Probabilistic Risk Analysis Framework for the Design of Coastal Flood Defences

H. Oumeraci
Leichtweiss-Institut (LWI), TU Braunschweig and Joint Research Centre for Coastal Engineering (FZK) of the University of Hannover and the Technical University of Braunschweig
E-mail:h.oumeraci@tu-bs.de

Résumé

On propose un cadre d'analyse probabilistique des risques pour la conception des défenses littorales contre l'inondation qui répond le mieux aux critères de "sustainability". L'approche générale prend en compte les mesures de contrôle et de maîtrise du risque résiduel comme partie intégrale du processus de conception des défenses. Cet article est concentré particulièrement sur l'analyse probabilistique du risque d'inondation qui exige trois étapes bien distinctes: (i) la prédiction du risque d'inondation, (ii) l'évaluation du risque admissible d'inondation ainsi que (iii) l'évaluation du risque résiduel, obtenu par comparaison des risques prédit et admissible.

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.

1. Sustainable Protection Against Coastal Erosion and Flooding

Since the publication of the first Brundtland Report (*WCED, 1987*), stating that:

> *"Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs",*

numerous attempts have been made among and across a number of disciplines to achieve agreement on how sustainability can be defined more precisely, on how it can be measured, and how it can be achieved and monitored. An important milestone in this direction was the "Earth Summit of 1992" in Rio de Janeiro which recommended that indicators "*need to be developed to provide solid bases for de-*

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cision making at all levels and to contribute to a self-regulating sustainability of integrated environment and development systems" (Agenda 21, Chapter 40)"

From a coastal engineering view point, sustainability may be defined as "*an evolving process including those measures and actions at all decision levels (design, operation, management) to optimally use and protect the coastal zones by meeting given socio-economic objectives of the present generation without affecting the foreseeable needs of future generations, and while preserving/improving the physical (hydrological and morphological) and ecological integrity of coastal zones and adjacent areas.*"

Given this definition the sustainability requirements and challenges in coastal engineering as shown in Figure 1 would necessarily follow which are thoroughly discussed in *Oumeraci (2000)*. In fact, Figure 1 clearly indicates that sustainable development of coastal zones can only be achieved within an integrated PRA-based framework. The latter must indeed (i) confront the uncertainties systematically and explicitly at all stages of decision making, (ii) fulfil the physical, ecological and socio-economic development criteria associated with sustainability and (iii) equally cope with structural and non-structural (managerial!) measures to prevent/reduce coastal hazards.

With this general background more promising approaches than in the past can be developed to solve the dilemma generated in coastal zones by the needs for more infrastructure and concomitant measures for the protection of human life and assets against erosion and flooding on the one side, and on the other side by the needs to preserve/improve the natural coastal environment (Figure 2).

Although an integrated approach to coastal protection must include both erosion and flooding issues, in this paper focus has been put only on coastal flooding because (i) a single paper is not sufficient to address both issues properly, (ii) focusing only on flooding enables to make the proposed conceptual framework and associated methodologies more understandable, so that they can be extended to include erosion aspects such as beach erosion, dune breach etc..

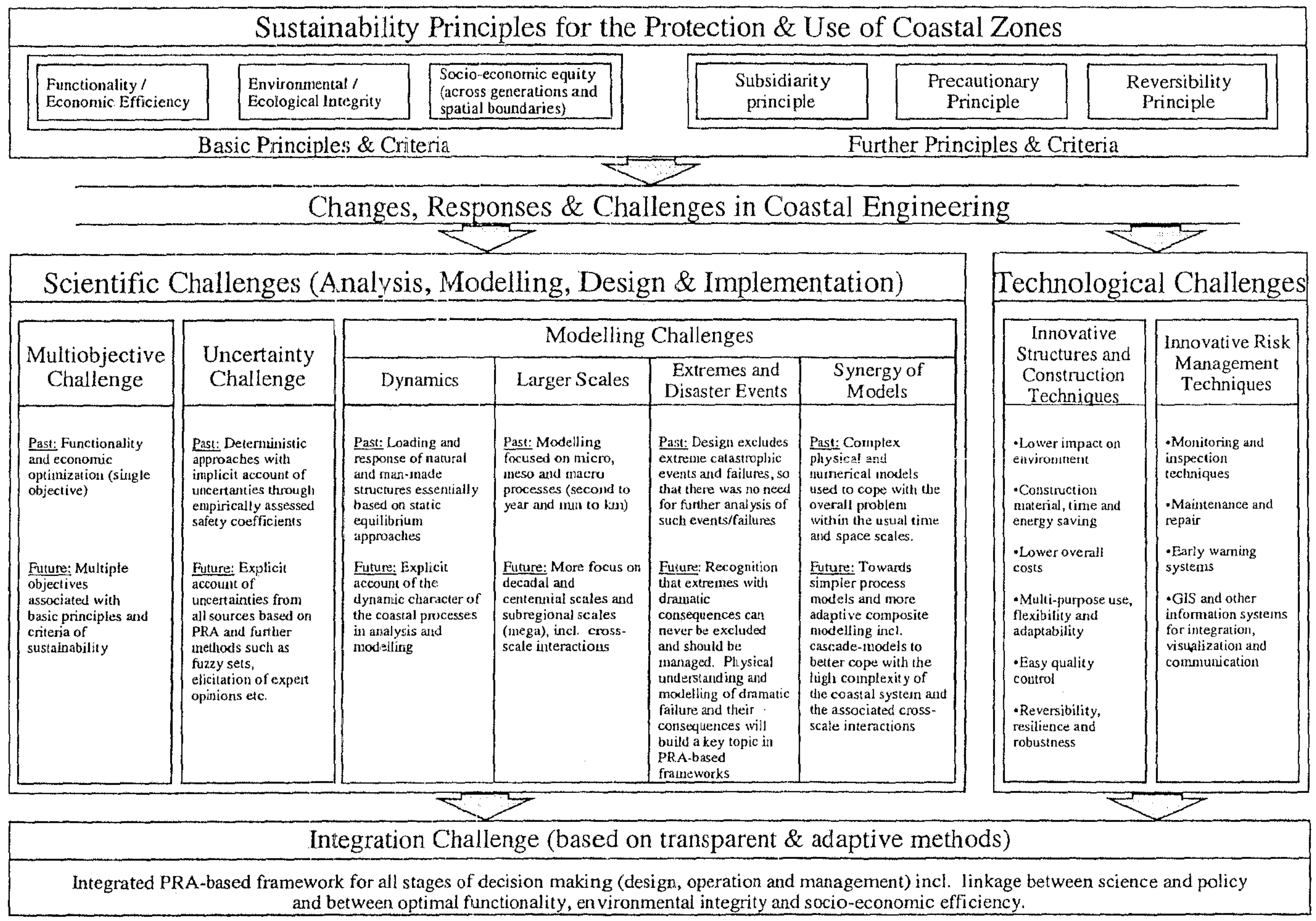


Figure 1: Sustainability Principles & Subsequent Challenges in Coastal Engineering (Oumeraci, 2000)

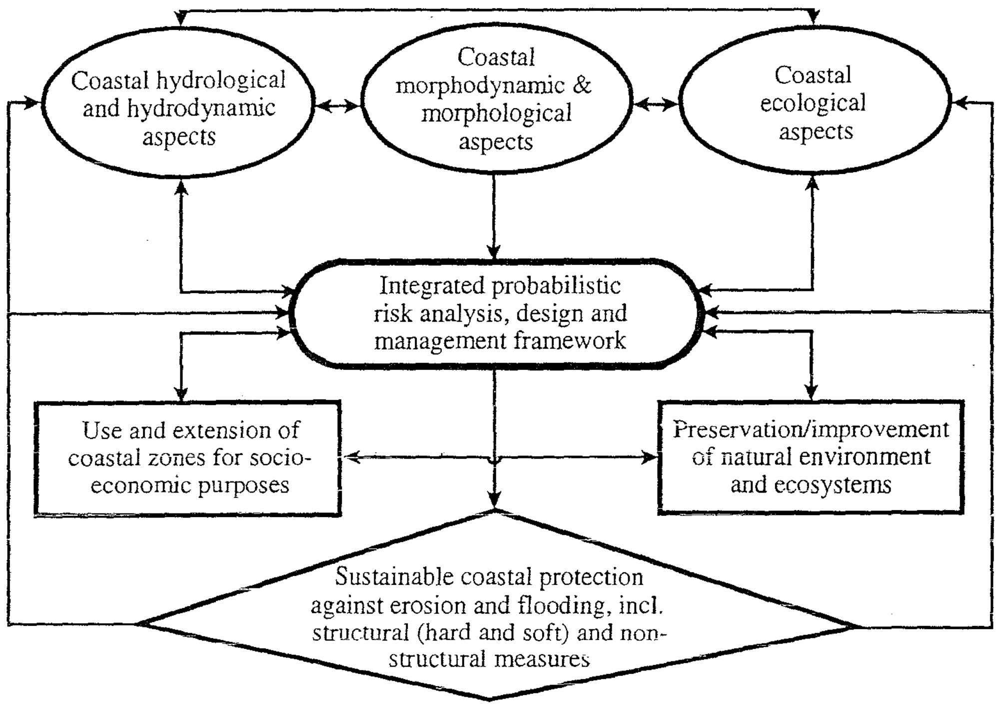


Figure 2: PRA-Based Design and Management Framework for Coastal Protection Against Erosion and Flooding

2. Necessity of New Design Approach for Coastal Flood Defences

Besides the general motivations suggested above, more specific motivations for the development of a novel approach for the design of coastal flood defences are addressed in this section.

