Towards Improved Flood Defences
Five Years of All-Risk Research into the New Safety Standards

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Oosterhout
Noord
Over-Betuwe
Oosterhoutsche Waarden
9.3
9.5
Over-Betuwe
Oosterhoutsche Waarden
9.5
Over-Betuwe
Oosterhoutsche Waarden
Over-Betuwe
Rijk van Nijmegen
11.2

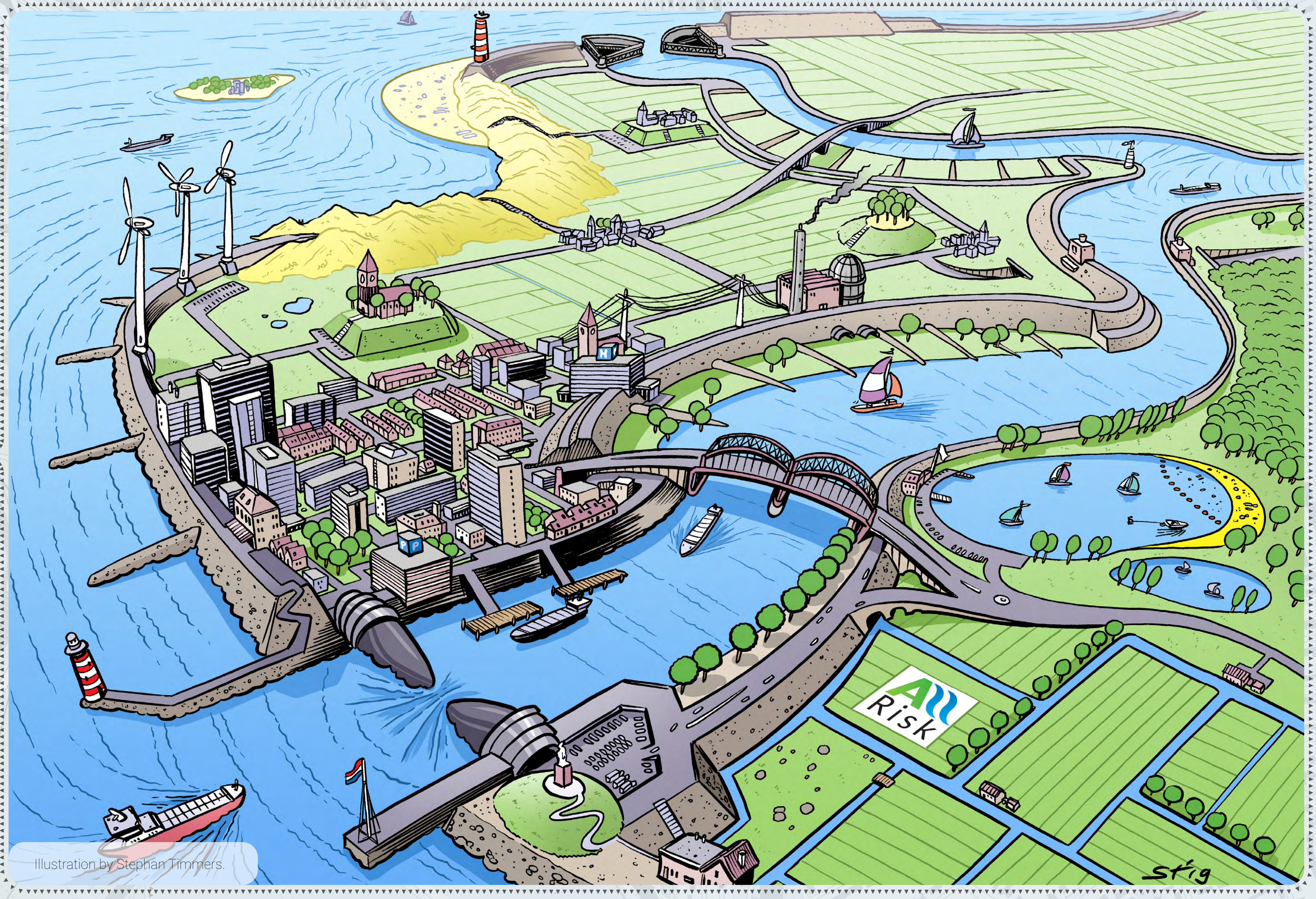

Illustration by Stephan Timmers.

Risk

Towards Improved Flood Defences

Five Years of All-Risk Research into

the New Safety Standards

Editors

Matthijs Kok | Juliette Cortes Arevalo | Martijn Vos

TU Delft OPEN

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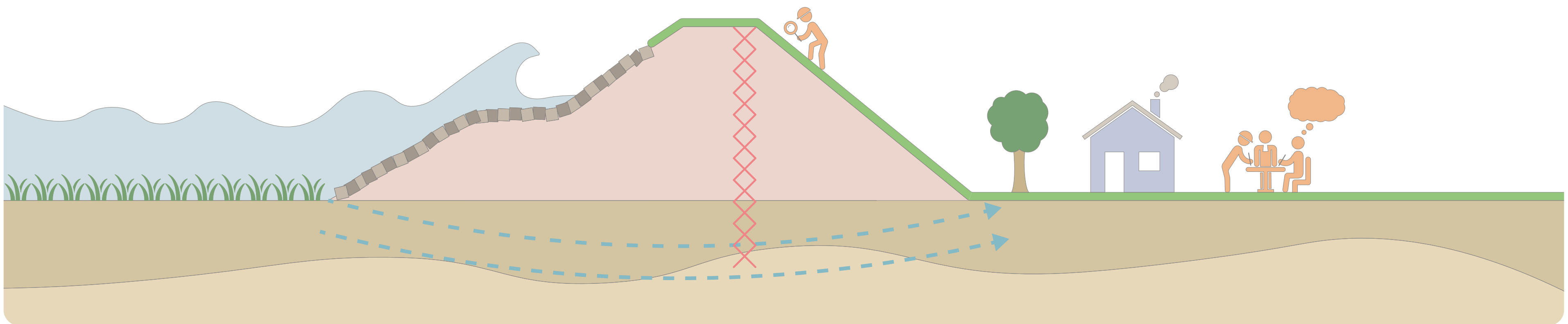

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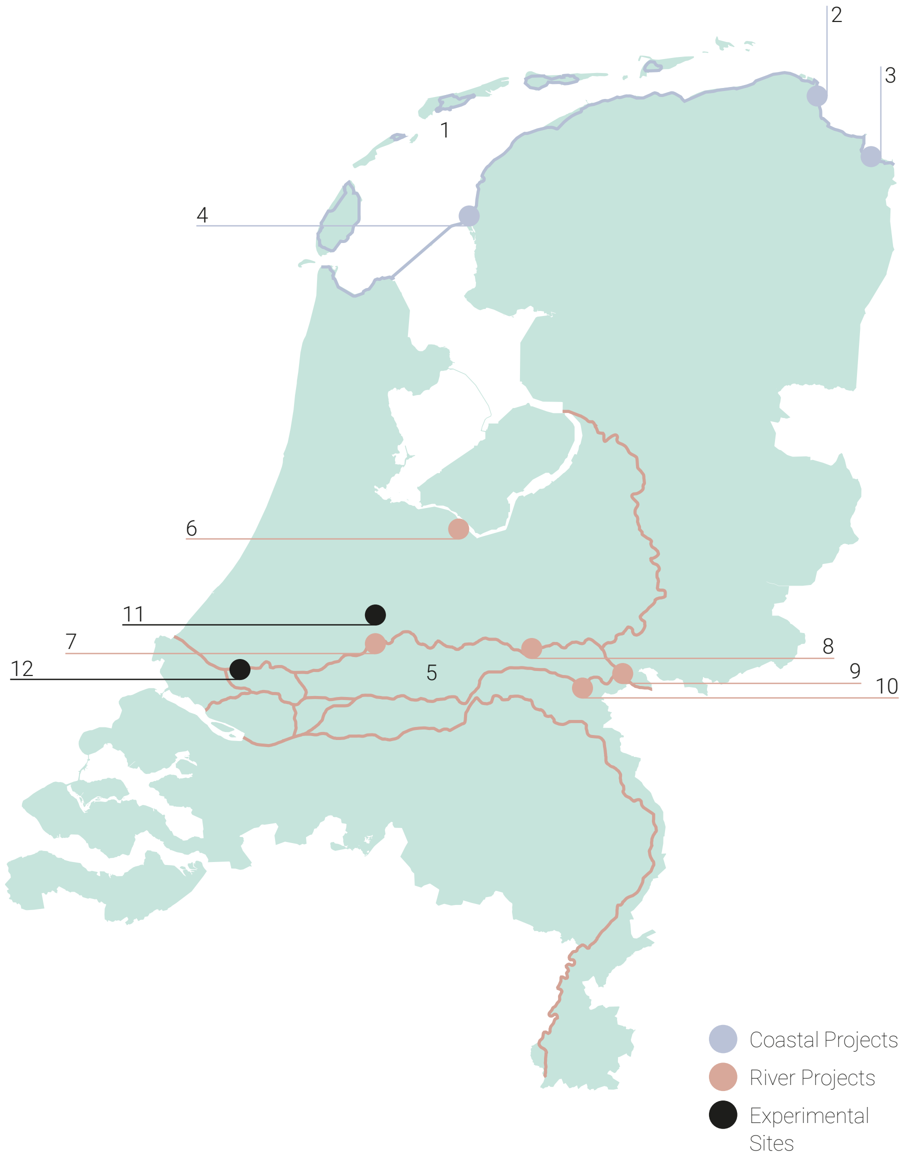

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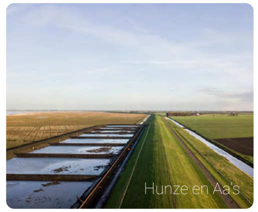

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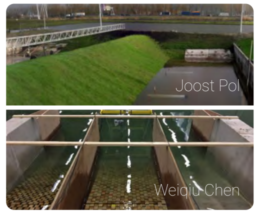

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Water level measuring station along the Waal River near Herwijnen during high water. Photo by HWBP.

