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Comprehensive Risk-Perspective for Flood Defence System Management

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ABSTRACT

This paper synthesizes recent elaborations for comprehensive risk analyses for flood defence system management in den Heijer (2025). Since risk is a key parameter for asset management, risk management capabilities are important for the maturity and quality of flood defence asset management. The elaboration's main objective is *to develop and test methods for risk analysis in flood defence system management subject to deterioration and climate change*.

Asset management of flood defences systems includes strategic, tactic and operational decision levels. On the operational decision level, a novel integrated risk analysis enables to assess structural robustness caused by ductile dike behaviour. This behaviour may be provided by a clay core, eroding slowly after occurrence of initial dike damage due to a failure mechanism. On the tactical decision level, a systems risk approach has been set up to compare different tactical plans to prioritize and plan measures in interdependent systems, like dikes along rivers. This enables to reduce system risks most effectively and efficiently, dependent of specific tactical preferences such as the risk metric or planning conditions. On the strategic level a simple analytical relationship is derived to tune the economic optimal reliability of a flood defence based on its structural robustness, in combination with its optimal design horizon. This enables to adapt the optimal reliability to a specific dike design.

Today, mostly the decision levels are mutually disconnected for practical reasons. The presented approach differs from today's practice because of the opportunities for coherent use in between the decision levels: the dike design relates to its optimal reliability and to the optimal planning of its reinforcement in system. This concept is called a 'dynamic connected risk analysis'. This provides a comprehensive perspective for the utilization of risk analysis as a tool supporting efficient flood defence system management.

KEYWORDS: flood risk, flood defence, reliability, system management, risk-based planning

1 INTRODUCTION

'Flood risk management' can be defined as the continuous and holistic societal analysis, assessment and reduction of flood risk. From all opportune flood risk reduction measures, structural and non-structural, flood defence management is the most important for those areas protected by a system of flood defence assets like dikes. Asset management of flood defences systems includes strategic, tactic and operational decision levels. Since risk is a key parameter for asset management, risk management capabilities are important for the maturity and quality of flood defence asset management.

Flood risk concerns both the probability of flooding and its consequences. For flood risk in low lying areas protected by dikes, the undesired event is a flooding, most likely due to dike breach caused by natural hazards anywhere along the flood defence protecting the area. The assessment of probabilities of flood defence failure depends on the hydraulic loads and the flood defence strength. The consequences are dependent on failure-, breach- and flood characteristics, and on the exposed values in the considered area. Consequences of flooding are mostly expressed in economic damage, number of victims and number of affected people.

This paper synthesizes the thesis (den Heijer, 2025) which main objective is to develop and test methods for risk analysis in flood defence system management subject to deterioration and climate change. While the thesis and previously published work (den Heijer & Kok, 2022, 2024; den Heijer et al., 2023, 2025) provide an in-depth comprehensive treatment, the present paper integrates the main aspects to support and enhance knowledge transfer to the flood risk management community. It focuses on three questions which elaboration can improve the risk-based management of flood defences, one at each of the three asset management decision levels. Together these questions refer to the asset managers needs to find out why, when, where and how to intervene.

At operational decision level it concerns optimization of dike design, to assess how to intervene: How can the structural robustness of the flood defence contribute to flood risk reduction? This paper introduces the opportunities of ductile dike behaviour to value structural robustness of designs.

At tactical decision level it concerns portfolio prioritisation of measures in system, to assess when and where to intervene: How can planning of measures contribute to effective system risk reduction? Different asset managers may differently develop and apply intervention criteria and conditions, leading to different plans. In this paper the interventions are narrowed to dike reinforcements, since its objective concerns flood defences.

At strategic decision level it concerns flood risk standards, to assess why to intervene: How can risk-based standards for flood defences reflect the benefits of structural robust designs? Individual and economical risks provide a risk-based target or standard to keep a system safe under changing conditions.

