Risk-based monitoring, inspection and maintenance framework for coastal structures

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ABSTRACT:
A risk-based strategy for monitoring, inspection and maintenance (MIM) is described as a key component of an overall framework for life-cycle engineering and management. Its application for coastal structures is exemplarily outlined for sea/estuary dikes and quay walls .The necessity of time dependent reliability analysis to account for changes during the lifetime of a structure is exemplarily illustrated for quay walls and sea/estuary dikes for which extensive research on the failure mechanisms has already been carried out in the past years.

1 INTRODUCTION

The challenges associated with the sustainable design of coastal structures and the considerable uncertainties associated with climate changes and socio-economic developments necessarily require robustness and flexibility over the entire structure life time. In the framework of a joint research project of Leibniz Universität Hannover (LUH) and Technische Universität Braunschweig (TU BS), Germany, a risk-based strategy for monitoring, inspection and maintenance (MIM strategy) for coastal protection and harbour structures is being developed which considers these features. This strategy will be a key component of an overall framework for life cycle engineering and management to reduce life cycle costs in line with sustainable principles. The new MIM strategy is outlined and illustrated using examples of typical coastal structures: sea and estuary dikes as well as quay walls.

This paper particularly focuses on the application of the MIM strategy to dikes and quay walls for which extensive research on the failure mechanisms has already been carried out in the past years (e.g. Voortman (2002), Kortenhaus (2003), Steenbergen & Vrouwenvelder (2003), Zesch et al. (2007), Vorogushyn (2009), Schüttrumpf et al. (2009), Mai Van (2010)).

However, in those reliability analyses the time dependency of the processes and the degradation mechanisms leading to dike breaching were not fully considered. Further extensive investigations are still needed to explicitly address time-variant failure mechanisms and fault trees in reliability analyses. A methodology to consider the time dependency in terms of duration, sequencing (cascading effects), and simultaneity (overlap) is proposed for different time scales.

First, a scientific basis for an improved understanding of the degradation mechanisms and their effects on failure probability and serviceability of coastal structures had to be generated. Based on the gained knowledge, the methods, models and techniques, which are required to fully implement a risk-based strategy for monitoring, inspection and maintenance (MIM strategy) in the engineering practice were developed. As the MIM strategy is risk-based, the prospective methods and models explicitly account for the associated uncertainties (probabilistic approaches), for the failure consequences (risk analysis) and for the gained new information and data (Bayesian updating techniques).

2 COASTAL STRUCTURES

2.1 *Design of sea and estuary dikes*

Reliability and risk analyses are performed for a typical dike profile at the German North Sea consisting of a sand core, clay and grass cover (Fig. 1).

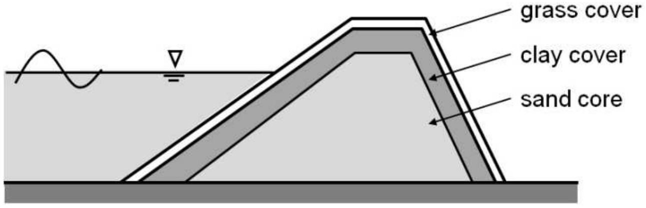

Figure 1. Typical dike cross-section at the German North Sea (Principle sketch)

2.2 *Failure mechanisms*

To allocate the failure mechanisms to different locations of the dike cross section, the dike profile is divided into three parts: seaward slope, dike core and landward slope. Hydrodynamic processes as well as morphodynamic and geotechnical processes are described. An overview of processes involved in dike breaching and the position of occurrence is given in Figure 2.