Preface

Dike reinforcement operation from Utrecht to Barcelona based on new knowledge

By Anouk te Nijenhuis
Innovation coordinator at the Flood Protection Programme

and Erik Wagener
Director of the Flood Protection Programme

Without our dikes and dunes, 60% of the Netherlands would flood on a regular basis. This area is home to 9 million people. The latest report of the Intergovernmental Panel on Climate Change (IPCC, February 2022) underlines the importance of reinforcing water safety. Sea levels are rising and extreme weather is becoming increasingly common. The Flood Protection Programme, the largest Dutch water safety operation since the Delta Works, will help us minimise the likelihood of flooding.

Flood Protection Programme to reinforce 1,500 km of dikes

The Flood Protection Programme (HWBP) is based on the water safety standards laid down in law in 2017. The underlying principle is that every person in the Netherlands should enjoy the same level of protection. The risk of death as a result of flooding must be less than 1/100,000 per year.

To meet this requirement, between now and 2050, across the whole of the Netherlands, the HWBP programme will be reinforcing 1,500 km of dike and 500 locks and pumping stations. The figures may sound abstract, but 1,500 km roughly equates to the distance between Utrecht and Barcelona. Between now and 2050, a budget of more than 12.7 billion euros has been set aside for this purpose. On average, around 400 million euros will be spent reinforcing 50 km of dike every year!

The dike reinforcement programme is not cast in stone. The water authorities have until 2023 to assess the status of the dikes. Subsequently, wherever necessary, the dikes will be reinforced. In other words, the scale of the challenge facing the HWBP will increase or decrease as we discover more about the condition of the dikes. New knowledge will make the difference in shaping and implementing this dike reinforcement programme.

New knowledge and innovation are urgently needed

The Dutch dikes have stood firm for more than 1,000 years. After disasters in 1916 and 1953, storm surge barriers and dams have been added to the network of protective dikes. Following the floods in 1993 and 1995, the Room for the River programme was implemented. New knowledge of flood risks led to the introduction of new, often stricter standards for flood defences in 2017.

Now, once again, new knowledge and innovation are of key importance. This gigantic challenge demands heavy investments and a fast pace of work. Moreover, the often extensive dike reinforcement projects directly affect people living along the dikes as well as important nature conservation areas and cultural and historical sites. Innovation is needed to reduce the costs per kilometre of dike reinforcement, to shorten the project lead time and to minimise the social impact of the dike reinforcement work.

With that in mind, on average, the HWBP is investing around € 10 million per year in new knowledge and innovations. These funds are used to develop technical knowledge and innovations that improve the work approach and enhance the integrated nature of the projects. These investments are now starting to bear fruit in the form of cost savings, increased sustainability and better integration in the landscape.

All-Risk has delivered a major boost

The All-Risk research programme represents a boost to the knowledge and innovation approach of the HWBP. With a future timeline of more than 25 years, the HWBP is an ideal programme for putting knowledge and new findings from research into practice. By building on scientific knowledge and by collaborating with Rijkswaterstaat, centres of knowledge and the STOWA foundation for applied water research, the HWBP can make practical use of newly acquired knowledge.

Science and practice

Our water safety operation requires a contribution from both (scientific) theory and practice. With All-Risk, we have built a bridge between research and practice. The success of the connections we have made is reflected in the fact that in each of their theses, the researchers have underlined the value of their work for practical applications. It is also reflected in the numerous reinforcement projects in which researchers have played an active role. Below we describe a selection of the inspiring results of their research.

Engineering

The first example is a practical trial for sheet piling. Within this project, a full-scale trial (**Figure 1**) was conducted and financed by the HWBP. In the trial, the load on the sheet piling was increased to such an extent that the piling actually began to bend. The data generated in this trial has been used by various researchers within All-Risk to describe exactly what happened during the trial and to embed the outcome of the trial in scientific literature. The trial also delivered a major boost to practice,

Figure 1: The full-scale Eemdijk test site from an aerial perspective. Photo © NOS / Eric Feijten.

resulting in even more efficiently designed dike systems. The results of the trial and the related research have led to cost savings on sheet piling systems. The trial also revealed that the inflow of water into the polder can be much reduced. This in turn generates a huge reduction in the flood risk, an effect that can certainly be taken into account in the design of dikes for the long term.

A second example is the 'foreshores choice menu', according to which land managers can determine how actively they wish to manage the higher-lying areas in front of the dike. These areas reduce wave impact and as a result mitigate flood risks. Taking this into account reduces the need for dike reinforcement. Now we have a sound scientific basis that has removed concerns about the scouring of foreshores in extreme situations. The choice menu developed in this programme assists in determining the design of foreshore management; an excellent example of symbiosis between All-Risk and the HWBP innovation projects for the Wadden Sea and Voorlanden (Foreshores).

Project approach

In respect of the project approach, remarkable results have also been achieved. The reinforcement of the Grebbedijk along the Nederrijn offers an ideal opportunity for investigating improved integration in HWBP projects. Promising All-Risk results related to integration in HWBP projects provide a positive incentive to continue efforts to find integrated solutions. This study programme revealed that a great deal can already be achieved with a combination of sound motivation, like-minded project leaders and good knowledge. Within the SAFE project, organised by the Rivierenland Water Authority, All-Risk studies were used to remove uncertainties in the project planning and approach. This new approach led to cost savings. Finally, researchers involved in the Double Dike project by the Noorderzijlvest Water Authority and the Wide Green Dike of the Hunze en Aa Water Authority have shown that existing legislation and regulations in fact offer more possibilities than is often believed.

Into practice

It is excellent to see how science is helping to identify smart solutions to address the huge challenge of water safety. The reinforcement projects are now able to reach out to researchers to help tackle real life challenges, while for their part the researchers can experience the dynamic nature of the projects. The HWBP cannot wait to put the results of All-Risk into practice in the dike reinforcement programme. Further work will of course be required, because no matter how favourable the outcome of the research, changing everyday practice still requires considerable time and effort. The relevant water authorities, the programme management and HWBP *'Innovatieversneller'* (Innovation Accelerator) are pleased to help convert the results of All-Risk into practical applications.

Executive summary

In a significant part of the Netherlands, people live below sea level and are also vulnerable for river floods. That is why we have learned to take early action to prevent floods. Since the beginning of the Delta Works, luckily, there have been only a few small floodings. However, these few have always brought their lesson. For example, the Wilnis dike breach in 2003 put in evidence that not only floods but also droughts can affect peat dikes. More recently, the latest flood in Limburg reminded us and our neighbouring countries that weather extremes like the ones we saw in the summer of 2021 are possible. The Flood Protection Programme (HWBP) has been working to prevent the next disaster by reinforcing the 'primary' flood defences. To help strengthen about 50 km of dikes per year over the next 25 years, the All-Risk research programme started in 2017 by bringing together five universities and over 30 partners from the government, research institutes, NGOs and private sector. The research was sponsored by the Dutch Research Council (NWO), which is one of the most important science funding bodies in the Netherlands. Each year, NWO invests almost 1 billion euros in curiosity-driven research, research related to societal challenges and research infrastructure. NWO considers involvement of users and societal impact very important.

After five years of research, we are pleased to share in this book the All-Risk legacy for dike professionals working in related projects in the Netherlands and abroad. Chapter 1 begins with the opportunities and challenges of the technical and legal implementation of the new Dutch risk-based approach while putting into perspective lessons from the German flood risk management context and the most recent flood in Limburg to draw our view into the future flood risk prospects.

Each chapter dives into one of the five All-Risk themes (A to E), ranging from the risk framework to the legal implementation. Starting with a summary of each project, we highlight the innovative contributions and recommendations for practice and share into storylines some case study applications or case studies. We conclude with the reflections from the webinar series discussions of the main findings with representatives from research and practice.

Chapter 2 dives into the risk framework that responsible authorities and technical advisors should use from now onwards to assess the risk of flooding. From the engineering perspective, project A1 proposed methods to choose cost-efficient strengthening measures and look into the quality of dike inspections. Project A2 used a scenario approach to improve dike failure estimations of multi-functional flood defences, also applicable to investigate the principles of a double dike and the sensitivity to sea-level rise of the Wide Green Dike and its dike-marsh system in the Wadden Sea. Together with researchers in other chapters and the related Dutch SafeLevee project, project A3 used past events and experiments to investigate the dike performance. From the spatial perspective, project A4 aligned efforts with the European SARCC project to develop new alternatives for flood protection, for example, in the Vlissingen municipality in the southwest of the Netherlands.

Chapter 3 looks into the 'muddy' coasts of, for example, the Wadden Sea and the Scheldt estuary and the main cross-connected branching rivers that shape the Dutch delta. With a combination of measurement techniques, project B1 looked into the design of salt marsh ecosystems to effectively reduce wave loading during extreme storms. Using existing physical model tests and numerical data, project B2 proposed a less computationally expensive method to account for the full wave-loading spectrum that can reach the dike and its vegetated foreshore. Project B3 re-analysed historical discharge data and used 1D models to quantify and explore the sensitivity of water levels to river channel roughness and discharge distributions into the Dutch Rhine bifurcating system.

Chapter 4 improves the assessment of the subsurface characteristics by looking into the natural development of the Rhine-Meuse delta, the historical dike body buildup, and the performance of novel geophysical survey methods. Thereby, project C1 obtained a delta-scale overview of the subsurface influence on dike failure potential. Project C2 used parameters related to dike geometry, drainage conditions and material properties to estimate dike stability. Project C3 tested and validated statistical methods to convert geophysical signals into physical properties of the subsurface.

Chapter 5 looks into the models and empirical equations of dike failure mechanisms and reinforcement techniques to improve the reliability and strength of flood defences. Project D1 took the Material Point Method to the next level for the purpose of evaluating the failure process after a dike slide. Project D2 evaluated, among other things, the full-scale *"Eemdijk"* failure test – an earthen dike reinforced with sheet piles was brought to failure.

Project D3 showed how the growth of pipes under a dike could be better understood and modelled. Project D4 showed how the performance and settlement of dikes during construction could give important information about their strength during their entire lifetime. Project D5 gave insight into when and how wave overtopping leads to erosion of the inner slope. Project D6 investigated the role of oblique ("diagonal") wave attack on dikes and the effects of transitions.