Coastal flood defence has a long tradition worldwide. In spite of the variety of design methods and safety standards adopted in each country, the design criteria for flood defence structures are still essentially based on design water levels associated with specific exceedance frequencies. This is exemplarily shown in Figure 3 for the design of sea dikes as it is presently practised in Northern Europe.

The specified exceedance frequency is implicitly interpreted as a failure probability which is again equated to a flooding probability. This approach is too simplistic, as it may lead for instance to:

(i) too high and expensive dikes, because the dike must not necessarily fail when the design water level is exceeded (modern dikes have generally a substantial safety margin!), so that the catastrophic water level might certainly be much higher than the design water level,

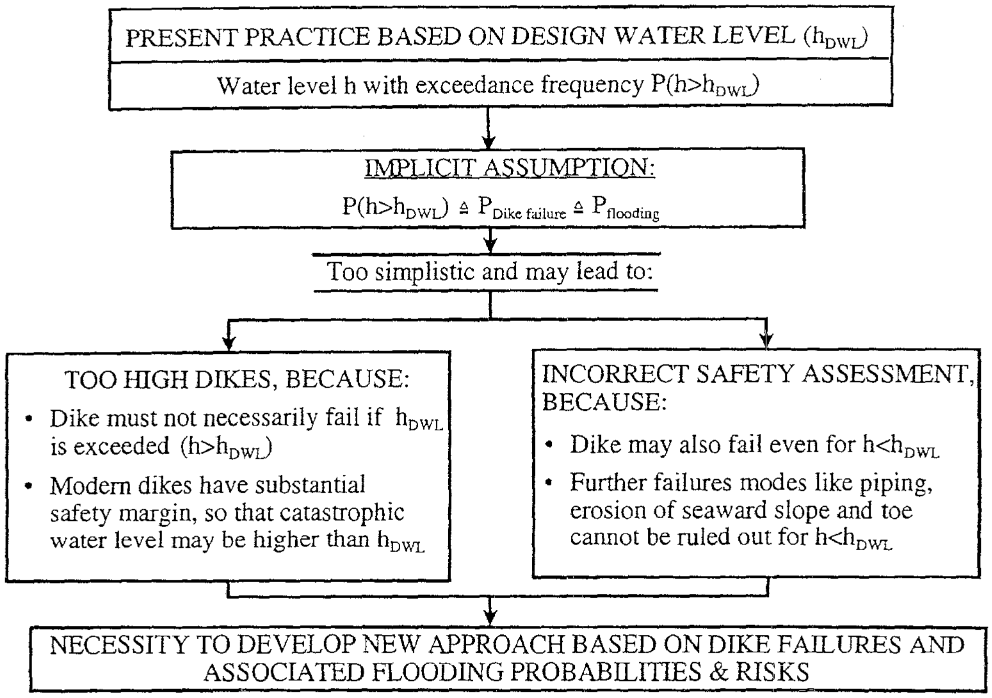


Figure 3: Present Design Practice for Coastal Flood Defences and Necessity of New Approach

(ii) an incorrect safety assessment, because the dike may also fail, even if the design water level will not be exceeded (seaward slope and toe failure, piping etc.), thus leading to a dike breach and subsequent devastating damages in the protected area.

Moreover, the present design practice is not only inconsistent with sustainable flood protection of coastal zones, but is also lacking rationality and transparency which constitute both an indispensable basis for a wide acceptability and thus for the unification and harmonisation of safety standards of coastal flood defences.

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.

Among the reasons pleading for a probabilistic risk analysis (PRA) as the sole candidate framework through which rational, transparent and thus widely accepted and harmonised safety criteria can be achieved, the following are noteworthy: (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.). Innovative results within such a PRA framework are not only expected with respect to the overall risk analysis procedure for coastal flood defences, but also with respect to the related prospective models, techniques and methodologies. Noteworthy in this respect are among others the models to predict the following processes and issues: (i) wave transformation on shallow foreshores with complex topographies, including the joint probability of water levels and wave parameters as well as the associated uncertainties; (ii) failure mechanisms of coastal flood defence structures, their interaction and consequences on the flooding probability; (iii) breaching mechanisms as well as the subsequent flood wave propagation and potential damages; (iv) acceptable flood risks within the protected areas by accounting for economic losses, loss of life and further intangibles like environmental and cultural losses.

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.

3. The New Conceptual PRA-Based Framework as a Response to the Sustainability Challenge: A Brief Outline

A recently completed MAST III-Project on "Probabilistic Design Tools of Vertical Breakwaters (PROVERBS)" which was led by the author, concluded that *"the design process for coastal structures is expected to develop within the next decade from pure deterministic to probabilistic analysis methods embedded into a risk based design and risk management framework to achieve sustainable protection of the coastal zones"* (*Oumeraci et al., 2000a*). Based on the results of PROVERBS and the lessons drawn from this and other projects on coastal defences, the conceptual PRA-based framework shown in Figure 4 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. Hence, the strategy for the assessment of this remaining risk is further elaborated in Figure 5.

The main sources and types of uncertainties which must be explicitly considered in the PRA framework are summarised in Figure 6. Some methods on how to assess and consider these uncertainties in PRA have been used for vertical breakwaters (*Oumeraci et al., 2000a*), 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*).

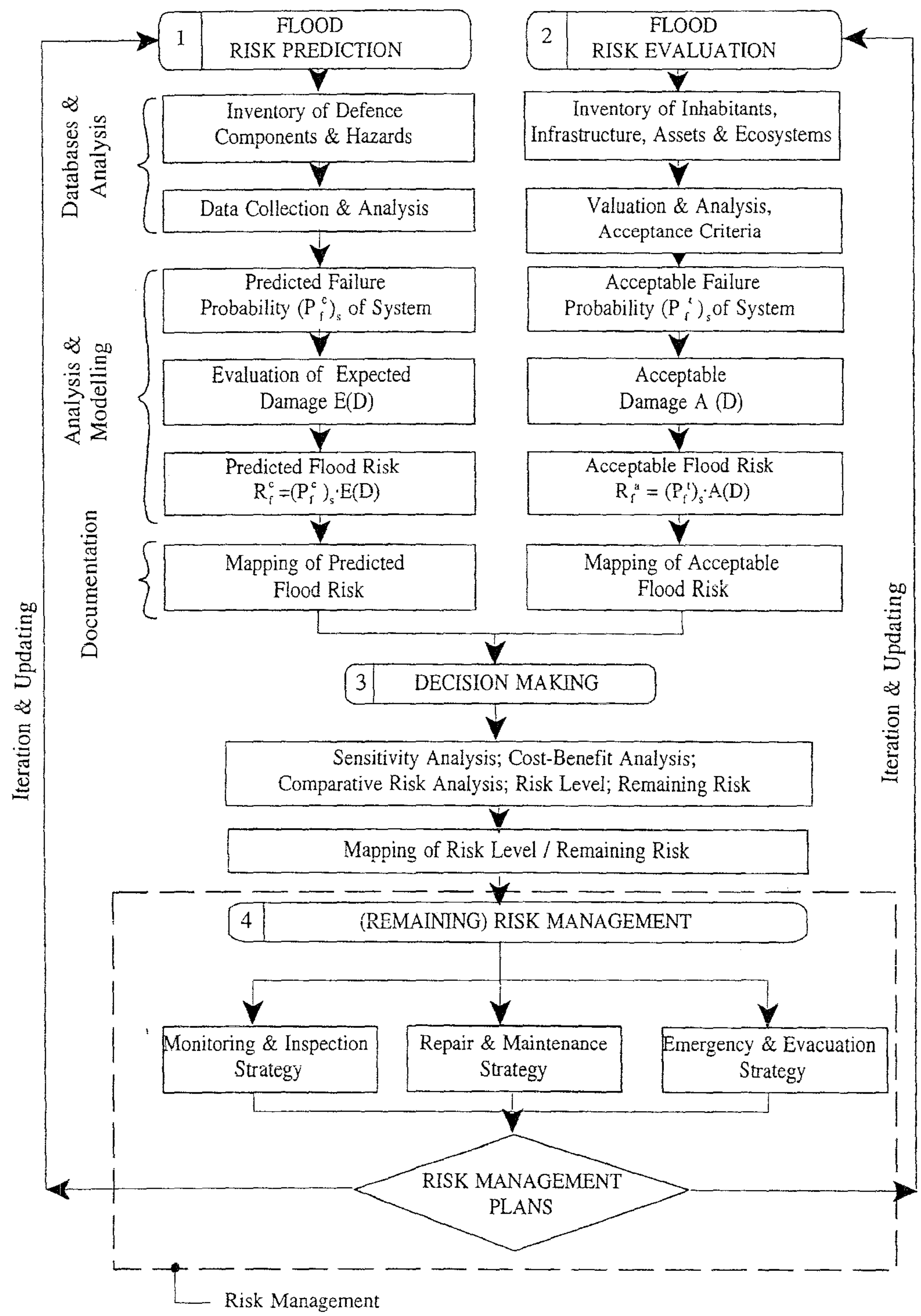


Figure 4: Probabilistic Risk Analysis Based Framework for the Design of Coastal Flood Defences