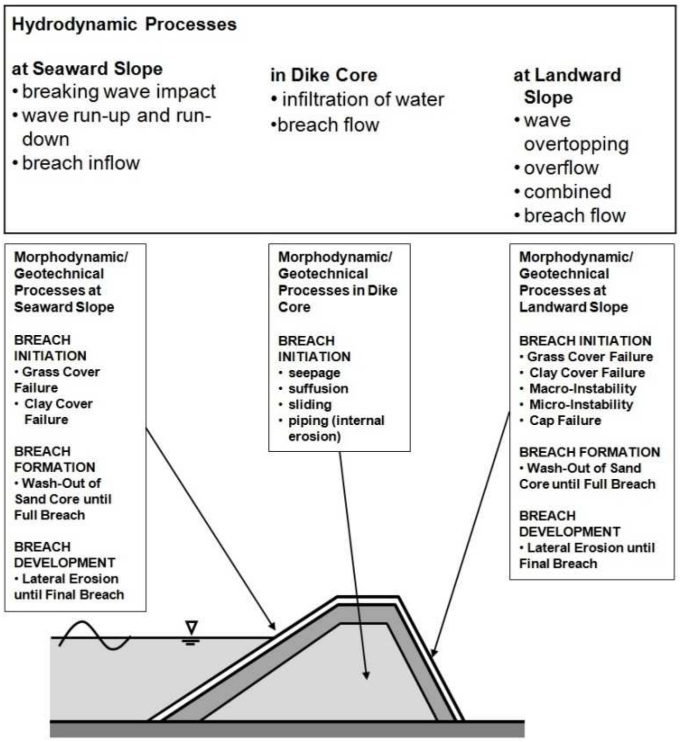

Figure 2. Overview of processes and failure mechanisms leading to dike breaching (Naulin et al., 2012)

3 QUAY WALLS

3.1 *Quay wall design*

Quay wall constructions could be e.g. gravity walls constructed with concrete blocks. But especially at German coast lines with weak soils sheet pile walls have been developed in the past years (Fig. 3). Wall elements of these structures are U-shaped steel profiles, connected together with bolted on Z-profiles.

Due to increasing ship sizes and resulting water depths in harbors sheet pile walls need to be anchored. A compact superstructure placed on the wall and on raked piles ensures the transfer of the crane beam load and all traffic loads directly into the subsoil.

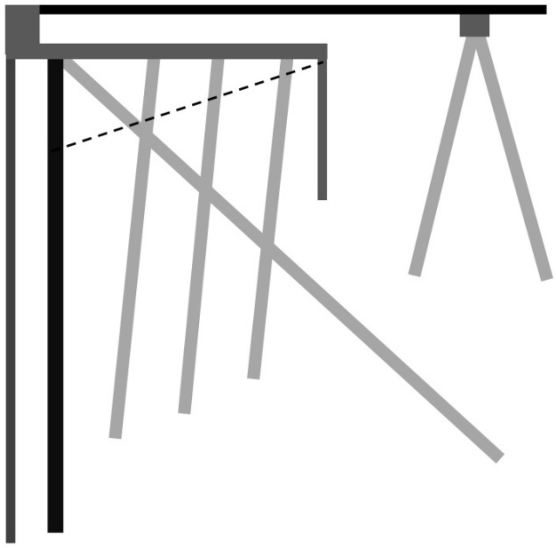

Figure 3. Sheet pile structure as a typical quay wall construction in German harbors (Principle sketch)

3.2 *Failure mechanisms*

Due to direct contact with sea water most failure mechanisms are caused by chloride penetration into the superstructure which leads to corrosion of the reinforced steel and failure of the concrete.

Corrosion of the sheet piles is also a main problem which can lead to a collapse of the total construction.

Principally, quay walls are not affected by failures which induce a collapse but a reduction of serviceability e.g. settlement of the traffic space and crane way or corrosion of fender and bollards.

4 RELIABILITY ANALYSIS

4.1 *General information*

Risk of failure R is defined as failure probability P_f multiplied by damage $E(D)$ (Oumeraci, 2004):

$$R = P_f \cdot E(D) \quad (1)$$

To carry out the reliability analysis of dikes and quay walls the failure mechanisms have to be expressed in limit state equations. By combining them in a fault tree, the failure probability of the top event can be determined. These two key components are described briefly in the following sections.

4.2 *Limit state equations*

In order to implement and analyse failures mechanisms of dikes in a reliability analysis they need to be described by corresponding limit state equations (LSE). The LSE describes the balance between the load applied to the structure and its resistance and strength by the following general equation:

$$z = R - S \quad (2)$$

where R = resistance/strength; and S = stress/load.