Chapter 6 reminds us of the role of law and governance in implementing the technical innovations and research into the reinforcement projects of the Flood Protection Programme. Project E1 advised on legal questions such as the ones of the *'POV Waddenzee Dijken'* regarding the application of the Environment and Planning Act and the division of responsibilities in innovative projects such as the Double Dike project. Project E2 identified crucial factors and conditions for the success of cross-sector collaboration within reinforcement projects. Project E3 links back to the first chapter by reminding of the value of spatial planning and visual design in reaching out and appreciating different forms of knowledge that can contribute to reinforcement projects.

Even though the endeavour of the Flood Protection Programme has only spanned the first of about three decades in total, we hope that the insights, methods and tools developed into All-Risk can be of use and inspiration. We are open to receiving comments and suggestions and working together with dike professionals in the ongoing and upcoming research programmes and reinforcement projects to further test and develop research into practice.

Acknowledgements and partners

The research programme All-Risk (https://www.all-risk-program.nl/) is grateful to all its contributors. The programme was part of the Perspectief research programme, within the AES (Applied and Engineering Sciences) domain of NWO (Dutch Research Council). In Perspectief, researchers and users jointly submit new, challenging research programmes within the application-oriented and technical sciences that generate economic and social impact in thematic areas relevant to the Netherlands. We would like to thank the NWO, and especially Maartje van Dijk with her helpful attitude and smart suggestions.

The research programme could not have been carried without the support of the cash contributors to this programme (Rijkswaterstaat, STOWA, Deltares, HWBP and HHNoorderkwartier) and the many, many in-kind contributions.

We would like to acknowledge the following international institutes that collaborated with us in the All-Risk programme: U.S. Army Corps of Engineers, The University of Tokyo, Texas A&M University Galveston Campus, SSPEED Center, UFZ Helmholtz Centre for Environmental Research and the China Scholarship Council.

In the research programme, 14 PhD students and 4 postdocs were supported to do their research. Without the energy, power and smartness of these young and enthusiastic people, the programme would not have survived.

Universities

TU Delft

Wageningen University & Research

University of Twente.

university of groningen

Utrecht University

Radboud University

UNESCO IHE Delft

NIOZ Royal Netherlands Institute for Sea Research

Funding Organisation

NWO

Non-Government Organisations

It Fryske Gea

Natuurmonumenten

Research Institutes

stowa

Deltares

Government Organisations

Rijkswaterstaat
Ministry of Infrastructure and Water Management

Waterschap Rivierenland

Hoogheemraadschap van Schieland en de Krimpenerwaard

Wetterskip Fryslân

provincie groningen

Waterschap Aa en Maas

hoogheemraadschap Hollands Noorderkwartier

Waterschap Hunze en Aa's

Drents Overijsselse Delta

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HKV Lijn in Water

Element Advocaten

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FieldFactors

hillblock

Fugro

Royal HaskoningDHV
Enhancing Society Together

Arcadis
Design & Consultancy for natural and built assets

Illustration by Stephan Timmers.

Chapter 1
Flood Risk Approach

Introduction

By Matthijs Kok and Maartje van Dijk

This book is about the new Dutch flood risk approach, which aims to provide a more transparent and flexible framework for efficient flood risk reduction investments. It is financed by the Dutch Research Council (NWO) in the so-called *'Perspectief'* programme. Developing new technology requires setting up new lines of research, transcending old networks and creating close collaboration between scientists and industry. The financing instrument *'Perspectief'* focuses on stimulating this in order to solve innovation bottlenecks. Innovative knowledge takes shape in an application that contributes to technological innovation with potential economic and social impact for the Netherlands.

This chapter provides background information about the flood risk approach. In the first contribution, **Wim Kanning and Bas Jonkman** observe that the conservative estimation of failure probabilities implies that the latest safety standards are not met in many dike sections. They suggest options to overcome this conservatism by combining different types of measurements and monitoring techniques while also considering the experience of technical managers to plan inspection and maintenance efforts. However, the implementation of dike reinforcement brings many questions, particularly with the increasing calls for "smart and efficient" innovations, which clearly emphasised that connections with other sectors must be sought. **Willemijn van Doorn-Hoekveld and Marleen van Rijswick** point out that many of these questions are about the responsibilities and tasks of governments and the policy instruments that can be used. Therefore, early legal advice can help address these bottlenecks and find the balance between the desired (legal) certainty about the responsibilities and the flexibility to incorporate cross-sectoral innovation into the dike reinforcement projects scope.

Marleen van Rijswick and Moritz Reese further discuss the learning points between flood risk management in the Netherlands and Germany. Germany's lessons learned include considering a similar approach to the Dutch Water and Environmental planning Act instrument to coordinate cross-sectoral spatial developments and the Dutch disaster management as the third layer of flood risk management. For the Netherlands, it might be interesting to consider development bans in flood-prone areas as a spatial instrument. Moreover, the designation of flood emergence areas in Germany has allowed regulating critical hotspots where run-off has increased due to human interventions.

Furthermore, the fact-finding study of **Bas Jonkman** for the floods in Limburg remind us that regardless of the prevention efforts, extreme events will still occur. We should generally improve predictions by considering the probability of floods in summer, particularly for small rivers, while continuing testing and improving emergency management operations.

From the perspective of All-Risk researchers that **Matthijs Kok** summarises, future research prospects should also consider defining long-term integrated and interdisciplinary strategies to face the climate change scenarios. Nature-based solutions in salt marshes and foreshores offer opportunities to support many ecosystems. Moreover, the consequent reduction of flood risk should also aim to improve short-term response to avoid unpleasant surprises like in Limburg. To improve emergency operations, the flood defence structural robustness may give an additional response time in the case of a failure while considering the spatial demands when planning reinforcement efforts. Last but not least, learning from new data in combination with models offers an unexplored path to improving the assessment and design of flood defences.

How does the risk-based approach work?

By Wim Kanning
Researcher at Delft University of Technology

and Bas Jonkman
Professor of Hydraulic Engineering at Delft University of Technology

The Dutch risk-based safety standards

The Dutch risk-based approach to safety standards of flood defences dates back to the 1950s where Van Dantzig and others derived optimal protection levels for the main dike ring in the west of the Netherlands. Practically though, this optimal level of protection was translated to a design water level with an annual exceedance frequency of 1/10,000. The flood defences are designed in such a way that they survive the design water level, and this method is called the overloading approach. Later, this overload approach was translated to standards for areas with lesser consequences.

From 2017, after 20 years of study and consideration, new safety standards have been implemented. In contrast with the previous overload approach, the new standards are supposed to reflect actual failure probability and are based on various consequences. Flood defence segments are assigned to safety standards, defined as maximum allowable failure probability, where the standard (varying between 1/300 and 1/100,000 per year) depends on the consequences in the area and are based on the economic value these protect, individual risk and group risk. The *Beoordelings- en Ontwerp Instrumentarium (BOI)* – Assessment and Design Instrument – (Rijkswaterstaat, 2019) translates these safety standards into requirements for individual flood defences and failure mechanisms in such a way that if the defences comply with these requirements, the safety standards are fulfilled.

Efficient flood risk reduction

The probabilistic flood approach has several advantages. First, the new approach reflects the actual risk (probability and consequence) and facilitates efficient investments. The corresponding maximum allowable failure probabilities are relatively easy to communicate. Further, it is a flexible framework where uncertainties are explicitly incorporated. The consideration of uncertainties allows a more transparent safety assessment and design of both traditional failure mechanisms and innovative measures. Different measures such as strengthening, monitoring and measurements can be transparently evaluated using the risk approach. The flood probability approach is suitable for combining different types of knowledge, including physical knowledge about hydraulics and geotechnics, the behaviour of dikes, as well as the knowledge of statistics and uncertainties. For example, uncertainties arising from the available information and quality of models are included, as is shown in Matthijs Gensen's research on the uncertainties around the bifurcation points. The allowable failure probabilities connect well to the EuroCode definitions and provide a clear basis for the flood defences' design and assessments. Moreover, this flood probability approach allows including the actual failure (a dike breach) rather than only the initiating mechanisms, for instance, by incorporating that a slope stability does not necessarily result in a breach. All these improved considerations of the flood probability approach should result in more efficient investments in flood defences.

A recipe or a framework for decision making?

The flood probability approach provides clear advantages, but current implementation and results also highlight challenges to overcome. There is still conservatism in the BOI and especially in choices in the failure mechanism modelling, leading to very high reported failure probabilities, much higher than recent experience suggests. Also, it can be questioned whether the BOI is too much applied as a recipe; does it sufficiently stimulate critical thinking? There is a lot of emphasis on making many computations, but is there enough room for critical thinking, detailed analysis, measurements, technical managers' experience, monitoring and other uncertainty reduction? Dikes fail because of missed layers, missed connections between outside water and aquifer etc. This should be a main point of attention in design and assessment. The flood risk approach provides incentives for uncertainty reduction, but this should be much more applied, as was underscored by the expertise network for water safety (ENW, 2020) as well. The flood risk approach allows for optimal investment in time and space. This new approach can result in many optimisations as All-Risk research has shown. Practical application of this is, however, very limited. Also, inspection and maintenance should be an integral part of assessment and design, which is currently not the case as we tend to model a perfect reality that hardly exists, as this book shows. Most of the above may be attributed to the relatively short time the flood risk approach is being used.

Towards better water safety in the Netherlands

The new flood risk approach provides an efficient, transparent and flexible framework with clear safety standards to make efficient flood risk reduction investments. It has already proven its value in many projects. After an initial period of adjustment to get the old way of assessment and design adjusted to the new approach, it is now time to fully reap the benefits of the new approach. All-Risk has provided knowledge and tools to facilitate this. We hope and expect that more and more benefits will be applied in practice in the years to come.

Figure 1: Soil drilling for analysis of the layers of a dike body. Photo by HWBP.