The choices in the different decision levels interact. First, in this paper the structural robustness is outlined (paragraph 2), because the ‘how’ of the design is input for the adapted standardization, the strategic topic. Second, the tactical planning is outlined (paragraph 3), because the ‘when’ and ‘where’ is input for the adapted standardization as well. Third, the updating of the standardization is outlined (paragraph 4). Then the dynamic connected risk analysis is outlined, as well a proposed organisation to benefit from this approach (paragraph 5). Finally, paragraph 6 presents the conclusions.

2 STRUCTURAL-ROBUST FLOOD DEFENCES MAY REDUCE RISK CONSIDERABLY

Increase of structural robustness focuses on risk reduction. It differs from strength increase, which primarily aims at reducing the probability of failure. A dike's design not only influences its failure probability, but it may also significantly impact the scale of floodings consequences, especially when the dike exhibits structural robustness due to its ductile behavior. Ductile behavior is defined as a slow failure process of a dike, characterized by relatively slow or depth-limited breach growth, which ultimately leads to reduced breach dimensions and lower flood impacts. This is contrasted with brittle behavior, where a breach occurs suddenly, leading to increased flood impacts. The key insight is that a more ductile dike is not necessarily larger but rather employs different construction, such as a clay core instead of a sand core, to mitigate flood impacts.

To evaluate this, an integrated risk analysis method is developed (den Heijer & Kok, 2022). This method models the entire chain of events in an integral and time-dependent manner: from initial dike failure mechanisms and failure path development to breach growth and the resulting consequences. This comprehensive approach allows for valuing the risk reduction achieved due to the structural robustness of a specific construction type.

The methodology is applied to a case study on the Grebbedijk along the Rhine River in the Netherlands. Based on a database with flood consequence simulations (Helpdesk, 2020), the total volume of water entering the polder is used as a proxy for consequences. This enables a direct link between dike design and flood impacts. Probabilistic software (Brinkman, 2021) for Monte Carlo Importance Sampling (MC-IS) is employed to calculate probabilities of exceedance of polder water levels (F_H-curves). Six different dike construction types, representing variations in core material (sand or clay) and structural elements (with or without a sheet pile, or with extra width), are analyzed. Figure 1 provides the F_H-curves for various construction types for the same dike dimensions (crest height, slope and berm). Since the polder water level is directly related to the consequences, the surface below the curves represents the flood risk.

Elaborating a variety of combinations of dimensions, the economic optimal dimensions per construction type led to different dimensions, footprint and corresponding costs. A brittle sand dike might require larger dimensions than a more ductile dike with a clay core to achieve similar risk levels. The total societal costs and individual risks to victims strongly depend on the construction type. The study shows that optimizing the structural robustness dike construction can lead to substantial reductions in both societal costs and individual risks. In the case study, a dike with a sheet pile could reduce individual risk by a factor of 10. The additional budget needed is relatively small, because the sheet pile prevents dike height increase and the construction of a berm.

In conclusion, next to load reduction, strength increase, and consequence reduction, structural robust dike design is a fourth category of flood risk reduction measures. The integrated risk analysis approach provides valuable insights for comparing alternative designs, fostering decisions that go beyond mere compliance with probability standards to achieve optimal societal benefits, particularly in densely populated areas where flood consequences are high.