Parameter R represents the resistance/strength of the structure and is described as a function of geometrical and/or geotechnical properties of the structure, such as dike crown height, thickness of the revetment layer, cohesion of the soil.

Parameter S represents the load applied to the structure and is described as a function of hydraulic conditions, such as water depth, wave parameters.

Failure occurs when the loading exceeds the strength of the structure, i.e. $S > R$, and the structure functions when $S \leq R$. Therefore, $z = 0$ describes the limit state, i.e. the boundary between non-failure and failure.

4.3 *Fault tree analysis*

In fault tree analysis, events are connected by OR-gates and AND-gates to calculate the failure probability for a top event muliplying, respectively adding, the failure probability of individual events.

For dikes, several simple and complex fault trees have been drawn (e.g. Bakker & Vrijling (1980), Kortenhaus (2003)). In the literature, fault trees of dikes are usually described only qualitatively and calculated only partially (i.e. not for all documented failure mechanisms) or calculated using simple examples due to their complexity and dependencies between the individual events. Influences of duration, sequence and simultaneity of processes are not considered. The consideration of these time dependent characteristics in the reliability analysis is important for its use in life-cycle engineering and will be described in the following section.

5 CONSIDERATION OF TIME DEPENDENT PROCESSES IN RELIABILITY ANALYSIS

Input parameters describing the conditions of the structure (resistance) and the waves (impact), needed for the reliability analysis, like wave and soil parameter as well as temperature vary for different positions of the dike and over the lifetime of the structure. Despite this fact, reliability analyses are performed using constant values for resistance (R) and impact (S) with respect to their uncertainties (yellow) resulting in a constant, time independent failure probability (P_F) (Fig. 4a). In a time dependent approach, failures due to degradation processes over time decreasing resistance and the changing impact with their uncertainties need to be considered. Without any maintenance measures, the resulting failure probability increases over time (Fig. 4).

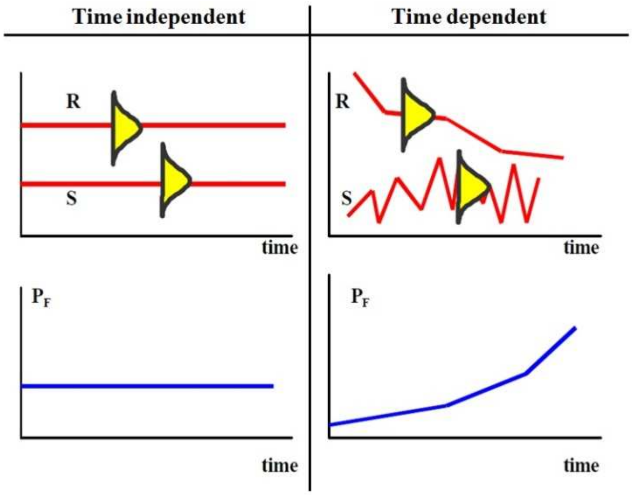

Figure 4. Comparison of: a) time independent and b) time dependent reliability analysis (Vrouwenvelder, 2001)

Furthermore, the time scales of the processes differ greatly. To apply a risk-integrated MIM strategy these facts need to be considered, since it will be applied over the entire lifetime of a structure of a minimum of 30-50 years. The changes are expected to be significant.

To consider these influences, the different types of events are divided into three time periods: short-term, mid-term and long-term (see Fig. 5). Short-term events are considered to occur over a timespan of seconds to hours. In case of dikes, grass erosion, wave pressure impacts and wave overtopping are to be mentioned. The second category contain changing mean high water levels (MHWL) over the duration of a year, maintenance work and seasonal vegetation growth. The long-term events occur over a timespan of years (e.g. re-design of the structure and relative mean sea level rise due to climate change).

Note, that not only the duration of the event is different, but that the effect can be either positive or negative. Furthermore, the number of short-term events that a structure experiences is much higher than that of mid-term and long-term events, respectively.

Reliable approaches to account for time dependency in reliability analysis are still missing though tentative approaches have been proposed for fault tree analysis (e.g. the combination of failure mechanisms in block scenarios in Kortenhaus (2003)).