Opportunities and challenges in the legal implementation of the new risk approach in water safety management

By Willemijn van Doorn-Hoekveld
Assistant Professor at Utrecht University

and Marleen van Rijswick
Professor of European and Dutch water law at Utrecht University

One of the special aspects of Dutch water management is that standards for water safety are laid down in law, in the Water Act. The fact that the primary water defences must meet these standards means that the competent authorities, the regional water authorities and the Minister of Infrastructure and Water Management, are and can be held responsible for whether or not these standards are met. In 2017, these water safety standards were changed from exceeding probabilities to a risk-based approach. This approach is in line with the European Flood Risk Management Directive, but has challenges for practice.

Proper implementation of the new flood protection standards brings questions. How should the standards be legally qualified and how can they be laid down in legislation to be workable in practice and at the same time provide clarity for citizens and governments? The new approach also offers opportunities. The question arises as to the extent to which the new risk approach leaves room for innovations and how water safety policy can be combined with, for example, nature conservation policy or spatial developments. That is why the Flood Protection Programme (HWBP) is working with innovative pilot projects to which the new risk approach and the associated legal safety standards apply, but which cannot directly be applied. This leads to questions about the responsibilities and tasks of governments, as well as the policy instruments that can be used. Attention also needs to be paid to how governments can cooperate both within and outside the field of flood risk management.

A number of these types of innovations with legal implications are also discussed from a technical perspective in this book, such as the Double Dike and the Wide Green Dike. Moreover, the use of foreshores in the assessment of flood defences has legal implications.

In addition to these substantive legal-administrative challenges, the coming into force of the Environment and Planning Act (Omgevingswet) confronts practitioners with new questions. This concerns a large legislative operation in which 26 environmental laws, including the Spatial Planning Act, the Nature Conservation Act, the Environmental Management Act and the Water Act, will be merged into a single law, the Environment and Planning Act. Even though the basic principle is to convert current legislation in a way that is 'policy neutral', questions remain, for example, about the safety standards for primary water defences.

The Environment and Planning Act has not yet entered into force and some people are suspicious of its features, such as the 'inviting planning approach' and the belief and trust in mutual cooperation between competent authorities, businesses, citizens and local residents. The associated flexibility, however, also offers opportunities for innovation.

What the various challenges have in common is the question of how far the tasks and responsibilities of the water manager extend and which policy instruments are available to legally implement the new risk approach, both in innovative projects, such as the Double Dike, and in application under the Environment and Planning Act. The necessary coordination with other policy fields – with sometimes clashing and sometimes overlapping interests such as nature conservation regulations – also requires attention and creativity. This came to the fore in the study of the Wide Green Dike, but also appears to be one of the biggest general legal bottlenecks in water safety projects, according to a survey among HWBP staff.[1] There are plenty of opportunities for innovation, but it is important to involve the legal discipline and governance approaches in such projects at an early stage. The law is often seen as the cause of implementation problems, but the law can also contribute to a solution. In the case of the Wide Green Dike, for example, a solution was found that complied with nature conservation law, even in a Natura 2000 area. In the case of the Double Dike the law leaves it up to the competent authority to designate the primary defence (i.e. the inner or outer dike or both dikes together) and thus the competent authority (the province that must designate it) is free to choose the most workable and suitable solution in practice.

[1] See project "E2 - Cross-sector collaboration"

In addition to the challenges that exist in the exploration, planning and implementation phases, there is always the possibility that a dike will fail. When this happens, there will probably be damage in all cases and that leads to the inevitable question of who is liable to pay for that damage. Again, the question is which governmental body is competent and responsible. This study shows once again that the tasks of the various governments, the responsibilities that go with them and the policy instruments available to the governments for meeting the tasks must be as clear as possible, whereby a good balance must be found between the desired (legal) certainty and the need for flexibility, which is necessary for realizing innovations.

Figure 1: The 'Wide Green Dike'. Photo by Waterschap Hunze en Aa's.

Looking beyond the dikes to improve the flood risk management in the Netherlands and Germany

By Marleen van Rijswick
Professor of European and Dutch water law at Utrecht University

and Moritz Reese
Helmholtz Centre for Environmental Research GmbH (UFZ), Department of Environmental and Planning Law

This article follows from the partnership of the Department for Environmental and Planning Law, Helmholtz Centre for Environmental Research GmbH – UFZ in the All-Risk project on new flood safety standards in the Netherlands. The article provides a comparison between the Dutch and the German approaches in flood risk management. Discussing the results of the project so far, the question arises in what way the situation in Germany can be compared to the Netherlands, both regarding the flood risks as well as the way these risks are managed and governed.

Flood risks

Well known is the fact that large parts of the Netherlands are vulnerable to flooding from both rivers and the sea, due to their low elevation. Therefore there are legally binding safety standards laid down in legislation. These safety standards align well with the EU floods directive (Directive 2007/60/EC), taking a risk-based approach as a starting point for flood protection.

The question arises what the flood risks in Germany are.

Flood risks in Germany

Germany has had serious *riverine floods* in the past decades and flood protection against river floods has been an important concern of politics on all levels, from the municipal to federal governments. German flood risk policy has prominently been driven by major flood events like the Elbe-floods in 2002 and 2013 which both triggered political responses, including amended strategies, legislation and funding programmes for better protection and prevention measures. The most recent flood event in the Eifel region in 2021 has, again, fueled the debate about whether flood risk and emergency management are fit for purpose. Also, the EU Floods Directive has newly introduced to German law the duty to determine risk areas, draw up risk and hazard maps, and devise flood risk management plans.

Coastal floods are playing a minor role, and risks are confined to a few regions in the Elbe and Weser mouths – such as, in particular, Hamburg and Bremen. The great Hamburg flood of 1962 appears to be the last event of major coastal flooding and has led to a strong reinforcement of dikes, compounds and emergency infrastructures in Hamburg, Bremen and other risk-prone agglomerations.

Pluvial flash floods have increasingly occurred in urban areas and are subject to urban development considerations across Germany. This aspect of flood risk management is strongly linked to new urban drainage, urban climate adaptation and "blue-green"/sponge-city infrastructure development.

In the following, the focus mainly lies on riverine flood risk management and the way law and governance concerning flood risk management have been developed. Some remarks on coastal protection will be added.

Management and legal/governance approach in Germany regarding riverine flooding

In Germany, technical flood protection has long been the predominant strategy of flood risk management. Rivers were strengthened and dikes built in order to gain land for human purposes, as was the case in many developing regions around the globe. At the same time, settlements sprawled rather uncontrolled into flood-prone areas alongside the rivers, and altogether, this led to a considerable increase of flood risk and, eventually, to high damage in the mentioned flood events. A further issue of increasing importance was the fact that narrowed flood plains and heightened dikes often led to a downstream shift of the flood risk. Therefore, in the past decades, the conviction grew that the continued taking and narrowing of the flood plains exacerbates flood risk and that heightening dikes is no adequate and (cost-) effective response to the above described problems.

Flood risk standards

Germany has no legally binding flood risk standards, reinforcement of flood defence capacity to HQ-100 is used as the default defence capacity. Major dike defence lines are developed and maintained by the German States, or Länder. They decide about the defence capacities. According to Federal and State water law, they are entitled to expropriate land-owners as far as needed to build, enforce or relocate dikes. The default standard for flood protection measures and, in particular, the dimensioning of dike lines in Germany is not regulated by formal law but mainly entrenched in a "private" standard of the *Deutsche Institut für Normierung* (DIN, https://www.din.de/en/about-standards/din-standards)". According to DIN-standard No. 19712, dikes and dams should be built in a way that protects settlement areas against an "HQ-100" flood, i.e. a flood event of a statistical 100-year incidence. However, this standard basically only applies to new and rebuilt dikes and is not implemented everywhere alongside the rivers. Whether and in how far existing dikes are reinforced and heightened is not regulated by laws or standards and principally at the discretion of the relevant Länder authorities. The Länder are following a multi-criteria approach taking into consideration not only the height of dikes but, of course, also the cost-benefit ratio with regard to the values and potential damage in the respective areas and the potential of alternative measures to lower the flood levels like, most notably, extension of flood plains and polders. Depending on the values accommodated in the protected areas, considerably lower or higher safety degrees are pursued than merely HQ 100. For example, the safety levels of flood protection in the German Rhine basin extend from HQ 30 (in upper stretches) to HQ 500 (in lower stretches and densely populated areas of NRW). Safety policies also diverge among the German Länder. Bavaria has, for example, introduced a climate-adaptation-surplus to the HQ-100 standard with regard to all its dikes in its Danube catchment. The other German States refrained, so far, from applying such adaptation factors and rather pursued a more integrated strategy with more emphasis on precautionary and room-for-river measures.

In Germany, no legal standards exist as to the probability of a technical defence line breach as are seemingly included in the Dutch Local Individual Risk (LIR) and Social Cost-Benefit Analysis (SCBA) concepts. Dikes are to be constructed in a way that they should withstand the flood-level they are designed to hold back (according to the measures and within the discretionary leeway described above). In order to ensure this, rather stringent technical standards were established. Moreover, flood defence structures are subject to regular technical assessments, partly regulated formally by Länder laws (once or twice a year, so-called *Deichschau/Deichzustandsuntersuchungen*, see technical standards DIN 19712, DWA 507/2011).

Persisting problems revealed by the 2021 flood

The 2021 flood made some major vulnerabilities visible that were also exposed by the Elbe flood in 2013 and before. Concerns, in particular, are that old town quarters are built too close to rivers and creeks in valley locations (**Figure 1**). These locations still suffer from deficient technical protection, and it is often difficult or even impossible to enforce flood protection within the historic structures. Action has to focus – on the one hand – on making further room for the rivers upstream and on improving emergency and evacuation schemes. On the other hand, more consideration must be given to actively rebuild and relocate while withdrawing from the affected risk areas. The German building code does offer legal instruments to plan for and implement such restructuring of urban quarters but has never been implemented in such an intrusive manner.

Where the flood has now demolished buildings, the question is whether to rebuild them in the flood-prone area. In principle, this is now prevented by the development bans based on Article 78 FWA. But yet, there is now a lively debate whether these bans should apply to flood victims. Emergency management was particularly criticised as too cumbersome and inefficient. Political initiatives were launched at both federal and Länder level to reassess and improve the emergency management arrangements.

Are the results from the All-Risk project interesting for Germany? Are there lessons that might be valuable for the German situation/flood risk management? What triggered you to read the results? What can Germany learn from the Netherlands and All-Risk?