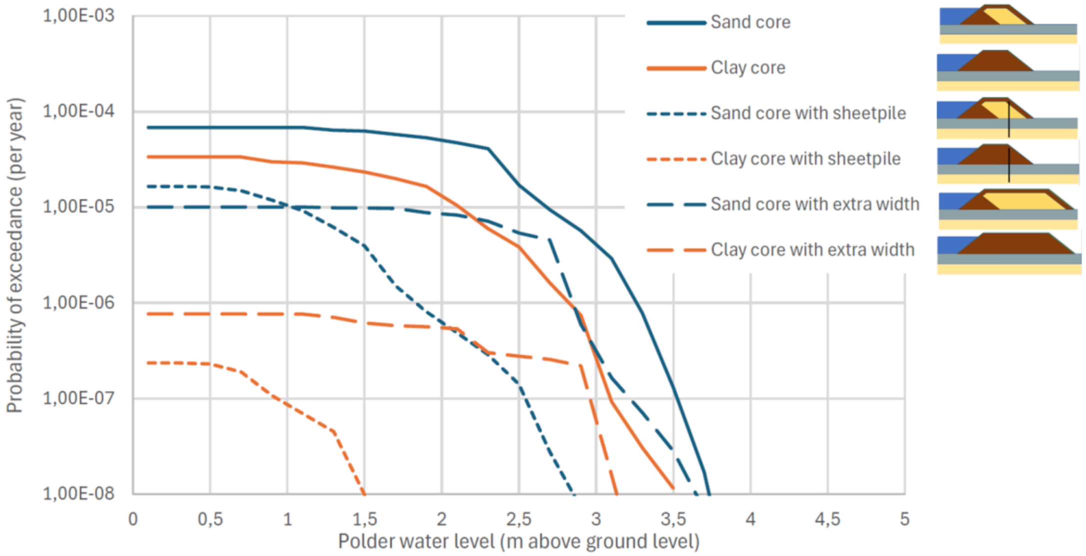

Figure 1: Examples of a series of probabilities of exceedance of polder water level H (F_H-curves), for different construction types at location Grebbedijk. Crest height = 12.2 m+ NAP, berm width = 10m, berm height = 0.75m, inner slope 1:2.5. Source: adapted from (den Heijer & Kok, 2022).

3 PROPER TACTIC PLANS REDUCE TIME-AGGREGATED SYSTEM RISKS

Tactical plans define the planning of consecutive measures (interventions) required to implement a flood risk reduction strategy, a process which may take decades. Tactical plans may consist of several features, such as a planning metric, the budget and specific planning constraints. Planning these costly measures requires proper insight into system risk effects. The tactical decision level concerns the portfolio prioritization of interventions in the dike system. Dike systems require continuous intervention to mitigate changes such as ageing and climate change.

In (den Heijer & Kok, 2024) a method was developed to compare different tactics to prioritize and plan measures in interdependent systems of dikes to reduce risks most effectively and efficiently. The time-aggregated system flood risk (TAR) is introduced as a novel measure. Existing measures consider different types of risk separately, and mostly per polder and per year. The TAR is the combination of the total economic and individual risk in a system of polders over a reference period of time, in (den Heijer & Kok, 2024) taken over 100 years. The TAR enables comparison of different tactics, because it identifies the effectivity of the man-induced changes like dike reinforcements during the reference period, with respect to the system risk reduction. The importance of tactical planning is underscored by the finding that time-aggregated risk reduction can be introduced as a decision variable for plan evaluation.

A case study, meant as a proof of concept, was carried out for the reinforcement of approximately 500 km of dikes along the Rhine River branches in the Netherlands. The research studied the effects of 12 different tactical plans on the aggregated risks over time. The results demonstrated that tactical planning decisions are critical for reducing time-aggregated flood risks. Specifically, the present value of the sum of costs and economic risks differed by up to about 40% between the plans, while the risks on victims differed by up to 70%. Figure 2 summarizes these outcomes by plotting expected victims (individual risk) against the total present value of costs (investments and economic risk), for the 12 tactical plans. This illustration revealed that combining a risk-based prioritization metric with a priority condition for the top 3 ranked dike segments (filled red and green triangles) yields a comparable effect on reducing total costs and risks as doubling the budget when using a safety-level based metric (open yellow dot). The case study underlines the crucial role of tactical planning decisions, alongside prioritization metrics and budget constraints, influencing the resulting risk pattern.

By aligning fragility curves with ductile designs, the tactical planning analysis can balance the structural robustness of designs against the optimal time-aggregated system risk reduction, supporting efficient and well-considered reinforcement decisions.