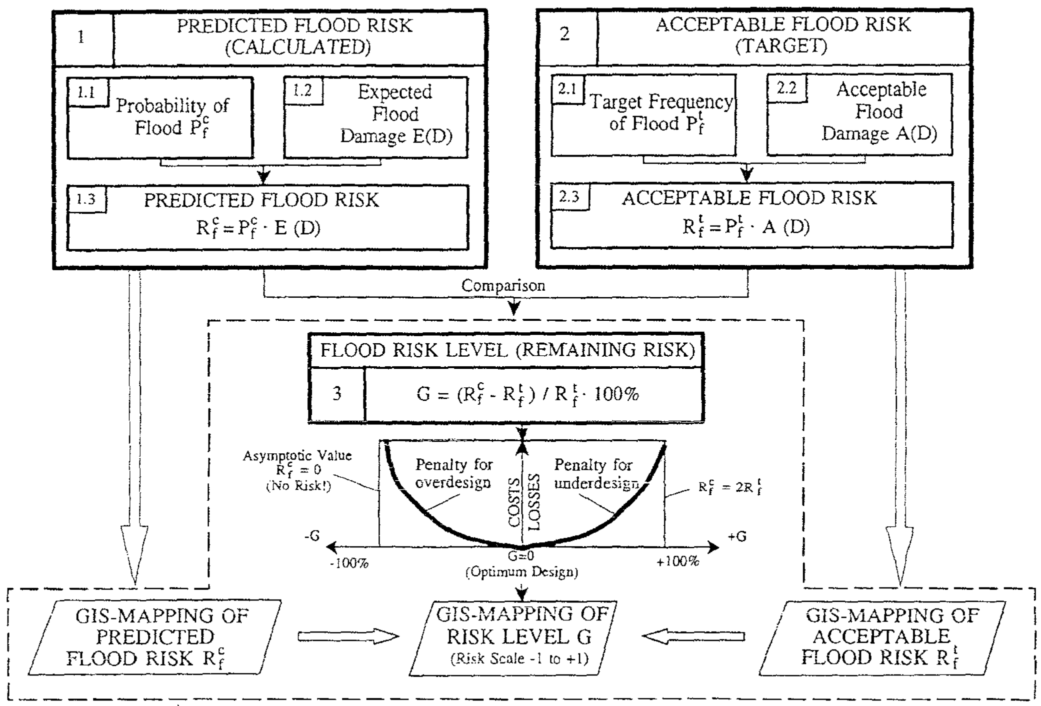


Figure 5: Methodology for the Assessment of the Remaining Risk

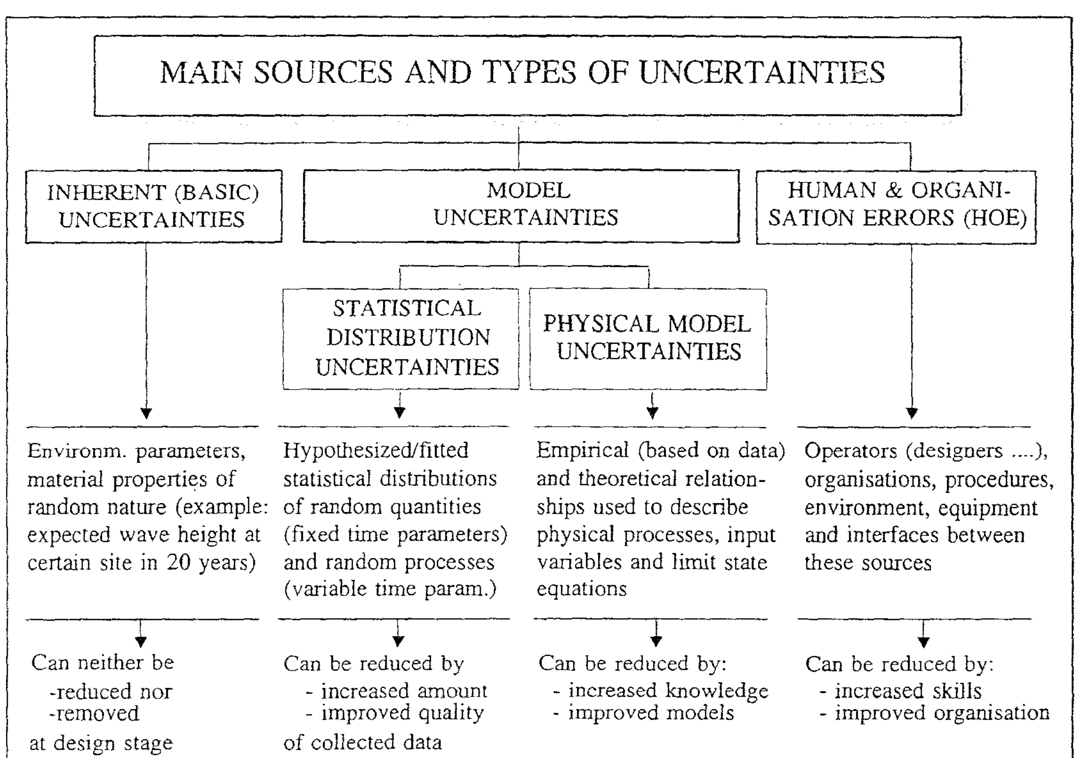


Figure 6: Uncertainties to be Considered in Proposed PRA-Based Framework (Adopted from Oumeraci et al., 2000*)*

In the following sections particular focus will be put on the methodologies related to three aspects illustrated by Figure 5, including (i) the prediction of flood risk, (ii) the evaluation of acceptable risk and (iii) the calculation of the flood risk level (remaining risk). In view of the constraints associated with the limited length of the paper, the fourth aspect (management of remaining risk in Figure 4) will be addressed in a forthcoming paper.

4. 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.

4.1. 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 7) and a plan view representation (Figure 8) 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 (see Figure 15).

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 (Figure 8a) and (ii) threat only from the sea (Figure 8b). 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).

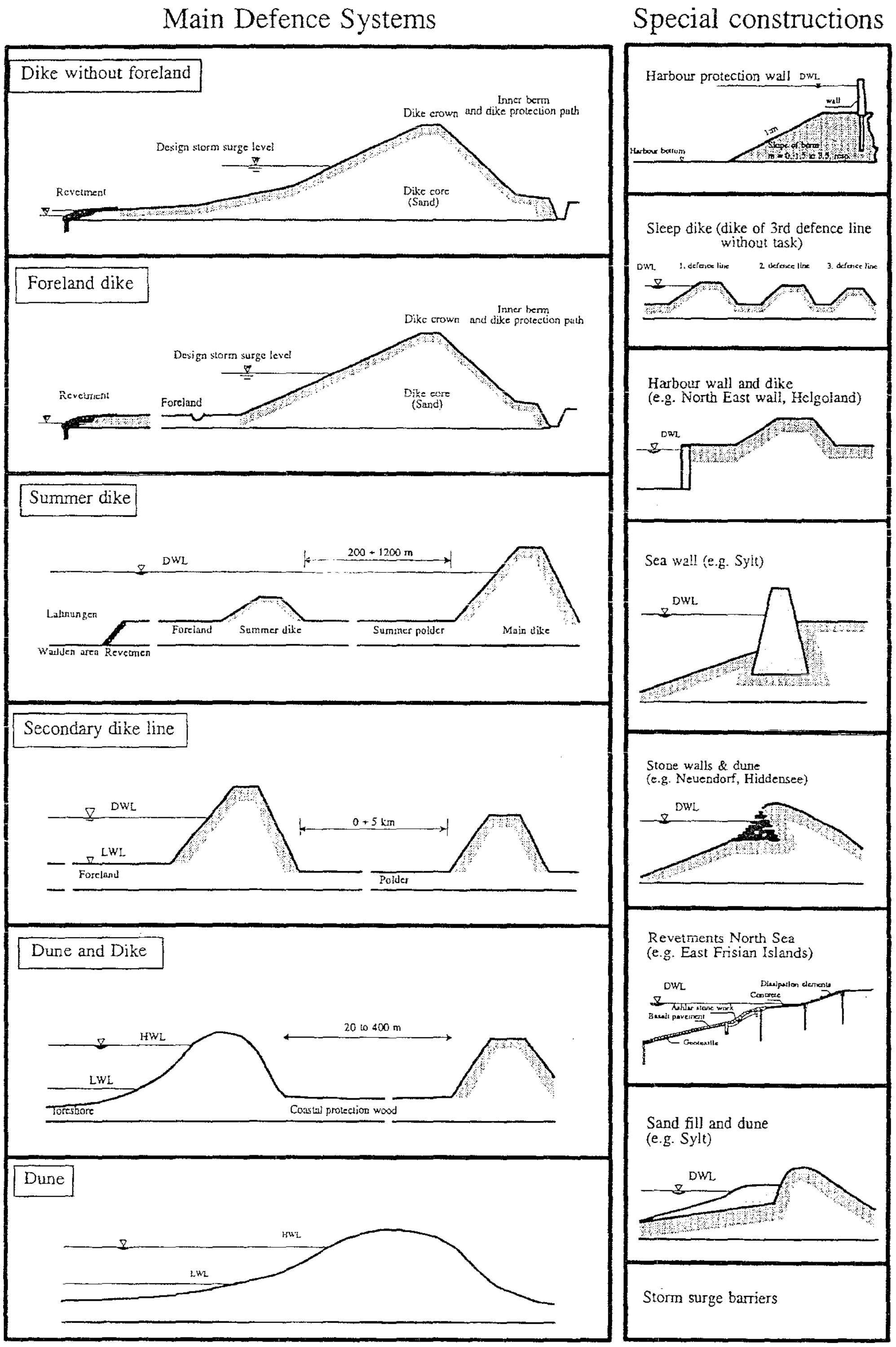
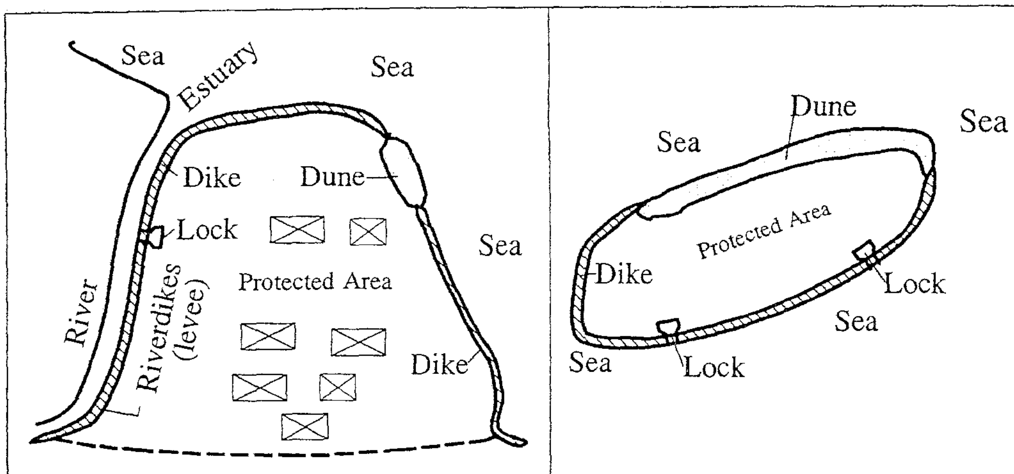


