Towards an integrated evaluation framework for Multi-Functional Flood Defences

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ABSTRACT: This paper reports on work, which is currently conducted under the Dutch Technology Foundation STW-Perspectief program “Multi Functional Flood Defences”. This program aims to develop both the technology and the governance required for the implementation of multifunctional flood defences. It involves in total 12 PhD students and 4 postdocs. This paper elaborates on the methodology and organization of this program. The program has two components: in depth research about the needed technology and the corresponding governance, and on the development of an integrated framework for the design based on a diversity of quantitative and qualitative evaluation criteria. The utility of this framework for the appraisal of the effectiveness of multi-functional flood defences will be demonstrated in this program using the context of case studies. These case studies will also integrate the research of the PhD students, since groups of PhD students will investigate the different cases.

1 INTRODUCTION

According to the OECD up to 140 million people and euro 30,000 billion of assets could be dependent on flood protection in large port cities around the world by 2070. A large proportion of these flood protection systems are aging and need to be replaced and/or adjusted to comply with the prevailing or more ambitious safety standards, requiring significant investment. Besides, the population pressure on coastal areas increases the need of new flood defenses in expanding cities, and it is often nowadays preferred that these flood defenses are well integrated in the urban design. Most of these infrastructural systems have been built based on a ‘extreme value’ statistical analysis of historical water levels, and on a scenario of possible increase in water levels due to climate change. Nowadays there are some concerns about the finances to cover the investments needed for improvements and upgrading of existing (mainly mono-functional) flood protection structures. At the same time, competing land claims for urban development and other functions such as flood protection and recreation urge for multi-functional and efficient use of land, including the land claims for flood defence systems. Waterfronts are attractive places to live. An increase in economic and climate uncertainty on the one hand and land scarcity on the other urgently call for technological and institutional innovations in flood defence technology such as multi-functional flood defences. The development of multi-functional flood protection infrastructures solicits the need for a multi-dimensional evaluation framework, which is not only applicable to evaluate alternative designs for a floor risk problem, but is also able to evaluate alternative designs in response to a multitude of challenges.

In section 2, the scientific challenges of the program are described. Section 3 focuses on the disciplinary extension problems, whereas section 4 describes the transdisciplinary integration challenges. Section 5 presents an overview of the program, and section 6 present more details of the research questions.

2 SCIENTIFIC CHALLENGES

In this research project we focus on the transition from the current mono-functional flood protection infrastructure to multi-functional flood protection infrastructure and onwards to infrastructures incorporating a flood protection function. Triggers of this transition are the changes in flood risk management (increase of safety is needed around the world), the need to design a better landscape and the uncertain climate change. For an overview, see Figure 1.
The predominant scientific challenges are:

- Reliability and risk evaluation of multi-functional defences. This requires new methodologies since the risk to a multi-functional defence is not simply the sum of the risk to the individual functions. Currently, extra functions are often neglected in the assessment of the failure probability (see for example Jongejan et al, 2011). For example, it is unknown how a (bicycle) road on top of a dike influences the failure mechanisms ‘overtopping’;

- Knowledge of behaviour of (e.g. concrete) objects in soil bodies has not yet been well investigated. We will apply modern numerical modelling tools in combination with experimental work (e.g. laboratory experiments to validate these models) in order to assess the structural behaviour;

- Governance strategies, financial forecasting and real estate predictions under uncertain future conditions. The appeal of multi-functional flood defences in the long term: flood defence managers tend to prefer mono-functional flood defences because the governance of the reliability of multi-functional dikes is more difficult to assess than the mono-functional dikes. Moreover, because the time scale of changes of the so called added functions can differ from the function of flood protection. Hence, it is reasonable to expect that the financial and governance principles of multi-functional flood defences are needed because without adequate financing and governance, their reliability will decrease, and might be blocked;

- Integration of multi-functional flood defences into urban and rural river landscapes. The flood defence is now sometimes seen as an unwanted obstacle, since it does not follow the natural flow. Of course, it can be questioned whether the natural flow should be followed. The challenge is to find ways to integrate protection into urban and river landscapes;

- The flexibility and ability to adapt of multi-functional flood defences to accommodate for large uncertainty in future safety standards (due to changing hydrological conditions by climate change or socio-economic evolution);

- The integration of the challenges above into an integral design of multi-functional flood defences.

Case studies are important in this research program. The users provide these case studies and the advantages are twofold: the new knowledge can immediately be tested, and the users receive new knowledge in a very efficient way. In the program, we distinguish two research lines: disciplinary extension research themes and multi-disciplinary integration challenges (see Fig. 2). Extension research themes aim to extend disciplinary theories and to develop new theories and knowledge, while trans-disciplinary integration challenges (interdisciplinary research) extends knowledge to adjacent research fields.