Messervey (2008) proposed the “point in time” approach where the time effects are not only considered at the end of the structure lifetime, but at certain intervals.

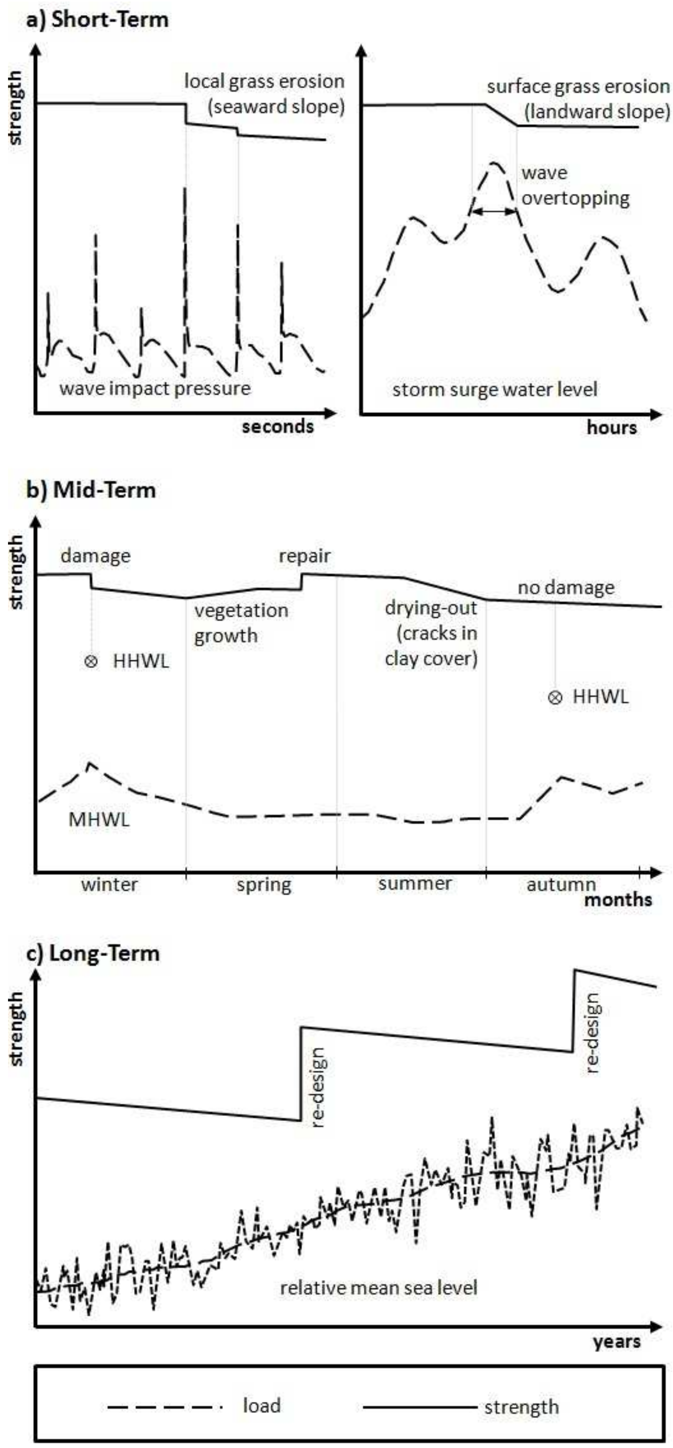

Figure 5. Loads and strength for different time scales: a) short-term, b) mid-term and c) long-term (Naulin et al., 2012)

The advantage of this approach is the possibility of time invariant calculation of failure probabilities. Overall, this approach represents only a discrete combination of multiple analyses.

In contrast, the cumulative-time approach as e.g. performed by Melchers (1999) is continuous. The main disadvantage is its complexity and thus the required computational effort.

Dynamic fault tree analysis introduces new gates (priority-AND gates, functional dependency gates, spare gates and sequence enforcing gates). For more information see Kloul (2009). This is a promising approach to deal with time dependent problems, but the computational effort is still very high and the implementation for very complex structures such as dikes or quay walls have not yet been performed.