Figure 1: Aerial photo of the 2013 floods of the Mulde river (tributary of the Elbe river), flooding the town of Grimma. Photo © Helmholtz Centre for Environmental Research (UFZ), Leipzig.

The first lesson could be the introduction of the Water Assessment. This instrument for waterproofing and coordinating spatial developments and water/flood management does not exist in Germany. In the face of climate change and the need for urban transformation, it appears that Germany should consider introducing such an assessment, too, perhaps as a distinct part of the Environmental Impact Assessment (EIA).

The second lesson refers to Dutch disaster management as a third layer of flood risk management. This has been developed further in Germany, especially after the Elbe floods of 2002 and 2013. However, there still seems to be potential to improve this pillar and perhaps common legal standards could be a booster in this regard.

Are there lessons the Netherlands can learn from Germany?

Perhaps the following German policy instruments can be inspiring for the Netherlands.

As to the failure of municipalities to adequately confine and regulate development in flood risk areas: in my view, the **designated flood-prone areas** and the pertaining **development bans** are very strong and innovative instruments to effectively link flood protection and spatial development that deserve attention beyond Germany. The same holds true for the obligation for the Länder administrations to formally designate existing flood plains as "**flood-room areas**". After designation, no developments or uses are permissible in these areas that impede their function as flood plains or pose particular risks (e.g. by storing hazardous substances). In addition, there is the instrument of so-called **flood emergence areas** relating to major run-off areas where the challenge is to reduce run-off of, at least, avoid increase e.g. by deforestation, melioration and so on.

Furthermore, the German flood protection programme and its underlying **priority criteria** might also be interesting abroad. The criteria applied in this programme – mainly to identify priority projects and direct funds – seems to be similar, in part, but also partly different from the Dutch standards. The German criteria seem to leave more room for local weighing and priorities, and the priority list of reinforcement measures is based on common guiding criteria and prior evaluation/applications from the Länder. In this manner, the German approach seems to go further in the **regional differentiation** you describe as a possible trend for the Netherlands.

The 2021 summer floods in the Netherlands: some findings and lessons

By Bas Jonkman

Professor of Hydraulic Engineering at Delft University of Technology

The heavy precipitation along with the floods of July 2021 in the Netherlands and surrounding countries was an extreme and exceptional event. In the Netherlands, the event had major societal impacts in the south, particularly in the province of Limburg. Commissioned by the Dutch Expertise Network for Flood Protection (ENW), a broad consortium of knowledge institutes, led by Delft University of Technology and Deltares, has performed an exploratory fact finding study (Jonkman et al., 2021). Several All-Risk researchers have contributed, focussing on topics such as dike performance, damage and river systems. As a flood affects the whole society, a broad range of topics has been assessed: meteorology, civil engineering, societal and health impacts, and emergency management. This contribution summarises preliminary findings and lessons for the future.

Damage larger than for the 1993 and 1995 floods

The measured amounts of precipitation and river discharges have never been so large, particularly during summer. It is estimated that the event of July 2021 occurs only once every 100 to 1,000 years. The peak discharge (3,280 m^3/s) on the Meuse River near Maastricht in Eijsden (at the Dutch border with Belgium) and on a number of tributaries such as the river Geul (north of Maastricht) were the highest discharges ever measured. Water levels further downstream the river (past Roermond) were lower due to attenuation of the discharge peak.

In total 2,500 homes and 600 business were flooded. The estimated total damage due to flooding amounted 350 to 600 million euros and took place to a large extent in the river Geul valley. The damage was therefore greater than during the floods along the Meuse river in 1993 and 1995.

The primary flood defences along the Meuse withstood the exceptionally high loads well. However, incidents such as piping (erosion of the sand under the dike) and local height deficiencies did occur in some places. Temporary measures such as sandbags were therefore used on a large scale. During the event, the first floods occurred along the river Geul. A warning was given, but no guidance for citizens to evacuate (out of the area). Along the river Meuse, 50,000 people were evacuated and multiple hospitals and care facilities.

Insight has been given in health impacts. Two thirds of the surveyed doctors reported an increase of psychological conditions. In addition, drinking water intake was stopped due to pollution. During the same period, severe flooding caused billions in damage and hundreds of deaths in Germany and Belgium. There, the situation was more catastrophic than

Inhabitants are evacuating from the flooded area in Limburg. Photo © Marcel van den Bergh.

in the Netherlands, also because of the greater precipitation amounts and the steeper – faster flowing – rivers.

Lessons learned

The findings from the fact finding study can be used for follow-up research, evaluation and for future-proofing the system. Although this study was an initial exploration, some lessons and recommendations can be formulated:

- **Improve the predictions, flood warnings and crisis management and their interfaces.** Predictions of rainfall and flooding changed during event and the severity of the floods was therefore not anticipated, and insufficiently addressed in warnings and emergency response.
- **Knowledge of river floods:** Evaluate (the likelihood of) the occurrence of river floods in summer, including the effects of climate change. Improve the understanding of the combination of floods in the river Meuse and its tributaries. Develop an integrated model for this entire river system, including rainfall, runoff, and use this for river management and flood warning. Implement observation stations that will remain functioning during extreme floods.
- **Impacts:** Collect and analyse data for damages and compensations, in order to improve damage modelling and the understanding of the effect of interventions. Evaluate and monitor the longer-term economic and health impacts in the affected area.
- **Flood defences**: Evaluate the effects of the measures that were in place before the floods – i.e. room for rivers and dike reinforcements. Analyse the performance of the defences along the river Meuse under the extreme loads (including "proven strength"). Use the outcomes to update the safety assessment of the defences. Improve the knowledge and modelling of failure mechanisms, by evaluating incidents, such as observed cases of piping. Also evaluate the performance of structures such as weirs.
- **Risk management and risk reduction:** Evaluate for the smaller rivers whether there is a need to adapt the safety standards[1], based on a cost-benefit analysis. Consider the performance of the system for scenarios higher than the design scenario. What would be the effects of the rainfall observed in Germany and Belgium, would it have occurred in the Netherlands? Particularly the smaller rivers require attention: elaborate engineering, spatial and organisational measures to reduce the risk (through a "multiple lines of defence" approach), to prepare emergency management and inform decision-makers. In these flood risk reduction plans, include other needs, such as drought, ecology, housing and climate adaptation.

[1] Many of the populated areas in Limburg, e.g. along the river Geul, had a safety standard of 1/25 per year. This is smaller than the safety standard that is normally applied for such water systems in the Netherlands (1/100 per year).

- **Governance and knowledge:** Evaluate the effectiveness of the current governance for the river Meuse and tributaries (with involvement of the federal government, province, regional water authority, municipality and citizens) and the funding arrangements. The crisis in Limburg has shown the importance of knowledge and expertise within the organisations. During crises, decision-makers can insufficiently rely on models only. Consider the implications for the required expertise in water management organisations and the utilisation of this expertise during crises.
- **Implications for other regions in the Netherlands.** The extreme rainfall and flooding in Limburg has surprised experts, water managers and citizens. Assess what the effects of such extreme events would be for other areas in the Netherlands, and whether there is a need to implement additional measures.

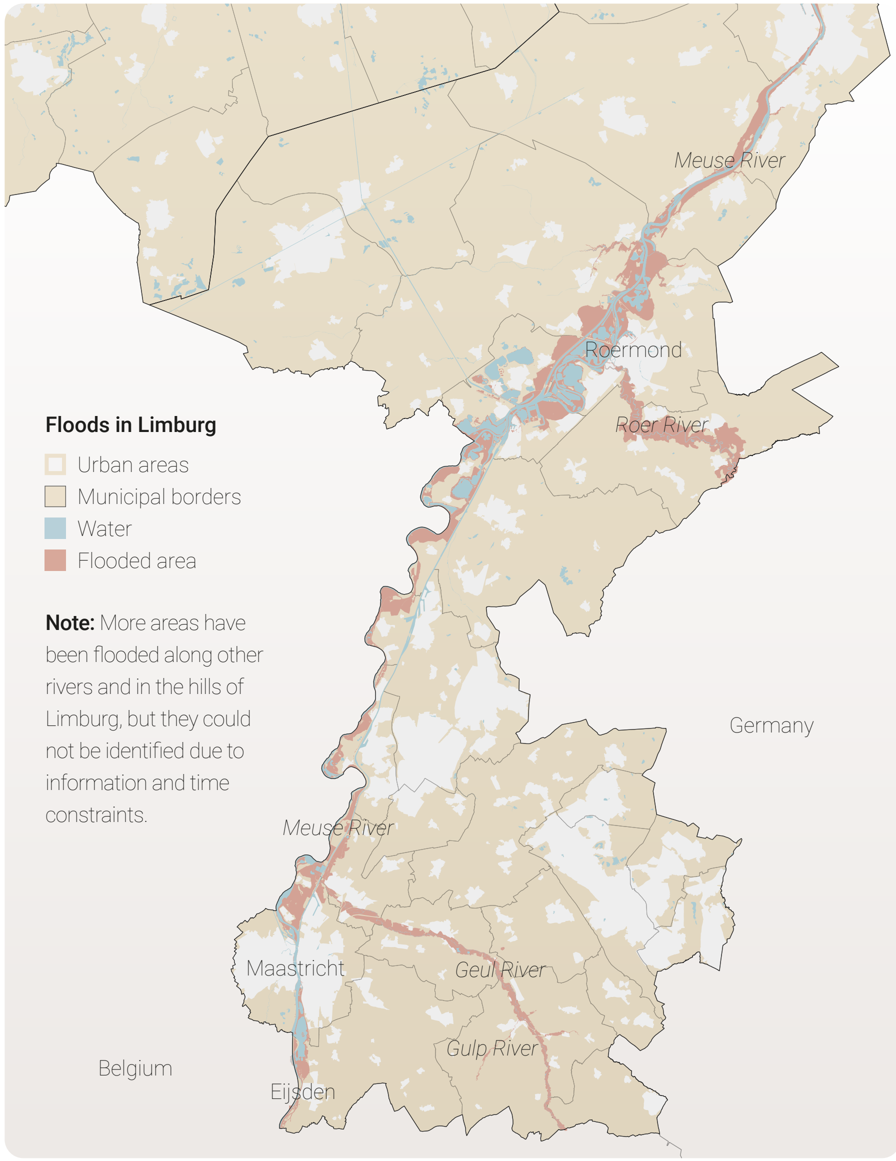
Many of these topics need to assessed in an international perspective – with Germany and Belgium – as the water systems in this region are transboundary.