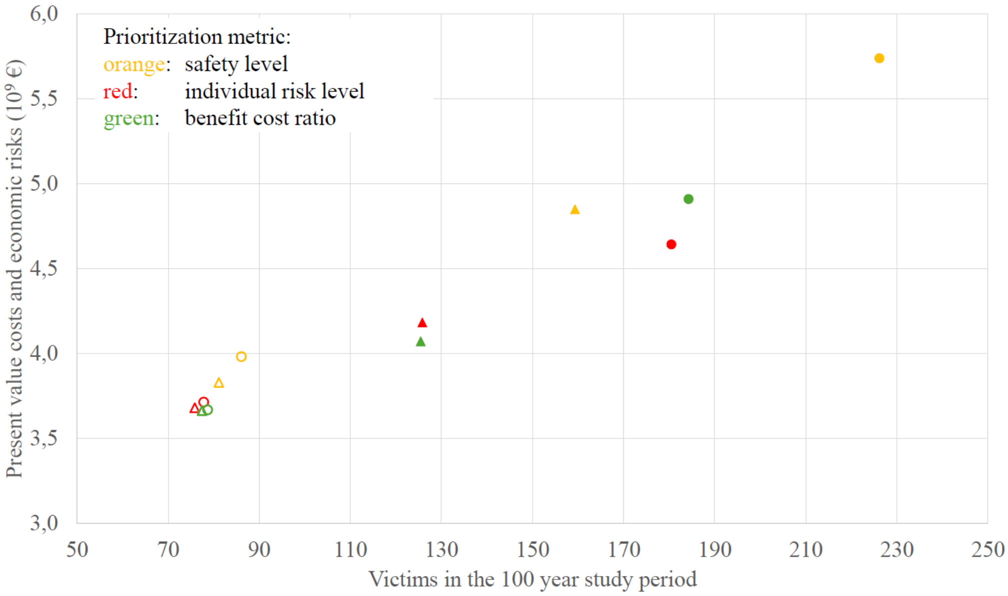

Figure 2 Model result for 12 tactical plans in the case study. Prioritization metric denoted by color. Budget and priority condition by marker shape: proportional budget (filled marker), doubled budget (open marker), no priority condition (dot), top 3 first (triangle). Source: (den Heijer & Kok, 2024).

4 UPDATING FLOOD RISK STANDARDS

A standard defines the performance requirement for flood defences, typically expressed as an acceptable probability of flooding per year, to keep a system safe under changing conditions. These standards provide the rationale for organizations to invest in a complex portfolio of risk-reducing assets.

In the Netherlands, standards are based on acceptable limits for individual and economic risks. Despite being risk-based, formal standards are generally static, set in law.

The optimal standard is derived based on the principle of minimizing total societal costs, which comprises the sum of investment costs and the present value of risks. The methodology to update the standard consists of an adapted analytical approach developed by Van Dantzig (1956) and Kind (2014), whose work provided the numerical basis for the current formalized Dutch standards (2017). The Adapted Van Dantzig method includes the dynamic effects of relative water level rise (due to subsidence and climate change) and reinforcement interventions over time (den Heijer et al., 2025). The analysis focused on the failure mechanism of wave overtopping. To account for structural robust dike behavior (ductility) in the Adapted Van Dantzig method, a translation factor was proposed to update existing probability standards to risk-optimal probability that reflects a specific design. This factor translates the marginal investment costs and the economic damage corresponding to the proposed design against the reference values used for standardization in Kind (2014). Since ductile designs reduce consequences after a breach, this allows a structural robust construction to be associated with a less stringent reliability standard than a less robust construction.

The methodology was compared with Kind (2014). The comparison focused on the middle probabilities (the average of the intervention limit and the design limit) for over 70 dike segments. The agreement was considered to be sufficiently convincing, see Figure 3

. Specifically, the results for the adapted analytical approach were comparable to the detailed numerical study, showing the average difference in return periods was only about 5%. This convergence supports the use of the simpler analytical model in (den Heijer, 2025) for standard estimations and its updates due to dike design or new information.