6 PRINCIPLES OF THE MIM STRATEGY

6.1 *General information*

Despite the importance of sea and estuary dikes for the protection of the hinterland as well as quay walls for port companies, there is currently no coherent and systematic strategy for their monitoring, inspection and maintenance. Especially, the risk associated with the residual strength of German sea dikes and quay walls should be considered and determined in the same way.

Therefore, the MIM strategy is integrated as key component into a framework for life cycle engineering of coastal structures as an approach to quantify and evaluate risk, and finally to manage the remaining risk (see Figure 6).

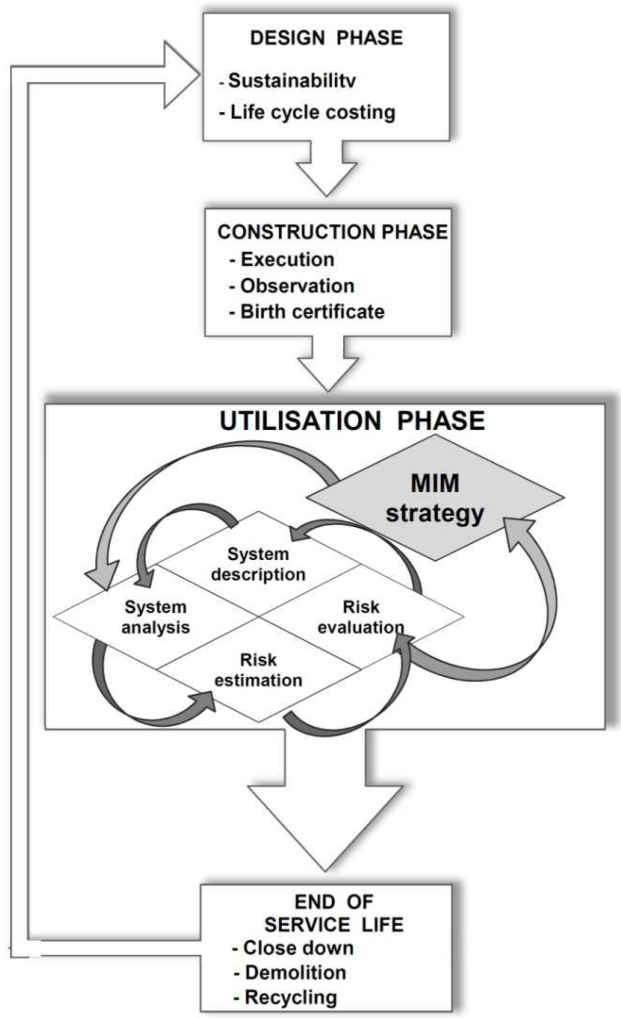

Figure 6. Life cycle phases including monitoring, inspection and maintenance (MIM) strategy (Horstmann et al., 2012)

Every structure, e.g. sea and estuary dikes as well as quay walls, undergoes certain steps throughout its lifetime. In the design phase of a structure, both sustainability and life-cycle-costing should be considered. In the construction phase it is important to collect information and parameters of the execution and observation of the erection process to generate a birth-certificate which is necessary as input data set for the MIM-strategy.

After the design phase of the dike and the ensuing construction phase, the longest-lasting time period named utilisation phase follows, to which the MIM strategy is applied.

This phase is subdivided in the steps “system description”, “system analysis”, “risk estimation” and “risk evaluation”, and the subsequent MIM strategy with the methodology for risk and maintenance management. These steps will be described in detail in the following section.

6.2 *Utilisation phase*

6.2.1 *Step 1: System description*

Initially, stakeholders or owners of dikes and quay walls have to analyze their dike systems and to specify the stresses and resistance of the total structure. For this purpose, a classification of the total structure in subsystems, components and elements as suggested by Krishnasamy et al. (2005) and Schießl (2007) has to be performed.

For example, subsystems represent different construction phases of the dike; components are the seaward and landward slope and the dike core; elements of the dike are sand core, clay layer and grass cover or different special parts of the dike as e.g. toe protection.