This figure shows that the case studies are very important, and that the project will adopt several cases studies (which might be big—for example the city of Rotterdam—, or they might be small—a garage in a dune, in Katwijk).

In addition to flood protection, multi-functional flood protection infrastructures fulfill societal functions like housing, recreation and leisure, ecology, mobility and transport, underground infrastructure and are a functional part of their urban or rural environment. We distinguish three disciplinary extension research themes and two multi-disciplinary integration challenges.

Extension research themes aim to extend disciplinary theories and practices to adjacent fields (interdisciplinary research), while trans-disciplinary integration challenges develop new theories and knowledge. In total we distinguish six research themes:

1. Disciplinary extension challenges
   1.1. Multi-functional flood risk assessment
   1.2. Urban and rural multi-functional flood defences design
   1.3. Governance and Finance
2. Trans-disciplinary integration challenges
   2.1. Adaptivity and robustness
   2.2. Integrated design

Disciplinary extension challenges address to development of the following disciplines: (urban and landscape) design, flood risk assessment (including for example erosion mechanisms of flood defences with buildings), governance (multi-level and multi-sectoral), and real estate development. Trans-disciplinary integration challenges address the flexibility and adaptivity issue and the integration of all new knowledge. The focus of the research program will be on the development of new technological principles in the theme “Multi-functional Flood Risk Management”. We will now describe the themes in more detail.

3 DISCIPLINARY EXTENSION CHALLENGES

3.1 Multi-functional flood risk assessment

In this research theme much attention is paid to extending the knowledge of the behaviour of flood defences. The following projects are part of this theme:

a. Behaviour of buildings on a multi-functional flood defence during overflow

The behaviour of buildings on a flood defence during overflow and wave overtopping is of importance for the design of the building. In this research, the behaviour of buildings on a flood defence during overflow and wave overtopping is investigated in a laboratory (experiments) and in advanced numerical models. Pressure on the building and scour of the foundation of the building are monitored and analyzed. With scaling rules the results can be translated to practical design guidelines.

b. Dike erosion of a multi-functional flood defence

In this theme two topics are investigated. First, the design of a multi-functional flood defence is investigated. Problems to be addressed are the complex interaction between load (water level, waves), structures and embankment for typical construction elements in an earthen dike (walls, road, boxes, etc). Furthermore questions regarding vibrations and deformations of the structure and construction restraints need to be addressed. The final goal is to show how to design structures that are part of a flood defence system and perform other functions Secondly, the use of relatively wide and low dikes opposite to current high and narrow dikes results in other dominant failure mechanisms. The erosion of the dike body will be one of the dominant limit states. In this research, it is investigated how and how quick a dike body erodes in case of different boundary conditions. The application of dike breach models to wide dikes is investigated and validated with laboratory experiments. The effect to different dike configurations (unprotected, protected) on the time the collapse is the main output of this research.

c. Flood damage assessment in the flooded area with overflowing defences

As flood defences are made overflow resistant, either by adding more volume or by applying erosion protection, the damage pattern is affected. This research focuses on the impact of multifunctional flood defences on the flood patterns and flood damage in the diking area for different boundary conditions by means of numerical modelling. The dike body erosion is an important input for this research.

d. Safety assessment of integrated flood defences

In practice, the implementation of integral flood defences is hampered by the lack of scientific knowledge of the behaviour of objects in soils. The interaction between these constructions under (uncertain) extreme conditions is not known. Examples of these integral defences are: roads on the top of a flood defence (the strength of a road is yet not taken into account), dunes combined with quays, service pipes in dikes, etc.

e. Failure probabilities of dike ring areas

The flood risk of an area can be assessed using ‘fault tree’ and ‘series systems’, which means that the weakest part of the system is responsible of the safety of the total system. There is no insight at this moment whether multifunctional flood defences influence the correlation between the dike sections and this insight is necessary whether multi-functional flood defences are widely used.