Parties involved

The study was carried out by a broad consortium: Deltares, Delft University of Technology, HKV consultants, VU University Amsterdam, Utrecht University, KNMI, WUR, Erasmus MC and the University of Twente, commissioned by the Expertise Network for flood protection (ENW) and with the full support of the Limburg Regional Water Authority and Rijkswaterstaat.

Interested to read more?

Task Force Fact Finding Hoogwater (2021). *Hoogwater 2021: feiten en duiding.* Doi: 10.4233/uuid:06b03772-ebe0-4949-9c4d-7c1593fb094e



Map of the 2021 floods in Limburg, the Netherlands, as a result of the fact-finding study for the Meuse river and the tributaries Geul, Gulp and Roer. Base map data from PDOK. Flood extents data by Slager et al. (2021). Illustration by Martijn Vos.

A look at future flood risk prospects: ideas of All-Risk researchers

By Matthijs Kok
Professor of Flood Risk at Delft University of Technology

Over the last five years (starting from 2017), the All-Risk research programme has investigated many topics to support the implementation of dike reinforcement projects. But, what are the All-Risk researchers' ideas and directions about future research? On 4 November 2021, almost all All-Risk researchers gathered in one of the forts of the 'Dutch Waterline' to discuss these ideas (**Figure 1**). This reflection is the author's subjective view, inspired by the research ideas pitched during the meeting (**Figure 2**).

Flood risk is a key concept that concerns the possible consequences of flooding and the probability of a flood. The risk approach is more than that, however. Flood risk can also be expressed in many risk measures, such as societal risk (the probability that a large group of people will lose their lives) and individual risk (the probability that an individual will die). Indeed, the Dutch flood safety standards set a basic level of protection for each dike segment, considering that the yearly probability of a person dying because of flooding may not exceed 1/100,000. An extra level of protection is added per dike segment the more serious the consequences of a flood are. For example, the increased disturbance to social and critical infrastructure. However, the added value of the risk approach lies not in the statistics concerning probabilities and consequences but in the ability to generate the impact and efficiency of measures to reduce flood risk.

The Dutch Flood Protection Programme reinforces almost 2/3 of the primary flood defences to maintain safety standards over the next three decades. In light of the new Environment and Planning Act, these reinforcement projects should improve to some extent the landscape quality through collaborative and innovative efforts between flood risk and other sectors. The All-Risk researchers think that more effort is needed to obtain more insight into failure events of flood defences, to make the utmost of current efforts to strengthen the flood defences and reduce the consequences of floods. Therefore, the Netherlands may also consider the spatial demands, population and economic growth to improve the preparation of possible floods. All-Risk researchers suggested starting by taking the utmost advantage of the ongoing efforts for reducing the probability of flood and reducing in an effective way the potential consequences. This way, the flood defence system and the surrounding landscape might be designed for the remaining - even if small - probability of failure. Such a 'design for the extreme events' emerged from the All-Risk researcher ideas during this event and is further elaborated into the following research categories:

1. Long-term integrated strategies

An important question is whether every area below sea level needs to be protected. From historical evidence, one can see that mankind like to live on dry land instead of living in floating houses. Also, voluntary moving away from these areas is not attractive. For the longer term, different strategies for different climate scenarios (for example, 1-5 m sea-level rise) need to be developed in an interdisciplinary design effort, not only using models, since the physical reality is much more complicated than a model can indicate. Next to spatial planning, technical issues need to be addressed: is there a limit in raising the dikes, and what about the financial issues? As flood defences, are constructions like sheet piles more sustainable than earthen dikes? How much space do earthen dikes need? It is sometimes suggested that flood defences cannot be heightened anymore. Still, this suggestion can certainly be discussed while also considering the impacts on the river behaviour and the future requirements for new climate development (**Figure 3**). Therefore, an integrated strategy is required to address the extreme events, the impacts on the river ecosystem and the built landscape from the proposed flood defence interventions.

2. Nature-Based Solutions

The main challenge is to assess the contribution of "nature-based solutions" to flood protection of society. For example, explore actions to increase the tidal flats to attenuate waves, promote marsh expansion and

Figure 1: Participants of the meeting held 4 November 2021 are presenting and discussing each other's ideas. Photo by Martijn Vos.

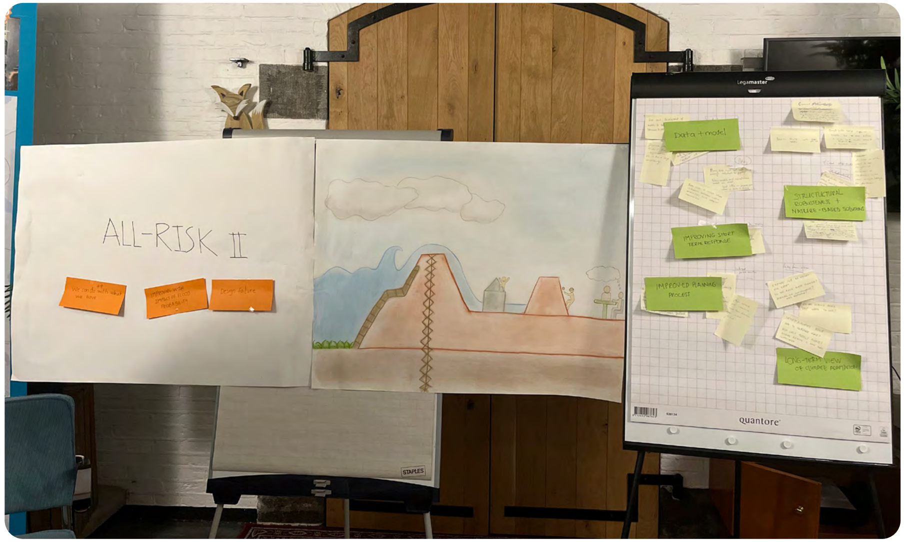


Figure 2: Wall with the summary of the researcher's sticky notes with future research ideas along the dike scheme that was used to illustrate the All-Risk research topics. This central scheme now depicts a dike that fails partly and gradually while the inland area is somehow prepared to outstand the flood. Photo by Martijn Vos.

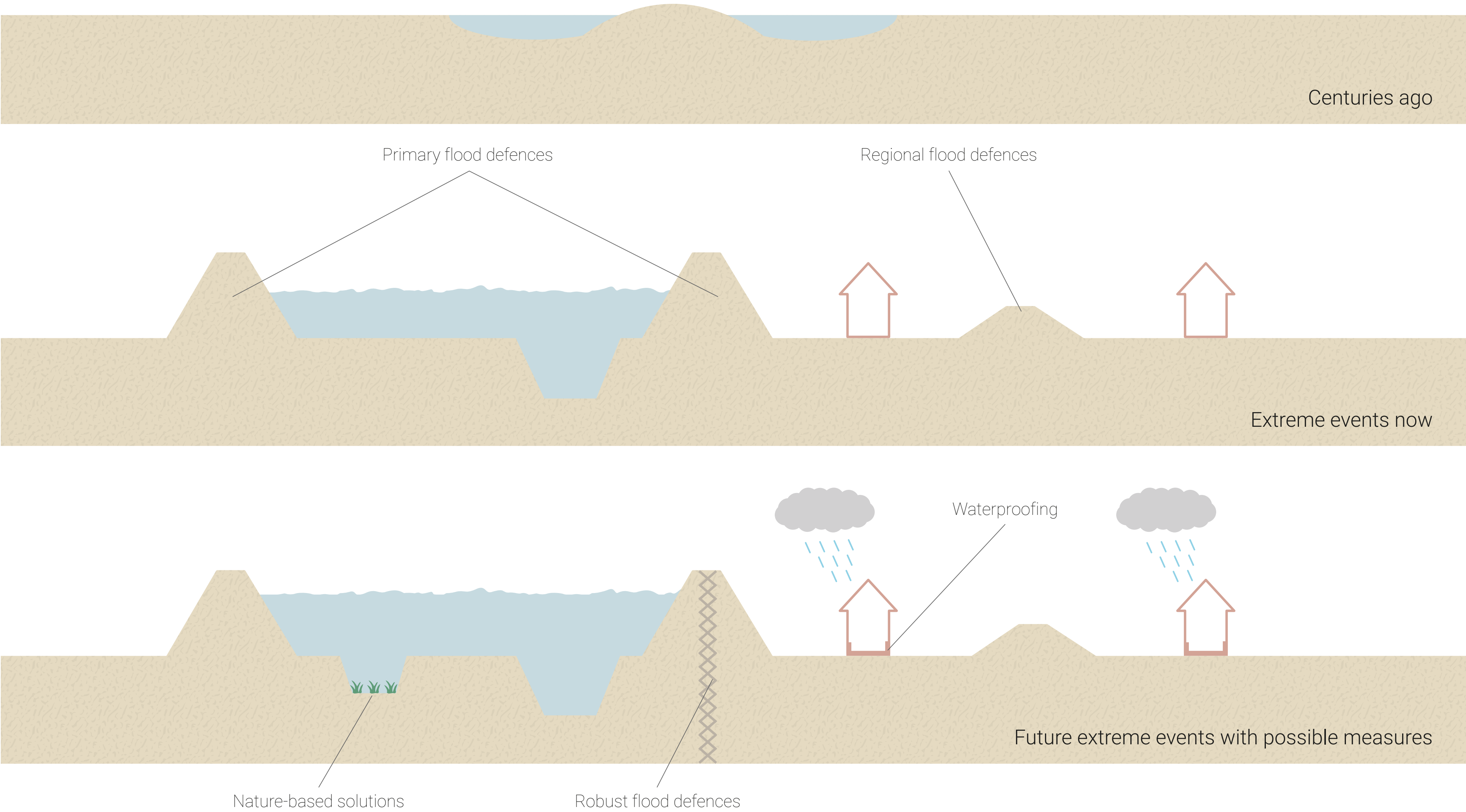


Figure 3: Compared to the rivers before human intervention (top), the flood defence system has provided flood safety and allowed us to benefit from the river, even under extreme conditions. However, the frequency and impact of extreme events may exacerbate in the future. Therefore, integrated flood defence interventions are required to address the extreme events, the consequences on the river ecosystem and on the built landscape (bottom). Based on Verhaal van de rivier, (Klijn et al. 2015, p. 14-15). Illustration by Pien Buters and Martijn Vos.

prevent erosion. Marshes reduce run-up and wave loadings on the dike. Moreover, marshes store carbon, purify the water, support fisheries and many more ecosystem services. Typical measures to maintain and expand marshes include: ensuring sediment supply, restoring shellfish reefs (trap sediment) and seagrass.