The classification of the total system in subsystems, components and elements for quay walls can be done by considering different exposure classes for concrete as shown in Figure 7 and Table 1.

For the entire system as well as each subsystem, component and element, the properties and functions have to be identified. This information has to be saved as an input for the next stage.

6.2.2 *Step 2: System analysis*

In this step, interactions of the subsystems, components and elements have to be defined. Additionally, degradation and deterioration mechanisms have to be analyzed based on experience.

This information is used as a basis to develop a performance matrix for the structure given by Takahashi et al. (2001) in which for each condition (serviceability, reparability, sustainability, collapse) and for every failure mechanism threshold values are defined. As an example proposed damage criteria for sheet pile quay walls developed by PIANC (2001) are shown in Table 2.

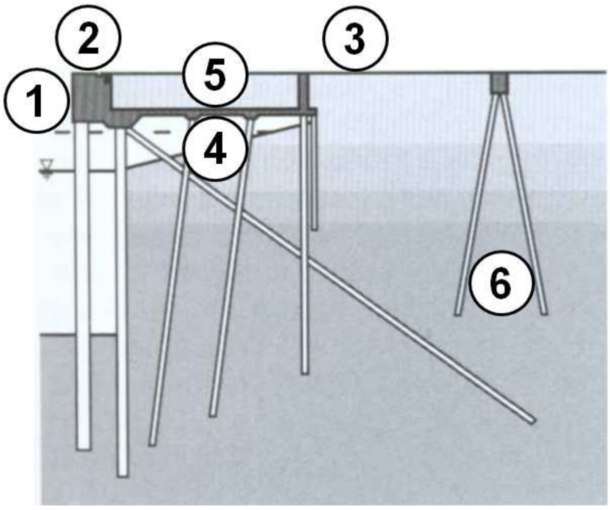

Figure 7. Different exposure classes for quay walls (Horstmann et al., 2012)

Table 1. Exposure classes for quay walls (Horstmann et al., 2012)

Reinforced concrete area		Exposure classes					
Superstructure	1	XC4		XS3	XF2	XA2	XM1
	2	XC4	XD3	XS3	XF2	XA2	XM1
Traffic space	3	XC4	XD3	XS3	XF2	XA2	XM2 XM3
Slab, bottom side	4	XC2 XC4		XS3	XF4	XA2	
Slab, upper side	5	XC2				XA2	
Piles, crane way	6	XC2				XA2	

Table 2. Proposed damage criteria for sheet pile quay walls by PIANC (2001)

Level of damage	Residual displacement	Residual tilting towards the sea	Differential settlement on apron
Level I: Serviceability	< 1.5%	< 3°	< 0.03-0.1 m
Level II: Reparability	N/A	N/A	N/A
Level III: Load capacity	N/A	N/A	N/A

6.2.3 *Step 3: Risk estimation*

For each failure mechanism and deterioration limit state equations have to be developed in this step. With the implementation of these limit state equations in a fault tree analyses the overall probability of a dike failure P_f can be calculated. By multiplying this total failure probability P_f with the consequences of failure E(D), risk R is obtained (see Equation (1)).

6.2.4 *Step 4: Risk evaluation*

Next, it is necessary to compare this calculated risk R with acceptable risk criteria R_{acc} (Oumeraci, 2004). Aspects regarding personally, socially, economically and ecologically accepted level of risk are given e.g. by VRIJLING (1984) or KUIJPER & VRIJLING (1998). The remaining risk R_r is obtained from the subtraction of the calculated risk R and the acceptable risk R_{acc} (Fig. 8).