3.2 Urban and rural multi-functional flood defences design

Multi-functional flood defences are designed in a societal context, and in this theme we develop the functional requirements in urban and rural areas.

a. Delta-Urbanism and future flood defences in the urban context

The flood defence system is an important physical element of the urban fabric, which can influence the development of urban programs, the cohesion of the city as a whole and the position of the waterfront in the urban structure. This last aspect plays an important role in Dutch river—and sea-related cities, because of substantial programmatic changes in the waterfront-areas of these cities: until recently dominated by port—and industrial activities, and during the
last decades changing to residential and other urban programs. The dikes play an essential role in the process of integration of the transforming waterfront-areas in the larger urban context. The question is in what sense the urgency to remodel the dikes because of climate change and rising water-levels can be combined with the urgency to remodel the dike as an element which integrates the new waterfronts in the urban context.

b. Landscape and natural aspects of multi-functional flood defences

Multi-functional flood defences require location-specific designs, which fit in the environment and use the opportunities that this environment offers. To define the optimal combination of the several functions a systematic method for function-evaluation is required. The focus of this research project is to develop a function-evaluation methodology especially for rural areas with agricultural (e.g. saline agriculture and biomass production for energy), nature functions (via ecosystem services and nature conservation) and functions for recreation. Information about landscape (e.g. quality and cultural-historical), and transport functions from other research will be used where appropriate. In this theme we focus on combining the technical expertise of water and catchment management with the approach of collaborative planning and dynamic, flexible, landscape design, to help improve the innovation of technically effective solutions to attenuate technology and landscape planning & design to policy decisions.

3.3 Governance and finance

The concept of multi-level governance describes the dispersion of authority upward, downward, and sideways from central government and takes the government as its basic object. The concept of multi-sectoral governance describes the concentration of authority over an issue that is subjected to governance, in this case multi-functional flood defences.

Types of multi-level governance are normally characterized by the way jurisdictions are structured in terms of territorial scales and levels. In the literature multi-level governance arrangements are generally differentiated into type I or type II arrangements. Type I multi-level governance is characterized by general-purpose jurisdictions, nonintersecting memberships, a limited number of levels and a system wide architecture. To the opposite, type II multi-level governance is task specific, has intersecting membership, has an unlimited number of levels and its design is flexible. The transition from flood-protection infrastructure to multi-functional flood protection infrastructures involves the development of a hybrid type of multi-level governance arrangements that combines type I and type II characteristics. This research project aims to design and evaluate hybrid multi-level governance arrangements for multi-functional flood protection infrastructures.

Opposite to multi-level governance, multi-sectoral governance starts from the concentration of sectoral jurisdictions on a single subject. In the case of multi-functional flood protection infrastructure, sectoral jurisdictions related to safety against flooding, building regulations and jurisdictions on issues like fire safety, communication services and utilities are concentrated in the governance of a single object. This research project aims to develop multi-sectoral governance arrangements for multi-functional flood-protection infrastructures.

This project is aimed at understanding how optimal synergy can be developed between safety requirements and economic (e.g. tourism, commercial real estate), housing and other functions. This project will focus on the design of multifunctional flood defences. Flood defences are primarily used for flood protection but they already have an important cultural heritage and ecological value. Flood defences are also often used as road, parking lots, boulevard, dwellings (as e.g. floating houses), and recreation area. These functions have a different life cycle and different requirements in terms of safety, maintenance and construction design. This theme focuses on:

- Assessing how innovative designs and alternative uses of flood defences could enhance commercial and other uses of flood defences.
- Developing decision-support and cost-benefit tools integrating flood protection measures and commercial and other functional requirements. Such tools require the integration of multi-criteria parametric decision support mechanisms and allow designers to communicate and account for the effects of different design alternatives for flood protection and other interests.

4 TRANS-DISCIPLINARY INTEGRATION CHALLENGES

4.1 Adaptivity and robustness

The performance of flood defences is expected to keep pace with external change drivers like climate change and to be resilient for uncertain future scenarios. Because flood defences typically have a lifetime of 50–200 years, the uncertainties associated with the process of risk management and planning can be significant and arise from, amongst other factors, a lack of knowledge about external drivers.
Therefore the planning or modification of such systems should effectively allow for the lack of knowledge by introducing and implementing system adaptivity and robustness.

System adaptivity is the capacity of the whole system to adaptively adjust to future change. Examples of adaptive capacity measures are building in flexibility and reversibility in flood defences, and making financial and spatial reservations to allow for adaptations. Flexibility can be built into infrastructure systems by using a ‘real options’ approach to facilitate managed/adaptive responses in the future when increased knowledge allows for uncertainty to be reduced. Real options may be utilised even when modifying existing flood defences. Real options thus provide: ‘the right, but not the obligation’ to adjust the infrastructure system in ways likely to be more flexible and resilient, as needed to continue to maintain acceptable levels of functioning in the face of uncertain future change. Real options analysis provides a rational means for deciding on the most effective ‘options’ to maintain the performance of an infrastructure system and when to implement these over the system lifetime. Real options analysis originated from the options analysis developed in finance, recognised by a Nobel Prize in Economic Sciences in 1997, and has been developed for the management of infrastructure systems since the 1990s.