Figure 7: Coastal Flood Defence Chain (Cross-sectional Representation)



(a) Flood Threat from sea and river (e.g. estuary)

(b) Flood Threat from sea (e.g. small island)

Figure 8: Coastal Flood Defence Scheme (Plan View Representation)

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 EU/MAST III project PROVERBS on „Probabilistic Design Tools for Vertical Breakwaters" (*Oumeraci et al. 2000a*) 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. 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, the problems associated with the joint probability of water levels and waves, including some indications on future research, are first discussed before addressing the problems associated with wave transformation and the uncertainties in predicting waves over shallow foreshores.

4.1.1. 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 (Figure 9).

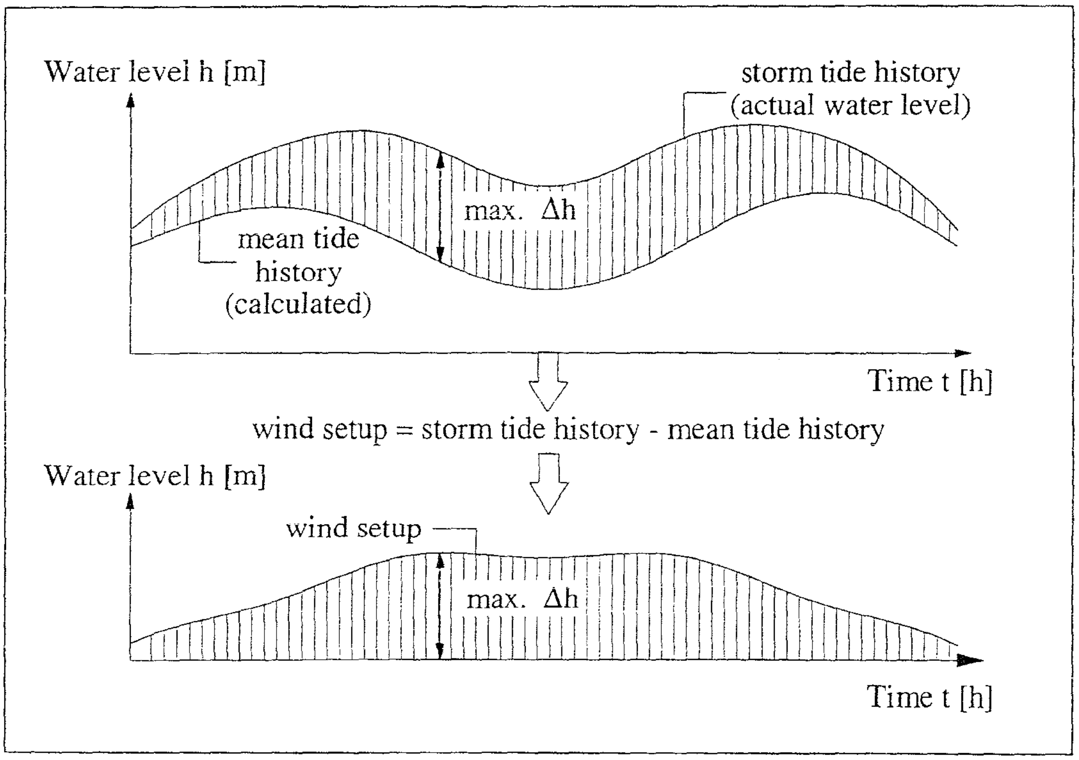


Figure 9: Surge and Astronomical Tidal Levels (Principle Sketch)

The yet available attempts to describe the joint probability of extreme water levels and waves do not explicitly include the distribution of wave periods (Figure 10). 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. Therefore, future approaches must explicitly include the variability of wave periods. The joint dependence between wave heights and periods can also be obtained by considering the variability of wave steepness which may represent a more robust variable than the wave period for statistical calculation.

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*).

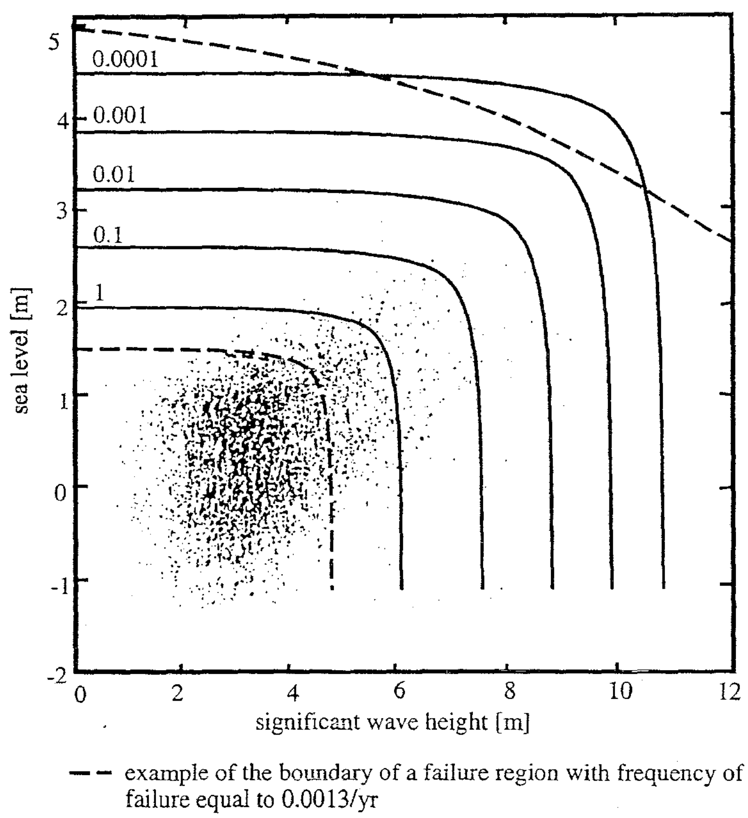


*Figure 10: Joint Distribution of Extreme Water Levels and Waves (*De Ronde et al., 1995*)*

Where possible, uncertainties should be assessed from statistical data. Otherwise, elicitation of expert opinions may represent a reasonable alternative (*Cooke, 1991*).

4.1.2. 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 reformation, 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.

Assuming a normal distribution and defining the uncertainty of a variable x by the coefficient of variation $\sigma'_X = \sigma_X/\bar{x}$ (σ_X = standard deviation and $\bar{x}$ = mean value), very approximate orders of magnitude of the uncertainties of incident wave parameters derived from wave hindcasting and calibrated by field measurements is given in Table 1 where H is the wave height, T the wave period and θ the incident wave angle (*Kamphuis, 1999*).

Table 1: Uncertainties of Wave Parameters (see Kamphuis, 1999*)*

Coeff. of Variation σ'_x	σ'_H	σ'_T	σ'_θ
Deepwater waves	0.3	0.3	0.9
Shallow water waves	0.45	0.3	1.0

For further details refer to *Goda (1994a)* 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 the coefficient of variation. Nevertheless, much remains to be done in this respect.

Caution is particularly recommended when using test results of wave transformation in shallow water obtained with regular waves. In fact, the wave height of regular waves are much more affected by shoaling than the significant wave height H_s of irregular waves (Figure 11).