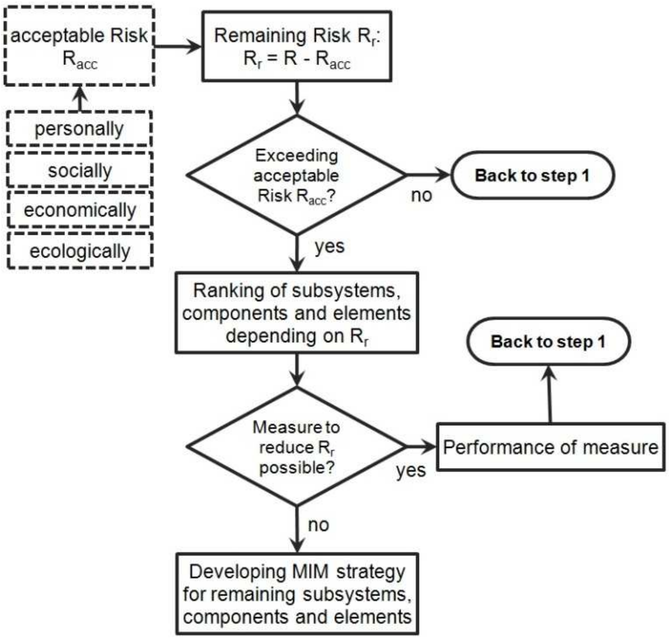

Figure 8. Flow chart 'Risk evaluation' (Horstmann et al., 2012)

The results of a comparative analysis of the calculated risk R with the risk accepted by stakeholders and owners of a dike or quay wall structure R_{acc} enable to set priorities for counter measures by ranking those subsystems, components and elements which execeed the acceptable risk R_{acc}.

If the measures to reduce the remaining risk R_r are appropriate and implemented, then those subsystems, components and elements are updated and the risk R has to be calculated again in step 1 to step 4.

If the measures are not feasible, the MIM strategy has to be adapted to the remaining subsystems, components and elements.

6.2.5 *MIM strategy*

It is essential to treat the remaining risk R_r in the ensuing MIM strategy with e.g. monitoring measures until a threshold value is reached which cannot be exceeded without any damage (Fig. 9).

Stakeholders and owners have then to decide whether performance of maintenance and repair measures is possible or if subsystems, components and elements should be treat in the ensuing maintenance strategy in which an inverse fault tree analysis has to be performed (Fig. 10).

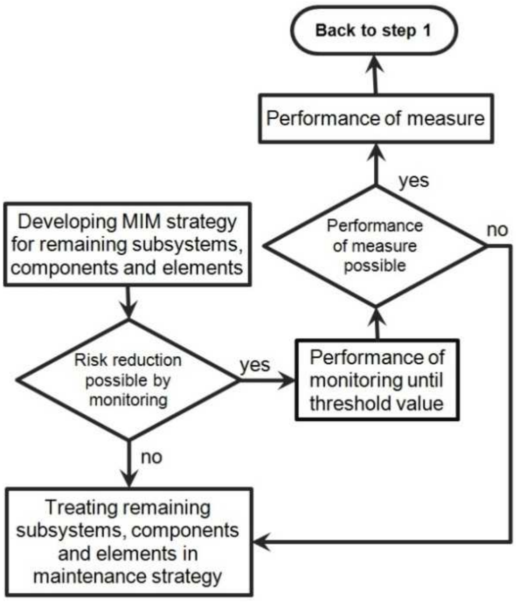

Figure 9. Flow chart 'Monitoring' (Horstmann et al., 2012)