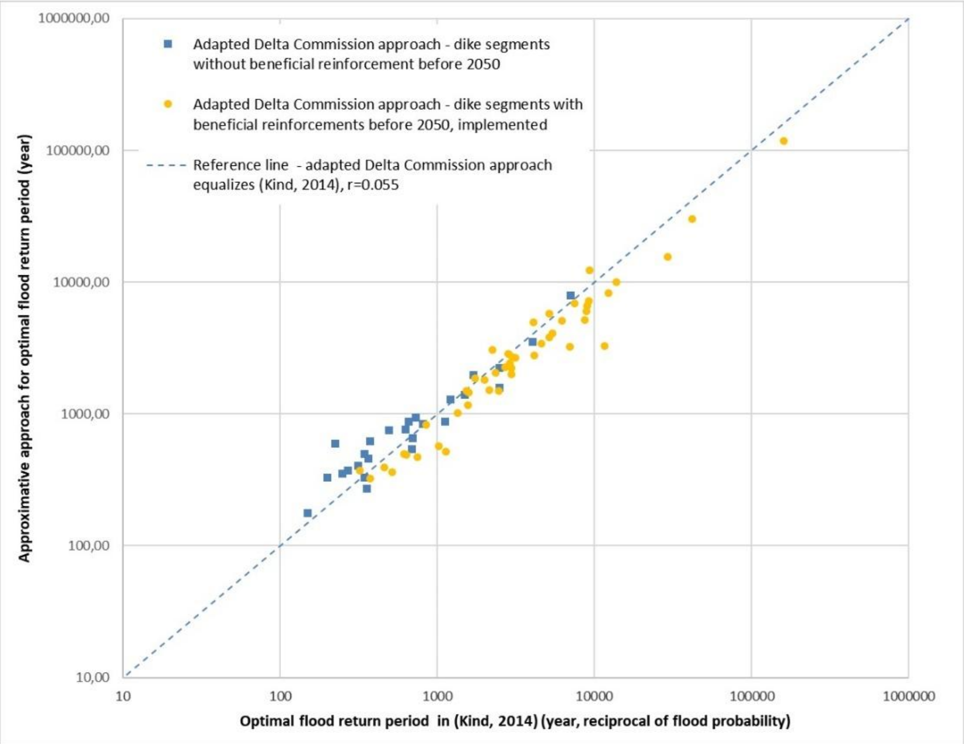

Figure 3 Comparison of adapted Delta Commission approach with the results of (Kind, 2014). Source: (den Heijer et al., 2025).

Regarding the optimal design horizon, the study developed an analytical relation for the economically optimal intervention timing. The analysis showed that the optimal life cycles (design horizons) for the dike segments averaged around 40 years. However, for a number of dike segments, the economically optimal life cycle was shorter than 25 years. This finding indicates that the typical design horizon of 50 years is not universally optimal, and shorter design horizons may be economically optimal.

In conclusion, the derived method makes it practically possible to update the flood defence performance requirement, enabling a dynamic focus on optimal risk reduction dependent on the intervention timing and the chosen design construction type. This capacity to risk-aware update standards is crucial because it allows the benefits of structural robustness to be valued and utilized in efficient asset management and reinforcement decisions.

5 ORGANISING A DYNAMIC CONNECTED RISK ANALYSIS: HOW IT COULD WORK

Dynamic risk analysis is defined as enabling the involvement of changes over time on the time scale appropriate for the considered decision level. This forward-looking approach is indispensable because risks develop in time. This affects each decision level. At the operational level (see paragraph 2 in this paper), analysis must be time dependent and integrated to model the consecutive occurrence of dike failure paths, breach growth, and consequences during a single flood event, which is necessary to value structural robustness accurately. For tactical planning (see paragraph 3), where interventions span decades, a dynamic approach is crucial to assess time-aggregated system flood risk under deterioration and climate change. Finally, at the strategic level (see paragraph 4), dynamic analysis allows reliability standards to be updated, reflecting both the effects of time-dependent parameters and the economic optimal design horizons.