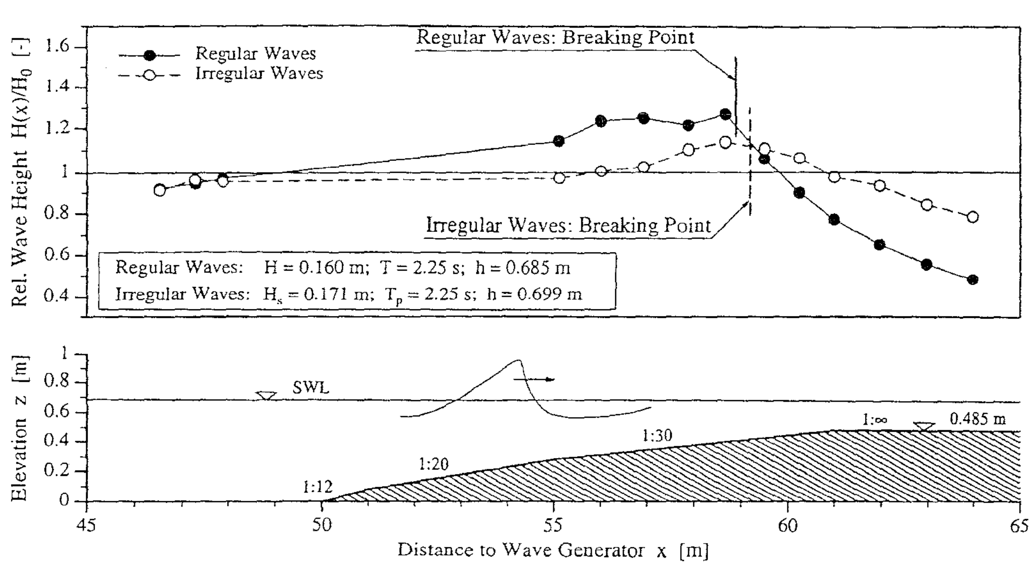


*Figure 11: Transformation of Regular and Irregular Waves in Shallow Water (*Oumeraci and Muttray, 1999*)*

A comparison of measured and calculated breaker indices $\gamma_b = H_b/h_b$ using the GODA formula is shown in Figure 12 for regular and irregular waves.

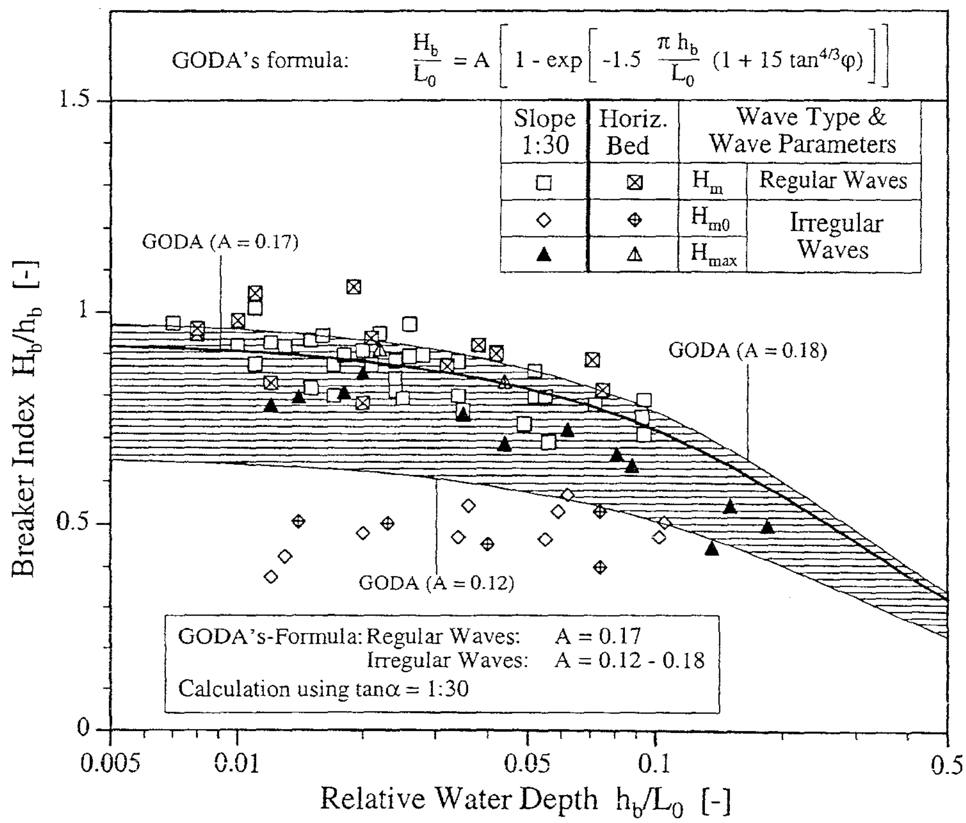


*Figure 12: Measured and Calculated Breaker Indices (*Oumeraci and Muttray, 1999*)*

The obtained coefficients of variation σ_y' shown in Table 2 are in the same order as those suggested by *Goda (1994a)* with $\sigma_\gamma' = 0.05$ to 0.13 for bed slope 1 : 100 to 1 : 10. Considering these orders of magnitude one should also keep in mind that the uncertainties in reflection analysis to determine the incident wave height H_i in laboratory testing may amount to $\sigma'_{Hi} \approx 0.05 - 0.15$, depending on the wave generation and absorption techniques used. The uncertainty related to the reflection coefficient K_r may even reach values up to $\sigma'_{Kr} \approx 0,3$ (*Oumeraci and Muttray, 1999*).

A further important issue is the threshold at which research to improve the accuracy of design waves should be stopped. In fact, the uncertainties of wave heights may diminish the benefits of research effort in improving the accuracy beyond a certain threshold. *Goda (1994b)* suggested for instance a limit corresponding to a coefficient of variation of about 5 % as a reasonable value. In this respect, the concept proposed by *Goda (1994b)* to judge the order of magnitude of accuracy and the research efficiency with regards to the final accuracy is highly recommended as a departure basis.

Table 2: Uncertainties in Breaking Wave Heights (Oumeraci and Muttray, 1999)

		Breaking Point	$\bar{\gamma} = H_b/h_b$ [-]	σ_γ [-]	$\sigma'_\gamma = \sigma_\gamma/\bar{\gamma}$ [%]
Regular Waves	H_m	on 1:30 Slope	0.850	0.078	9.3
		on horiz. Bed	0.916	0.077	8.3
Irregular Waves	H_{mo}	on 1:30 Slope	0.483	0.064	13.3
		on horiz. Bed	-	-	-
	H_{max}	on 1:30 Slope	0.700	0.108	15.5
		on horiz. Bed	0.807	0.035	4.3

For the integration of all the data related to topographical, hydraulic, structural and socio-economic boundary conditions, an appropriate Geographic Information System (GIS) can be used which should also include indications on uncertainties. The GIS-maps and data include topography and morphology, waves and water levels, defence structures and defence schemes, land use and distribution of population and assets, historical damages such as flood penetration depths and their consequences etc.

4.2. 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

(i) 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 (Figure 13),

(ii) 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 (Figure 13).

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 and Schüttrumpf, 1999*). Therefore and because of the limited extent of the paper, only the problems associated with wave overtopping and breach initiation from the landward side will be briefly discussed thereafter, before addressing the problems related to breach growth, flood wave propagation and subsequent damages in the next section.