3. Impact reduction of floods

Flood risk can be reduced by reducing flood impact. Worldwide, we have seen increased economic damages and a decrease in loss of life by natural floods in the last decades. An explanation for this is that is on one hand the substantial growth of the economy in vulnerable areas, and on the other hand the improvement of flood forecasting methods. But is it enough? So, future research may also be aimed at the short-term response by, for example, improving early warning applications for floods to make them more effective and to reach vulnerable groups better.

4. Flood defences structural robustness

Structural robustness means that the structure itself (for example, earthen structure with clay core) does not fail completely and suddenly, but partly and gradually. The consequences of a flood can also reduce if a structure shows more ductile behaviour. Also, more predictable dike failure leads to less uncertainty, and a better failure process understanding needs further lab and field tests. Therefore, another research topic is to connect type of flooding or dike failure to safety standards.

5. Learning from data in combination with models

From a data point of view, many suggestions can be made to improve the quality of assessment and design of flood defences. There are better ways to estimate relevant subsurface parameters such as permeability from geological characteristics. Also, the connection with models is important, for example, the development and use of models to better predict the actual dike behaviour and performance. Furthermore, the triaxial test interpretation can be improved as it has a large uncertainty. Finally, river model calibration for a large area and a large range of conditions can be improved for a "robust model calibration".

Field work to determine the accuracy of visual dike inspections. Photo by Wouter Jan Klerk

Chapter 2
Risk Framework

Introduction
By Matthijs Kok

The “risk framework” *project A* in the programme All-Risk considers the approach that responsible authorities and technical advisors should use from now onwards to assess the risk of flooding. For this project and the rest of the All-Risk projects, the existing Dutch probabilistic framework is the starting point of research (see Kok et al., 2017). Here, flood risk is defined as a function of flooding probability and consequences (economic damage and loss of life). If consequences are high, more protection is needed. An overview of a first probabilistic assessment of flood risk in the Netherlands is given in VNK (2015). Safety standards are derived and are part of the *Dutch Water Act*. These standards are maximal allowable flooding probabilities in a year and range from 1/100 (for areas with relatively low consequences) to 1/1,000,000 (for areas with very high consequences). The Flood

Protection Programme has the task to implement these safety standards. All-Risk focusses as a whole mainly on the probability part of the risk equation.

Wouter Jan Klerk investigated in project A1 the "Decisions on life-cycle reliability of flood defence systems". His research focused on the optimal dike strengthening measures, since many measures can be taken to strengthen the dikes (sheet piles, extra berm, etc). He also investigated the damages and inspections of grass revetments in a real-life experiment with inspectors. His finding is that inspectors do not always see all the damaged spots, and Wouter Jan gives recommendations on how to improve the inspections.

In the "Shared-use of flood defences" project (A2), **Richard Marijnissen** investigated several cases of multi-functional uses of flood defences. He developed a risk framework where the failure of an object in a flood defence can be incorporated as a scenario, with a probability that this scenario will happen. This scenario approach differs from the current practice, where it is always assumed that houses do not contribute to the stability of the dike and have disappeared. Richard also investigated the principles of a double dike system and the sensitivity of a dike-marsh system to sea-level rise.

In project A3 "Dike reliability analysis", **Wim Kanning** investigated the modelling of failure mechanisms and how uncertainties in dike performance can be accounted for and best mitigated. For example by using data from past events and experiments. Focus is also on the properties of the subsoil and how this affects dike performance.

In his research "Landscaping of flood defences" (A4), **Luca Iuorio** investigated the spatial dimension of flood protection. In his approach, spatial development is a part of the risk approach and engineering is a part of the spatial design. He investigates new alternatives for flood protection, for example, in Vlissingen, where wave overtopping of the dike system is an integral part of the urban landscape design.

We highlight two recommendations for practice. First, it is important to optimise the safety contribution of all type of measures as the costs of strengthening the dike can be reduced. A case study found a 50% reduction compared to current practice. The second recommendation is to apply the general risk framework for multi-functional dikes. Applying this framework leads to assessments that are much more credible than the currently applied method.

Project Summary

A1 - Life-Cycle Performance

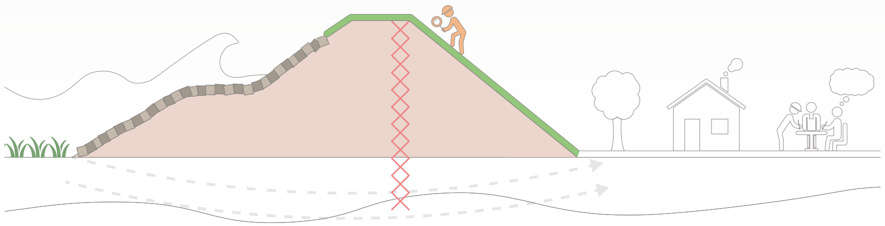
Methods to align dike inspection, maintenance and reinforcement

By Wouter Jan Klerk

Delft University of Technology

Project start: 09/2017

Project end: 09/2021



Promotors

Dr. ir. W. Kanning

Delft University of Technology

Prof. dr. ir. A.R.M. Wolfert

Delft University of Technology

Prof. dr. ir. M. Kok

Delft University of Technology

Outcome

This project developed novel methods for decisions on the life-cycle reliability of flood defence systems. By optimising flood defence reinforcements at a system level, the cost of reinforcement projects can be reduced significantly. Uncertainty reduction through monitoring and proof load testing lead to lower reinforcement and risk costs, both in short and long term. It has also been demonstrated that imperfect inspections and maintenance of flood defences lead to a failure probability increase. This contribution demonstrates the importance of including inspection and maintenance in flood risk assessments.

Figure 1: Experiment to determine the accuracy of visual dike inspection near Tiel. Photo by Wouter Jan Klerk.

Motivation and practical challenge

The asset management of flood defences in the Netherlands (**see Figure 2**) has been built upon centuries of experience. We have taken great leaps in quantifying the performance of these structures based on failure probabilities and increased our understanding of many potential failure modes. However, as a researcher and as an advisor on flood risk asset management, I saw some missing links in the translation of this knowledge to decisions. In this project, I considered three key topics that I'm convinced would help us to take the next step in flood defence asset management. Optimising flood defence reinforcement design at a system level can lead to more effective and efficient reinforcement projects. Countering large reducible uncertainties in dike strength and pore pressures by monitoring and proof load testing can lead to a more cost-effective dike design. And, quantifying the accuracy of inspections, and accounting for this in flood defence reliability estimates will greatly improve reliability estimates based on them.

Research challenge

Therefore, the challenge is to develop methods for addressing the missing connections between dike reinforcement, maintenance, monitoring, and inspection at different spatial and temporal scales. By doing so, how does, for example the reinforcement of a diaphragm wall at one spot (**Figure 2, bottom-left photo**) help the safety targets for a larger dike section in the coming decades? How does inspection help in maintaining sufficient reliability?

Innovative components

This research uses smart optimisation techniques to relate measures at different spatial scales. For instance, such a technique was applied to a dike reinforcement project to derive optimal planning of different measures (**Figure 3.1 and 3.2**). By using this technique, the system reliability requirement, incorporating all possible strengthening measures, was met optimally when looking at costs.

Figure 2: Example of the activities to ensure life-cycle performance: photo 1 and 4 reinforcement, 2 and 3 inspection. Photos by HWBP (2018, p.103) / Pascal Ogink, Wouter Jan Klerk, Mark van der Krogt and the Flood Protection Programme, respectively.

I use decision trees and Bayesian decision analysis (**Figure 3.3**) to translate monitoring outcomes into uncertainty reduction in dike reliability estimates. However, the accuracy of the inspections (i.e. the probability of detection) is unclear and to determine it, a field experiment was conducted (**Figure 3.4**).

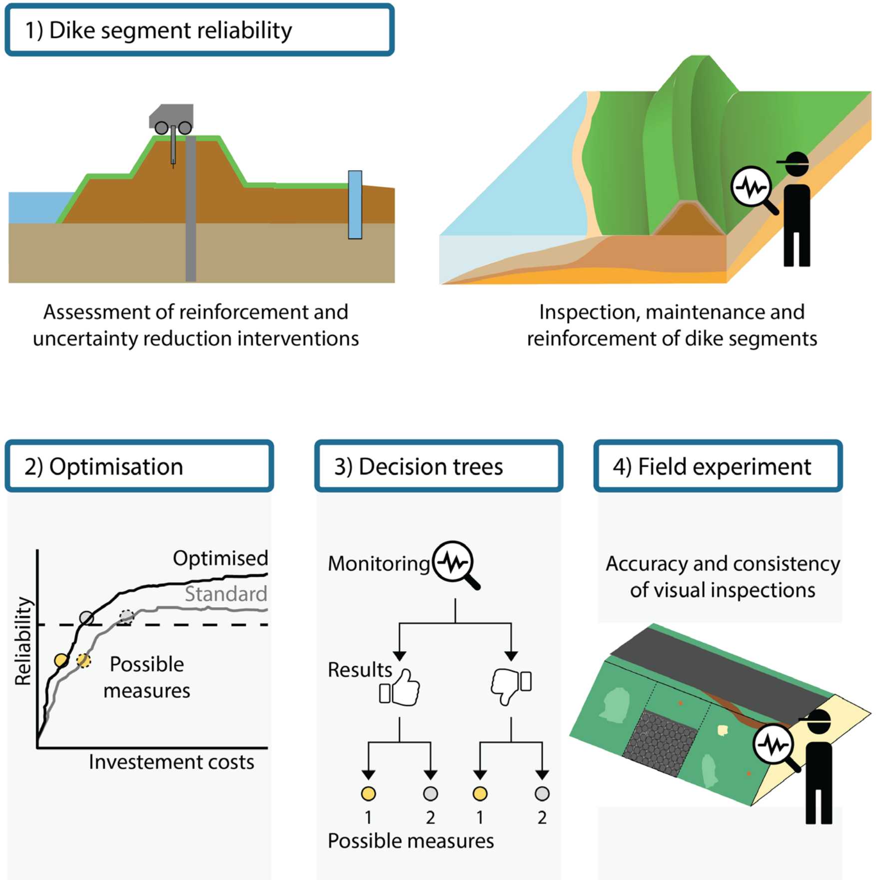


Figure 3: Components of the research relating decisions at a dike section to a whole segment. Figure 3.1 is based on schemes by Wouter Jan Klerk, dike segment scheme prepared by Richard Marijnissen.

