysed to derive the approach most appropriate for coastal flooding (see e.g. Starr,1969).

Integration of Method for Acceptable Risk Evaluation

The general procedure for the evaluation of the acceptable flood risk within an advanced ALARP framework is tentatively summarised in Figure 5. It includes seven steps requiring the use of techniques and tools which exist already in Cost-Benefit-Analysis (CBA), Reliability Theory and Multi-Criteria Decision Theory or needs new/further development.

The major problems with most of these methods is that they are very complex and hardly understandable for most prospective users. The greatest challenge will therefore consist in simplifying as much as reasonably practicable, i.e. without loosing the important aspects.



- Flood defence scheme, associated boundary conditions and assumption statements, incl. existing laws and regulations
- Advanced ALARP framework

1 Select Focused Undesirable Events (FUE) for which acceptance criteria are to be defined

2 Define acceptance criteria and assign adequate value. Add translated constraints for optimisation

3 Select set of adequate attributes for each class (safety, environment, etc.) and express them as random variables

4 Evaluate sub-utility function for each attribute class by putting relative weight on attributes in Step 3 and include simple risk aversion function if necessary

5 Evaluation of overall utility function by tradeoff analysis and add sub-utility functions from Step 4

6 Select set of appropriate measures having risk-reduced effects on the attribute from Step 3 and model these effects (e.g. fault tree)

7 Select set of best risk-reducing measures by maximising the expected utility functions from Step 5 under the constraints listed in Step 2

- Extensive use of techniques and tools of decision theory, cost-benefit analysis and reliability analysis in accordance with existing laws and regulations and with the ALARP framework
- Extensive use of influence diagrams as tools for communication during the entire evaluation process

(*) New / further developments necessary !

Acceptable Flood Risk R_f^t

(Possibly incl. a behaviourally relevant scale of risk acceptability with clear implications for regulatory actions)

Fig. 5. Flow Diagram for Acceptable Flood Risk Evaluation (Oumeraci & Kortenhaus, 2001)

RISK SCALE, DISCUSSION AND SUGGESTIONS FOR RESEARCH

Once the predicted flood risk (R_f^c) and the acceptable flood risk (R_f^t) are obtained, a measure of the flood risk level which is appropriate for the decision making under consideration can be formulated as a function of costs and further intangible losses. For instance, a risk scale $G = (R_f^c - R_f^t) / R_f$ will show that optimum risk level is obtained for $G = 0$. Negative G-values mean overdesign while positive G-values mean underdesign. In both cases, penalty curves provide the costs or losses associated with every over- and underdesign.

In addition to the suggestions provided in the previous sections, the following questions must be answered (for more details see Oumeraci & Kortenhaus, 2001):

(i) How to simplify the developed methods (**A**s **S**imple **A**s **R**easonably **P**racticable); i.e. without loosing the important aspects? This is a very important issue towards facilitating the transition from the older approach - where conservatism, local tradition and local authorities prevailed - to a new approach of quantitative analysis methods for design and management.

(ii) How to conduct efficiently and cost-effectively a quantitative risk assessment including two steps: (1) a preliminary approach under the constraints of the available data to identify the focus points and (2) a more detailed and costly step, namely the new proposed comprehensive PRA-approach.

(iii) How to demonstrate the superiority of the new approach as compared with the present approaches and with pseudo-risk assessment and management approaches, which ignore or grossly simplify the underlying physics of the processes involved?

(iv) How to apply the new proposed PRA framework to estimate the threshold between sustainable and non-sustainable flood protection? This may particularly be made possible through the high level of integration, including the evaluation of direct and indirect costs, loss of life, environmental, cultural and further intangible losses?

(v) How the new PRA-Approach can be used as a meaningful yardstick for determining priorities in design, management and maintenance as well as in scientific research designed to held developing coastal protection schemes meeting sustainability criteria?

(vi) How to make best use of the new PRA framework towards the implementation of a new transparent and unified safety concept for the design of coastal flood defences which also includes the management of the remaining risk as an integral part of the design processes?

CONCLUDING REMARKS

The proposed PRA-based framework and the prospective methodologies that would result are expected to help moving sustainable design of coastal flood defences from an academic debate into the realm of concrete work, performance and return. It will also help to overcome the conservatism of isolated national/regional safety cultures which typify the past and present situation in the design of coastal flood defences. Moreover, the proposed PRA-based framework has the capability to ignite the awareness of the coastal engineering community that time is ripe for a synergetic transnational partnership to forge the transition to a more integrated systematic and transparent design framework which is based on a physically, socio-economically and environmentally sound ground to meet the sustainability requirements.

One of the key features of the proposed framework is the focus on the underlying physics of the processes likely to lead to devastating damages (e.g. breach initiation, breach growth, flood wave propagation and its damaging effects) as well as on the explicit account of all uncertainties. This indeed makes all the difference with pseudo-risk assessment procedures which ignore or grossly simplify these important aspects.

Since the new proposed framework is intended to also provide a robust and transparent methodology to evaluate the acceptable risk, taking into account tangible and intangible losses associated with coastal flooding, the results will have clear implications for regulatory actions. In fact, the results will help developing unified safety concepts and thresholds between sustainable and non-sustainable flood protection schemes.

Besides further challenges associated with methodological aspects (e.g. usage of elicited expert opinions, etc.) and modelling aspects (e.g. breaching), the greatest challenge will certainly be to simplify as much as reasonably practicable so that the methods will be comprehensible and affordable by most prospective end users.

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