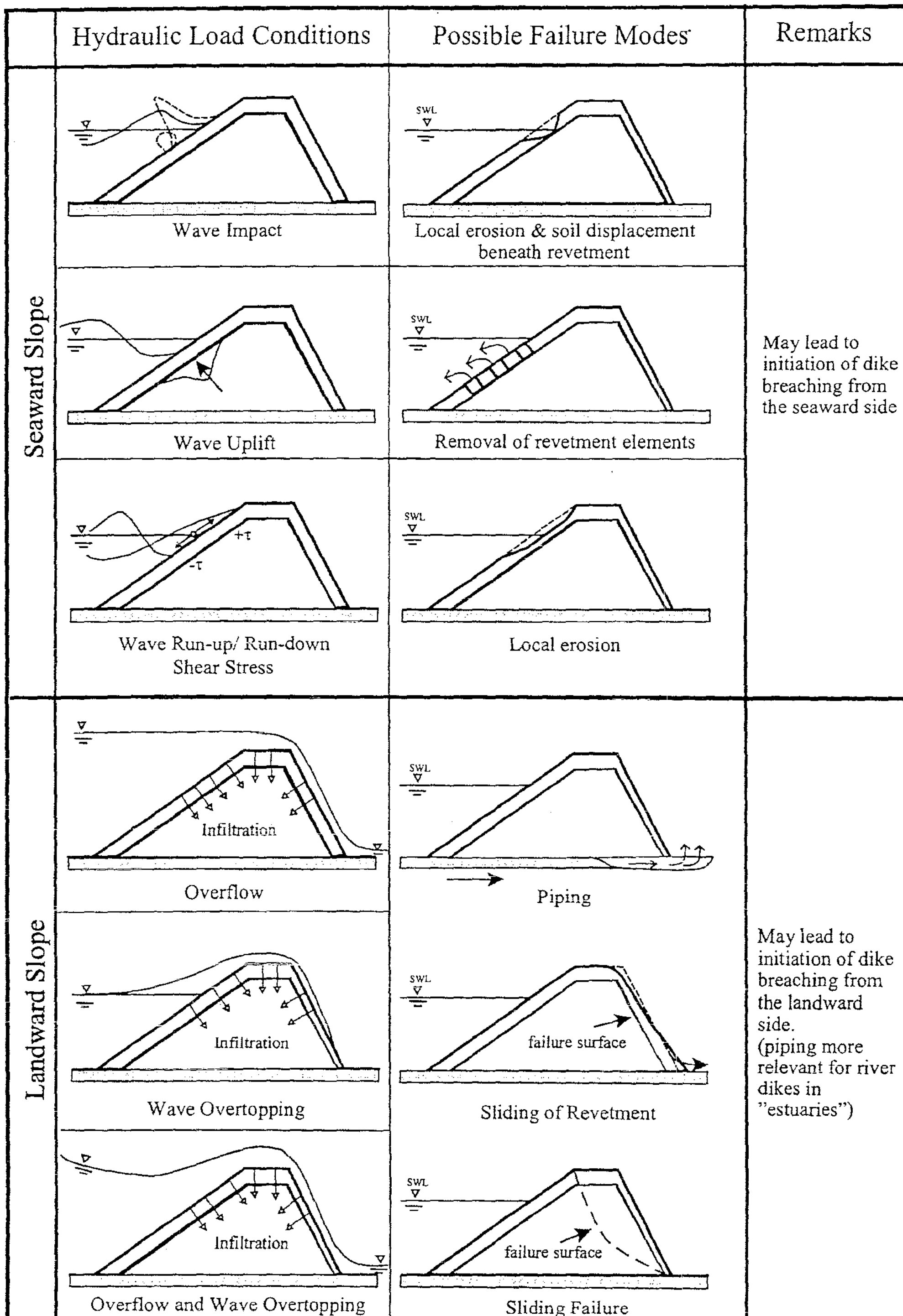


Figure 13: Possible Failure Modes Initiating Dike Breach From Seaward and Landward Side

4.2.1. Wave Overtopping

In the past, wave overtopping of coastal defence structures has been addressed in terms of predicted time averaged overtopping rate as compared to some tolerable overtopping rates for functional and structural safety. However, time averaged overtopping quantities rarely represent suitable parameters to describe structural or functional safety. Therefore, the available admissible average overtopping rates must be questioned. Very recently, some attempts have been made to address overtopping in terms of individual overtopping volume (per wave) by proposing a relationship between individual and average overtopping quantities based on the assumptions of a Rayleigh distribution of the number of overtopping waves and a Weibull distribution of the individual overtopping volumes (*Franco and Franco, 1999*). Although such relationships, which also account for the type and shape of the defence structure, are valuable to translate the traditional average quantities into individual maximum overtopping rates, future research should rather be directed towards the full description of the flow field associated with wave overtopping. A first attempt in this direction has been made by *Schüttrumpf and Oumeraci (1999)* who have been performing an extensive small- and large-scale study to describe the detailed flow field associated with the overtopping of sea dikes. This also includes numerical modelling using the VOF-concept.

In fact, 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.

A further important research issue is the effect of shallow foreshore on wave overtopping. 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 overtopping. Results of ongoing experimental investigations (*Oumeraci et al., 2000b* ; *Oumeraci, 2000*) have shown, that the wave period $T_{m-1,0}$ is more relevant than the peak period T_p of the entire spectrum. This might be explained by the fact that the longer waves in the spectrum (negative spectral moment m_{-1}) have more influence on wave overtopping than shorter waves. A more systematic examination of the influence of the lower frequency components (e.g. surf beat) on wave overtopping is also needed.

4.2.2. Breach Growth and Flood Wave Propagation

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.

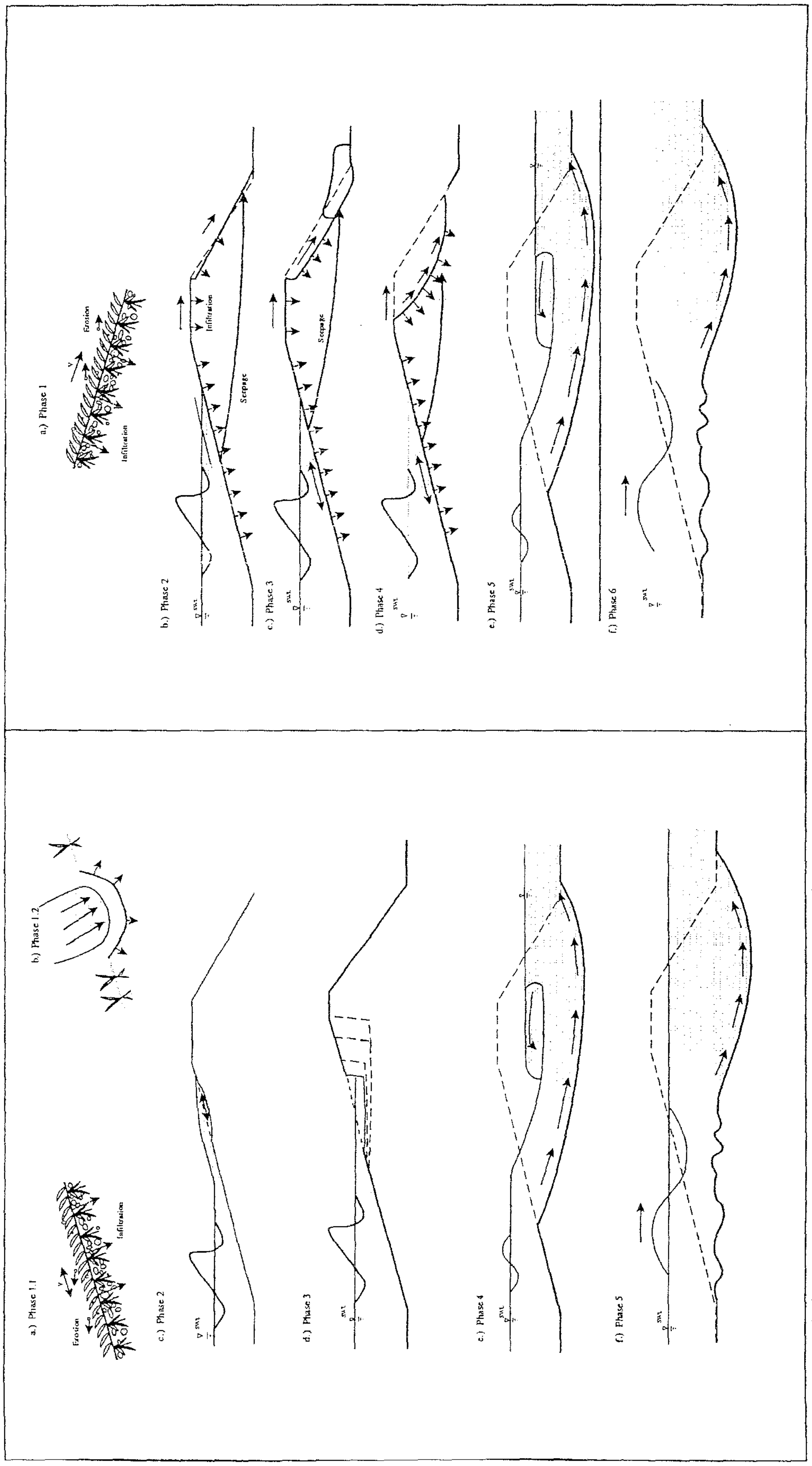
The large experience available in dam engineering with dam-break flood wave models cannot be simply extrapolated to coastal flood defences, due to several reasons such as (i) the initial conditions of the flood wave which interacts with the breach growth, (ii) the limited breach width along the defence 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.

Due to the very strong interaction between the expected extreme hydrodynamic conditions (high water levels, strong currents and high storm waves) and soil strength parameters (large Shield's parameter, variable shear strength etc.) associated with very high erosion and transport rate during the breaching process, serious scale effects would be expected, if common small-scale models are used. On the other hand, it will not be possible to achieve the required understanding of the physical processes by using only field experiments for which the control of the forcing functions (water levels, currents and waves) and the boundary conditions cannot be controlled (also too expensive and too time consuming!). Therefore, hydraulic model tests at almost full-scale in a large wave facility will remain the sole alternative.

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 (Figure 14). 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 (e.g. TELEMAC) 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.

4.3. 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, the general methodology schematically illustrated by Figure 15 is proposed for this purpose. 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. Figure 15 shows that both cross sectional and plan view consideration of the flood defences and the protected area are indispensable. 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.



(A) Breach Initiated From Seaward Side (B) Breach Initiated From Landward Side

Figure 14: Stages of Dike Breaching (Oumeraci and Schüttrumpf, 1999)

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 5, the flood risk associated with the area protected by a given flood defence scheme is obtained (Figure 15). The next step, i.e. the evaluation of the acceptable flood risk, is addressed in the following section.

5. Evaluation of Acceptable Flood Risk

5.1. General Methodology and Framework for Acceptable Flood Risks

Since the ALARP principle (As Low As Reasonably Practicable) 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:* this is in fact very important as 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 (Figure 16);

(ii) *introduction of weight factors:* this is important 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).