A connected risk analysis links involved technical disciplines and spatial system effects in the physical domain to bridge practical disconnections between asset management decision levels. Practical disconnections may be, among others, the distinction of individual dike segments, individual failure mechanisms, loads and strength calculations.

When combined with a connected risk analysis it forms a dynamic connected risk analysis. This integrated method facilitates efficient and comprehensive flood risk management. Its application supports risk management practices across operational, tactical, and strategic decision levels. This coherent approach is key to improving flood defence management. It enhances risk communication and supports continuous capability improvement.

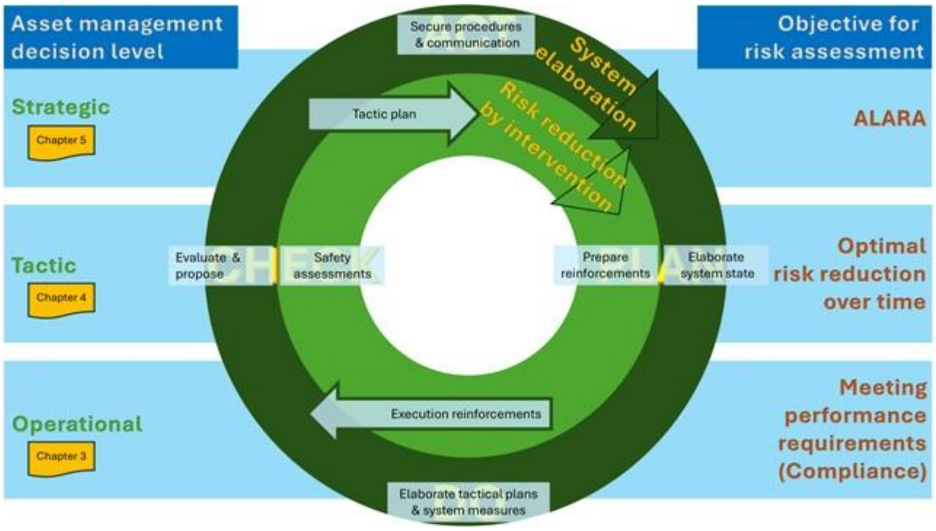

Figure 4: Schematic overview of dynamic concept for flood defence asset management. Source and reference to Chapters: (den Heijer, 2025).

Below a storyline is described for how the process could work, following the Deming circle (Deming, 1986), introducing the repeating process of PLAN, DO, CHECK and ACT for continuous improvement. Figure 4 presents the three decision levels (left) and the corresponding risk management objectives (right), with a double Deming circle for system elaboration (outer) and intervention (inner). Please note, the Deming's circles are turned a bit to better align with the decision levels.

Starting the process in the outer circle in Figure 4 at the strategic decision level (ACT), 'Secure procedures' is mainly about providing starting points for system development on the relevant sectors (e.g. technical, spatial, capacity, capability), as well as about communication of choices and investigating societal acceptability. One of the procedures can be the prescription of the Adapted Van Dantzig method for derivation of an economic optimal safety level, see paragraph 4. Most relevant for utilizing the risk analysis in a dynamic connected way are the starting points for tactical planning providing room for a series of tactical plans.

The system elaboration process continues with 'elaboration system state' (PLAN), inventorying the present system condition as a starter. For each dike segment a preliminary assessment is performed based on a preliminary safety level as the performance requirement. Further elaboration of interventions can be done without the dikes which reinforcements are certainly out of programme horizon. For the remaining dike segments an inventory of several reinforcement alternatives is made, including alternatives changing the construction type, and including future projections of ageing. NB. Performance requirements appropriate to alternative construction types can be based on the Adapted Van Dantzig method (paragraph 4).