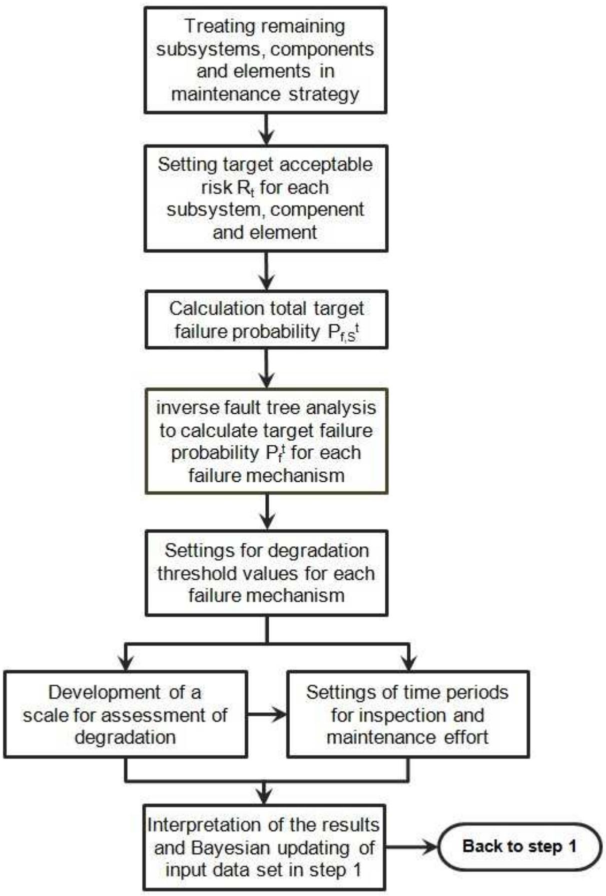

Figure 10. Flow chart 'Maintenance' (Horstmann et al., 2012)

By setting a target failure probability $P_{f,S}^{t}$ for the total system which is determined on the basis of the acceptable risk criteria R_{acc} as a top event in the fault tree it is possible to calculate the roots of the fault tree, i.e. the failure probability P_f^t of each failure mechanism.

With these results one can estimate the remaining resistance of the components and elements by using the aforementioned limit state equations. Stakeholders and owners of a structure then have to make a decision about minimum degradation threshold values of each component and element.

In Figure 11, a suggestion for a scale for the assessment of degradation is shown in which a first threshold as a warning value and a second threshold as an action value is mentioned (Vrijling, 2003).

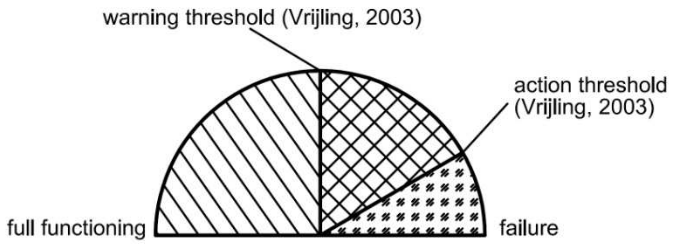

Figure 11. Scale for assessment of degradation (Principle sketch)

In a study by Hijum (1998), damage patterns and limits, failure limits and ultimate failure mechanisms for different condition parameters for a case study of the “Hondsbossche Seadike” are given. Also an application of a maintenance control system and safety assessment is briefly pointed out.

By comparing the calculated remaining resistance of components and elements with warning and action thresholds stakeholders and owners of a structure are able to determine the time when those thresholds will be reached. This method gives an opportunity to split time period in intervals for maintenance and inspection efforts.

The procedure described in steps 1 to 4 and the MIM-strategy with risk and maintenance management is iterative. This means that after the last step the whole strategy will be updated from the beginning by new data provided by inspection and maintenance reports. Hence, stakeholders do not always deal with perfect dike structures. Damages or pre-existing damages detected by inspection work have to be integrated in the calculation of failure probabilities.

7 SUMMARY AND OUTLOOK

To account for the changes which occur over the lifetime of a structure, a risk-based strategy (MIM strategy) is proposed as a key component of an overall framework for life cycle engineering and management. The proposed approach is intended to be applied iteratively during the utilisation phase of the structure. The proposed MIM strategy can also be used as an integral part of a risk-based design of coastal structures as suggested by Oumeraci (2004).

Exemplary applications are briefly outlined for sea/estuary dike and quay walls to illustrate the difficulties and challenges associated with the practical implementation. Among the most important challenges, the development of more time dependent limit state equations for the failure mechanisms as well as time dependent fault trees are noteworthy.

ACKNOWLEDGEMENTS

The risk-based strategy for monitoring, inspection and maintenance (MIM strategy) for coastal protection and harbour structures is part of the NTH Top-Down Cooperative Project: "Life Cycle Engineering for Engineering Structures and Buildings - Strategies and Methods" which is a joint research project of Leibniz Universität Hannover (LUH) and Technische Universität Braunschweig (TU BS), Germany, and funded by the German Federal State Lower Saxony.

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