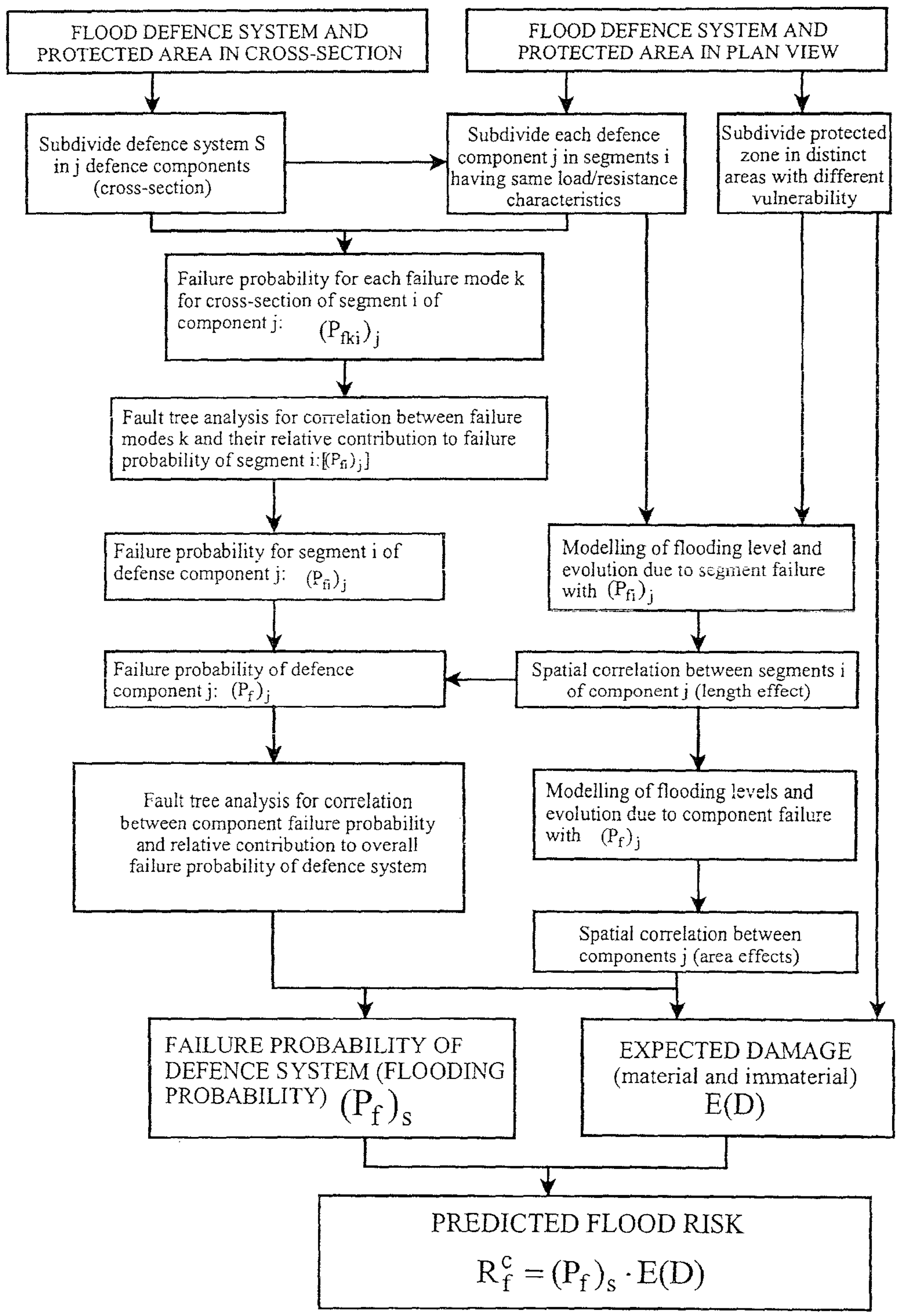


Figure 15: Integration Methodology for the Prediction of Flood Risk

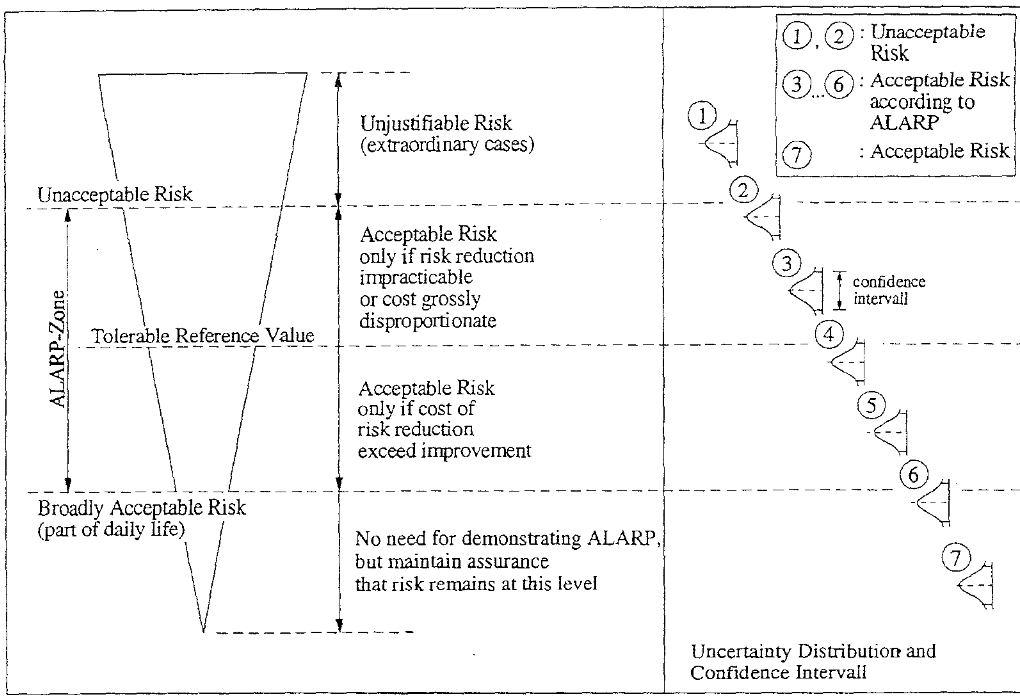


Figure 16: Introduction of Uncertainty into the ALARP Concept

5.2. 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) (see Figure 6).

If the damages are expressed in monetary terms the target flooding probability P_f^t may be formulated as a cost optimisation problem (Figure 17). 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.

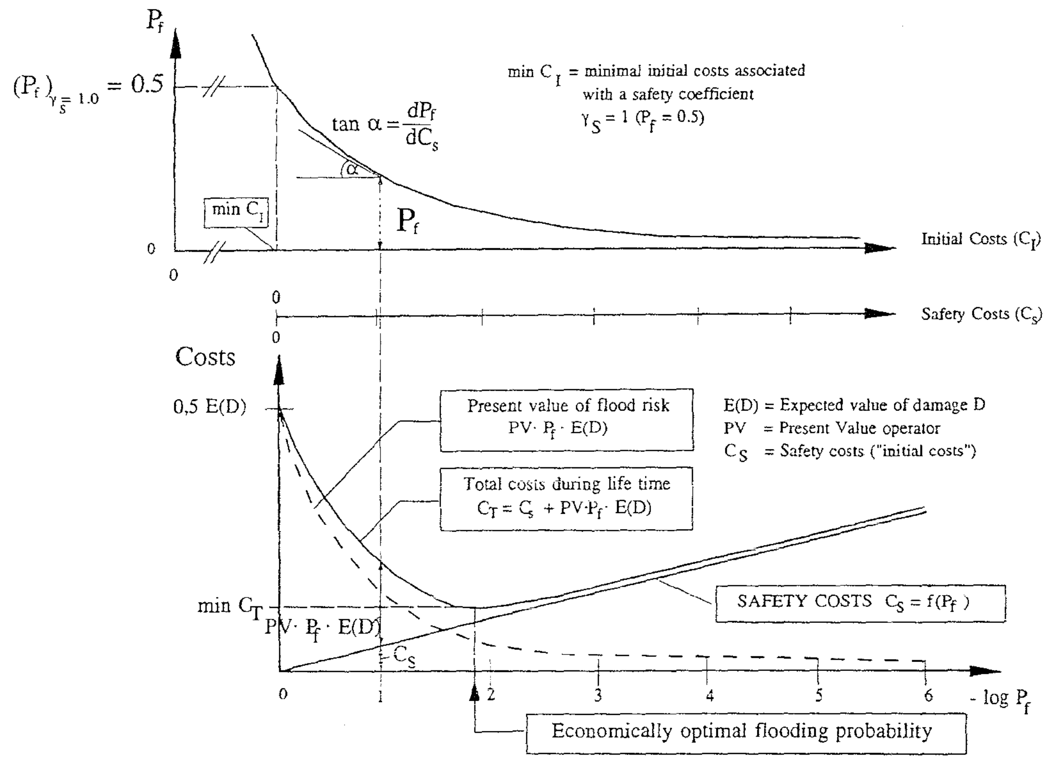


Figure 17: Formulation of Target Flooding Probability as a Cost Optimisation Problem (Adapted from Oumeraci et al., 2000a*)*

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.

5.3. Integration of Methods 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 18. 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 so complex that they are 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.