With 'elaborate tactical plans & system measures' (DO) potential intervention programmes are composed based on a series of tactical plans fitting which fit the strategic starting points, including potential system measures. For each dike in system reinforcement alternatives are analysed, for several structural robustnesses. For each tactical plan the initial safety level for the dike segments in system is derived based on actual assessments, and the intended safety level is based on the prescribed method from the strategic decision level in combination with and the structural robustness of the reinforcement alternative. Therewith, the time-aggregated risk reductions corresponding to the tactical plans and corresponding interventions can be calculated, see paragraph 3.

With 'Evaluate & propose' (CHECK) these time-aggregated risk reductions are weighed and a proposal has been made for a tactical plan, to be decided for at strategic level. At strategic level the proposal is confirmed or rejected (ACT).

In case it is confirmed the choice for a tactical plan is the start of the inner intervention circle in Figure 4 (ACT). In case it is rejected the argument for the rejection is added to the set of starting points provided to the next step in the outer system elaboration circle. In that case, a next iteration in the outer circle may lead to confirmation of a proposed plan, entering the intervention circle.

Following the strategic choice for a tactical plan, with 'prepare reinforcements' (PLAN) the corresponding intervention programme is set-up. The programme is based on actual assessments and the confirmed tactical plan including the budget. Therewith, the timing, construction type, safety performance requirement and design horizons are determined.

Following the system programme, the first upcoming reinforcements need a formal decision after which they cannot be withdrawn by programme considerations without loss. Then, the reinforcement can be executed (DO). Note, the formal reinforcement decision contains not only earmarking the dike segments to be reinforced, but the reinforcement plan as well, including construction type and safety level, because of its effect on the system.

Finally, the last step in the intervention circle is to update the 'actual assessments' for all flood defences in system (CHECK) based on the actual system and status of the interventions. These actual assessments are input for 'communication' (ACT) and for the next steps in the outer circle for system elaboration, evaluating interventions to continuously find the best coherent tactical plans.

In this way the executed reinforcements are tuned on their direct effects, reducing the risk in polders they protect, and on their system effects, due to the increased loads (e.g. in a river: for downstream located dikes). For each of the asset management decision levels the risk management objectives are met. Individually, the executed reinforcements meet the required safety levels, they are compliant. Due to the thoroughly evaluated tactical plans, the time aggregated flood risk in system is optimally reduced over time, within the strategic boundaries. At strategic level, due to the thorough consideration and communication on the progress, the process is related to societal acceptability, meeting the ALARA principle. For this process, cooperation between the actors is crucial (den Heijer et al., 2023).

6 CONCLUSION

The main objective of the thesis (den Heijer, 2025) synthesized in this paper is to develop and test methods for coherent risk analysis in flood defence system management, addressing deterioration and climate change. The primary contribution is providing a comprehensive perspective for the utilization of risk analysis as a tool supporting efficient flood defence system management. The conclusions address the three decision levels of asset management.

For dike design, regarding the operational level, the structural robustness of the flood defence contributes to flood risk reduction. A risk analysis was set up, time dependent integrating the disciplines loads, strength, breach growth and consequences. This allows for valuing the risk reduction provided by ductile behavior (e.g., by a dike with clay core). Case study results show that total societal costs and individual risks on victims strongly depend on the construction type.

For system planning, regarding the tactical level, the tactical plan of consecutive measures is crucial for effective and efficient reduction of time-aggregated system flood risks. The time-aggregated risk reduction can be introduced as a decision variable for plan evaluation. The effects of different tactical plans showed that economic risks can differ significantly.

For risk-aware updating of standards, regarding the strategic level, failure probability standards can reflect the benefits of structural robust designs. An easy-to-use analytical translation enables to maintain a dynamic and risk-aware focus on the economic optimal probability of failure, dependent on the design and planning of the intervention.

A dynamic process can be introduced to continuously focus on effective and efficient risk reduction, for which sound cooperation among flood defence system management actors is indispensable.

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