System robustness is defined in this study as the capacity of a system to absorb flood waves in annual variability. This implies the system capacity to avoid, alleviate and recovery from flood losses. In this context, the application of “wide” flood defence might be an effective way to reduce the probability of failure of a flood defences. In this research project it is investigated how much extra width is minimal needed for a flood defence that is for example a 100 times safer to deal with the inherent uncertain hydraulic load and strength. By means of cost-benefit analysis it is investigated which strategies are the most optimal. Strategies could involve: higher defences, wider defence and overflow resistant defences. This cost-benefit analysis partly depends on the results of theme 1.1, 1.2 and 1.3.

4.2 Integrated design

The development of multi-functional flood protection infrastructures solicits the need for a multi-dimensional evaluation framework, that is not only applicable to evaluate alternative designs for a given problem, but is able to evaluate alternative designs in reaction to a multitude of challenges. The object of evaluation, a design, and the diversity of quantitative and qualitative evaluation criteria will stretch current multi criteria methods to or even over its limits. More specifically the integration of criteria to evaluate the aesthetic qualities of a design in relation to for example flood risk poses numerous challenges. This project will develop and test such a framework.

5 DURATION AND AVAILABLE BUDGET

In the following table the input is given for each research theme.

The program is started at 1 January 2012. Duration of the program is 5 years (2012–2017).

6 CASE STUDY: VALIDATION OF PROBABILISTIC MODELS FOR COMPUTATION OF SYSTEM-INTEGRATED LEVEE FAILURE PROBABILITIES

One of the PhD students in this research program will determine the validation of levee failure probabilities. The student is Kathryn Roscoe, and in the project proposal the research program is described as follows. The effectiveness of a flood defense strategy such as multi-functional defenses is highly dependent on the computation of failure probabilities of the defense. In The Netherlands (but also somewhere else), we have that current safety assessments consider each dike section separately and use a legally mandated exceedance frequency as a standard for assessing the failure probability of a dike section. In the not-too-distant future (10 years), this approach may be replaced in The Netherlands by a more comprehensive one in which the failure probability of an entire dike ring will be assessed. Such an approach is philosophically more in-line with the purpose of a flood defense; that is, the focus is on the failure probability of the defense. Computing the failure probability of an entire dike ring is known as system reliability.
With in a complex probabilistic model, many approximations and assumptions are incorporated to make the computation possible. For example, the model includes a combination of failure probabilities due to a variety of different failure mechanisms, such as piping, overtopping, and erosion, and the spatial combination of failure probabilities over the various dike sections. Such combinations using standard probabilistic methods such as Monte Carlo or Numerical Integration are too computationally intensive for practical application, due to the small failure probabilities (for Monte Carlo) and the large number of stochastic variables (for Numerical Integration). Therefore, approximation methods are utilized, such as the Hohenbichler Method for combining probabilities. The combination of failure probabilities is also largely dependent on how the correlation between variables, as well as the spatial auto-correlation for a single variable, is defined and taken into account. The development of a new probabilistic model is currently being carried out based on the model PC-Ring, to be used in future flood defense assessments. The model PC-Ring was developed specifically for use in the Netherlands, and was never validated. Validation of a model requires observations with which the model output can be compared; in The Netherlands, no major levee failures have occurred (just after WWII in 1953) with which to validate the model. The proposed research will apply the new model in a pilot area where sufficient failures have occurred for the purpose of validation of the model. The proposed study area is the Sacramento-San Joaquin delta in the San Francisco bay area of California, which has experienced over 160 levee failures in the past 100 years. In this way, the research brings together a unique probabilistic model with a unique set of observations for the purpose of validation. The research will focus on methodologies for validation of a probabilistic model in which the computed probabilities are very small. Once a methodology is designed, comparisons between different approximation methods for combining failure probabilities will be carried out, as well as investigation of the appropriateness of different methods of incorporating correlation. Focus will also be given to the managing of uncertainty in model input data (such as subsurface soil types or water levels associated with a given return period). Typically, the more uncertain an input variable is, the higher the probability of failure; research therefore needs to focus on how to deal with uncertain input such that the computed failure probability is not unrealistically high. Validation of the probabilistic model used as the foundation of assessing flood protection strategies is critical if we are to have confidence in the assessment. However, it is a difficult subject, because it is relatively new, and no literature is available in case of limited available data. The contribution of the proposed research is important for the initiation of a new flood defense strategy using multi-functional dikes, as well as for the current assessments and design of flood protection.

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The website of the program is: http://www.flooddefences.nl/

More information?
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