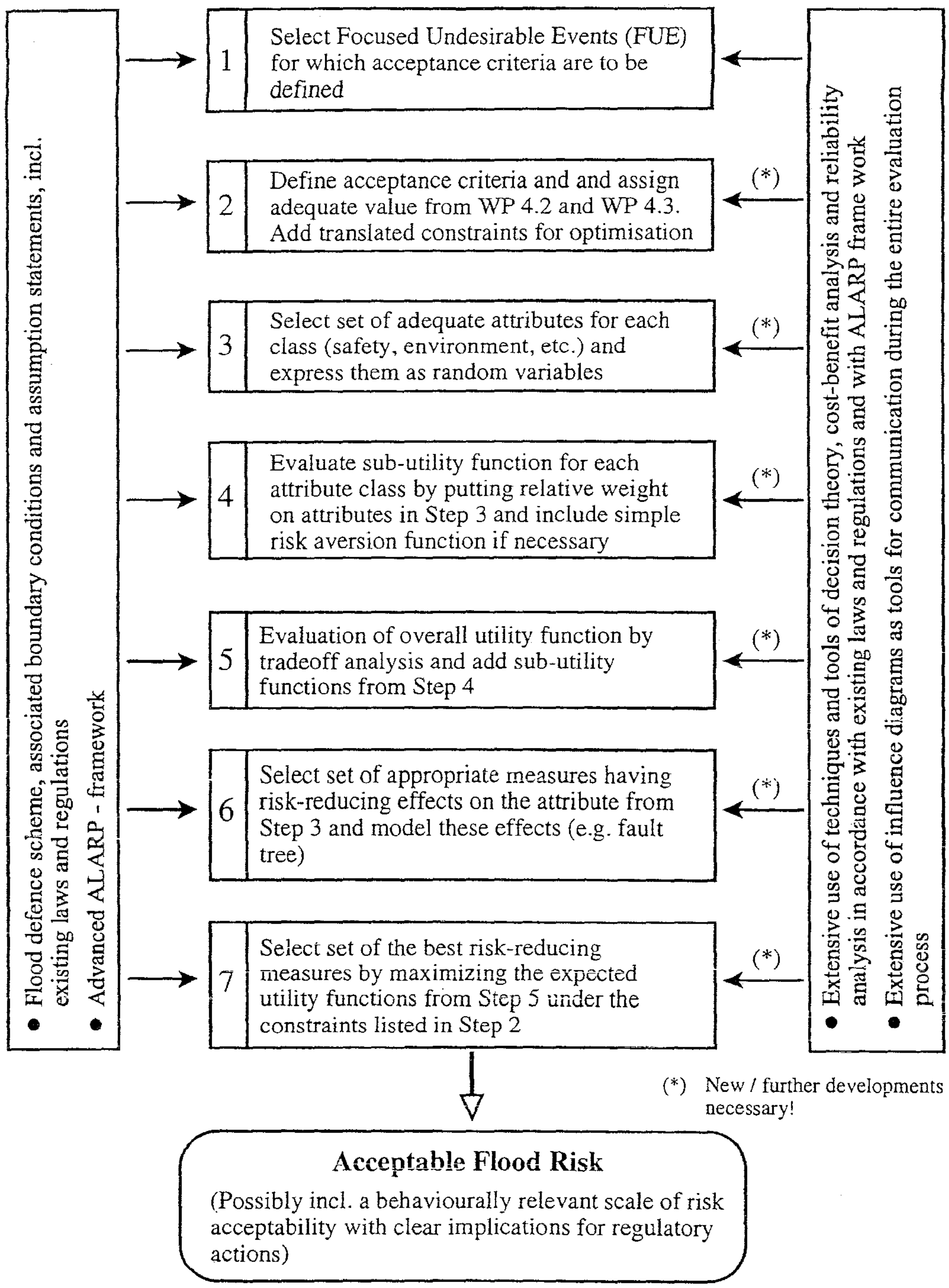


Figure 18: Flow Diagram for Acceptable Flood Risk Evaluation

6. Risk Scale, Discussion and Suggestions for Further Research

6.1. Risk Scale for Decision Making

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 $G = (R_f^c - R_f^t) / R_f$ is tentatively proposed in Figure 5, showing 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.

6.2. Comparison of Proposed PRA Framework with Other Approaches

The advantages of the prospective PRA framework, together with the new methodologies and techniques which would result, as compared to the present design practice based on design water level (see Section 2) and to the newly emerging pseudo-risk assessment approaches are summarised in Table 3.

Table 3: Comparison of New PRA Framework with Other Approaches

Comparison Criteria	Present Practice Based on Design Water Levels	Newly Emerging Pseudo Risk Assessment and Management Approaches	Proposed New PRA Framework
Physical Background for the Prediction of Flood Hazards / Flood Risk	Ignore the joint probability of storm water levels and waves		joint probability of water level and waves represents key input
	• ignore totally or partially the failure modes likely to lead to flood hazards • unable to quantify flooding damages	• grossly simplify or ignore underlying physics associated with breach initiation and breach growth	• account for all relevant failure modes likely to lead directly or indirectly through breach initiation to flood hazards • detailed prediction of breach growth and its effect on flood wave propagation and subsequent damages represents a key innovative issue of the new PRA-framework • breach initiation is considered both from seaside and leeward side • the linkage between the failure modes in cross sectional and plan view representation is properly accounted for (see Figure 15)
Social Safety, Economic and Environmental Background of Accepted Flood Risk	Only implicitly and arbitrarily considered	Explicitly considered, but lacking any clear and systematic framework and methodology	• based on a systematic and transparent framework and methodology for acceptable flood risk, with comparison to other risks • clear and systematic integration in a complimentary manner of all aspects into the evaluation of acceptable flood risk (see Figure 18)

Comparison Criteria	Present Practice Based on Design Water Levels	Newly Emerging Pseudo Risk Assessment and Management Approaches	Proposed New PRA Framework
Level of Integration and Complexity	very low level of (implicit) integration and complexity	Relatively low complexity and moderate level of integration, but lacking explicit sound backgrounds	Very high level of complexity and integration through explicit involvement of direct and indirect economic losses, loss of life, environmental and further intangible losses in the evaluation of acceptable flood risk and involvement of all aspects contributing to the flooding hazards in the predicted flood risk
Credibility Level of Safety / Risk Assessment & Management	• incorrect safety assessment • questionable overall safety coefficients • not appropriate at all for risk management	• overall risk figures evaluated on non-transparent basis • inappropriate evaluation of remaining risk making an effective management almost impossible	• clear evaluation of remaining risk for which efficient managing risk reducing measures can be developed • clear contribution of each aspect and hazard to the overall risk, thus facilitating the prioritization of management measures and investments for risk reduction
Potential for Acceptability, including Synergetic Power For Sustainability	Very limited and inconsistent with sustainable protection (accepted only at local level)	might be appropriate as a first step, before embarking into the detailed new PRA-framework	• through its highly integrative nature the new framework is ideal to help evaluating sustainability thresholds • high acceptability by end users when simplification or/and transfer into easy to use software packages have been achieved
Potential for Development of Guidelines, Software Packages and Operational Management Tools	possible only at local level, but impossible at transnational level	might be adequate at feasibility level, before embarking into detailed new PRA-framework	• indispensable for the development of any rational and modern integrated design and management guidelines • possibility to simplify the application by prospective end users through the development of practical software packages and through transfer of the methodologies into tools for different design levels (feasibility, preliminary, detailed and research level) • technical basis for the development of new operative management tools (e.g. new warning system)

6.3. Suggestions for Further Research

In addition to the suggestions provided in the previous sections, the following questions must be answered:

(i) How to simplify the developed methods (As Simple As Reasonably Practicable); i.e. without loosing the important aspects? This is a very important issue towards facilitating the transition from the older era - where conservatism, local tradition and local authorities prevailed - to a new era of quantitative analysis methods for design and management which are very sophisticated in their essence and background, but should made simple in their application.

(ii) How to conduct efficiently and cost-effectively a quantitative risk assessment including two steps: a preliminary approach under the constraints of the available (usually very limited) data to identify the focus points and to optimise the next 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 the diverse newly emerging pseudo-risk assessment and management approaches (see Table 3), which ignore or grossly simplify the underlying physics of the processes involved, particularly those associated with extreme situations like breaching? For this purpose indicators to measure the benefits of the new methods must be developed.

(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? This aspect is expected to particularly contribute to overcome the major present barrier to sustainable design and management of flood protection which at present certainly lies in the lack of a rational, transparent, impartial and integrated framework that could be broadly accepted at multiple scales, including local, national and transnational levels.

(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? For this purpose, the reliability indices and the penalty functions obtained from PRA may be used, together with the sustainability thresholds suggested in the previous item (iv).

(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 (monitoring and inspection strategy, review and safety evaluation update strategy, maintenance and repair strategy and emerging strategy) as an integral part of the design processes?

7. Concluding Remarks

Although there is still a long way to go and many mountains to climb, 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 the newly emerging 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 (e.g. linkage of elicited expert opinions and calculations, linkage of failure modes across and along the defence line, integrated method for acceptable flood risk) and the modelling aspects (e.g. breaching, damaging effects of flood wave), the greatest challenge will certainly be to simplify as much as reasonably practicable (e.g. without loosing relevant aspects!), so that the methods will be comprehensible and affordable by most prospective end users.

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