The insights have been used to determine the impact of damage and imperfect inspections on failure probabilities. To achieve this, degradation rates were based on data analysis of past inspection reports, and a Dynamic Bayesian Network was used to determine the life-cycle cost of different inspection and maintenance strategies.

Relevant for whom and where?

Within the Netherlands, this research is of relevance to the regional water authorities, the Dutch Flood Protection Programme and the Ministry of Water and Infrastructure. In an international context, anyone with a keen interest in risk/performance-based asset management of flood defences can use it in defining projects and optimising inspections and maintenance.

Progress and practical application

It is demonstrated that optimisation of flood defence reinforcements at a system level can reduce reinforcement costs by about 40%. For studies on the effectiveness of proof loading and dike monitoring, cost savings were in the range of ~25% due to the achieved uncertainty reduction leading to more efficient designs.

However, not only investment costs but also risk costs can be avoided. For example, when accounting for damage to grass revetments, the estimated failure probabilities differ several orders of magnitude from the estimates from the safety assessment. By including this, effective investments in, for instance, more frequent inspections can be properly valued, leading to more effective and efficient asset management.
Further improvements can be achieved by improving the collection of inspection data to more accurately estimated degradation rates, and further investigating the impact of damage to for instance revetments on their failure probability.

Recommendations for practice

- Take a system perspective towards flood defence reinforcement projects to achieve more cost-efficient and transparent reinforcement decisions.
- Ensure that reduction of uncertainty is considered properly within and outside the context of dike reinforcements, and ensure that funding arrangements facilitate this.
- Consider uncertainty reduction an effective starting point for long-term adaptation strategies of flood defence systems.
- Improve the collection of inspection data to better understand the degradation behaviour of flood defences.
- Aim for continuous and targeted improvement of visual inspection of flood defences.

Key project outputs

Klerk, W.J.; Kanning, W.; Kok, M.; Wolfert, R. (2021). Optimal planning of flood defence system reinforcements using a greedy search algorithm. Doi: 10.1016/j.ress.2020.107344.

Klerk, W. J., Kanning, W., & Kok, M. (2018). Time-dependent reliability in flood protection decision making in The Netherlands. Doi: 10.1201/9781351174664

Klerk, W.J.; Kanning, W.; Kok, M.; Bronsveld, J.; Wolfert, A.R.M. Accuracy of visual inspection of flood defences. Doi: 10.1080/15732479.2021.2001543

The research includes key locations for the reinforcement of a dike section and the field experiment to assess the quality of inspections.

Photos by Waterschap Rivierenland.

Project Summary

A2 - Shared use of flood defences

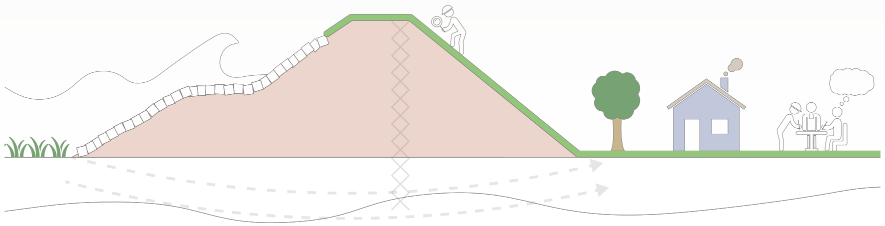
Assessment framework and guidelines for implementation

By Richard Marijnissen

Wageningen University & Research

Project start: 09/2017

Project end: 09/2021



Promotors

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Wageningen University & Research

Prof. dr. ir. M. Kok
Delft University of Technology

Prof. dr. C. Kroeze
Wageningen University & Research

Outcome

By analysing three case studies, we developed an updated framework for the probabilistic assessment of dikes considering traditional uses such as housing but also nature-based measures for the innovative reinforcement of dikes. On the one hand, we assessed how probabilistic effects of other uses could be expressed directly by scenarios and (hydraulic) transmission models. On the other hand, we explored how the dike geometry and composition can increase synergies with flood safety while considering additional uses. Finally, the vegetated foreshore of coastal dikes was found to present substantial long-term benefits for flood protection and thus should be considered in flood protection strategies.

Figure 1: A Dutch river dike winding through the landscape. Photo by Richard Marijnissen.

Motivation and practical challenge

My contribution both as an engineer and researcher is to understand the middle ground between man and nature. Flood defences protect us from the water but are also integrated with many other functions such as housing and nature. Depending on the location, some functions are more common than other ones (**see Figure 2**). This shared use of flood defences often comes with conservative estimates for a robust design that guarantees flood safety. While having multi-functional flood defences generally impose restrictions on the design, some elements in the natural foreshores or flooded areas near the dike can contribute to reducing flood risk. For example, vegetated foreshores in coastal areas can dampen the amount of wave energy that reaches the dikes. Aside from natural values, coastal salt marshes can also capture clay over time which may be used in future dike reinforcements. With the new probabilistic risk approach recently adopted in the Netherlands, we may be able to quantify the effects on flood safety of both standard and nature-based reinforcement measures. Yet, an integrated risk assessment framework is required.

Research challenge

This research project aims to gain more insight into the shared-use of flood defences on flood risk reduction. I do so by using the new probabilistic risk approach to determine the safety level of flood defences that are shared with traditional functions such as housing. I further assess the effects on flood safety of some nature-based measures applied in innovative dike reinforcements.

Innovative components

My research integrates already existing work in flood protection, risk management and nature-based engineering into a risk assessment

Figure 2: Range of functions that can be encountered on/near a flood defence including housing on a riverine dike (**top photo**), vegetated foreshores in coastal areas with adapted design for the extraction of deposited clay (**bottom-left**) and more (unusual) objects that can be found (**bottom-right**). Photos respectively obtained from Flickr (by Grotevriendelijkereus, CC BY-NC-SA 2.0), Regional Water Authority Hunze en Aa's and Richard Marijnissen.

framework. To develop this framework, I used existing assessment procedures to estimate the probabilities of dike failure for typical mechanisms (**Figure 3, top-left**). Under presence or absence scenarios of housing and trees, I compared the effects of multiple reinforcement measures such as broadening or heightening the dike for a more robust design (**Figure 3, top-centre**). I further extended the framework to assess the

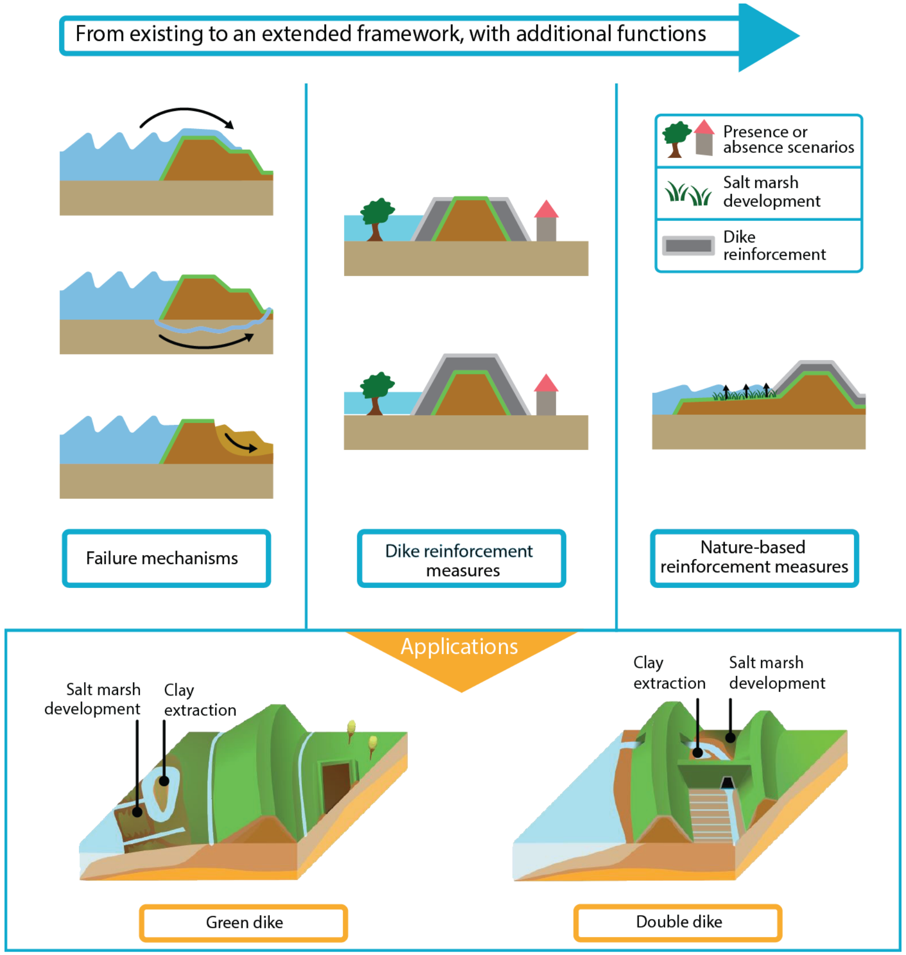


Figure 3: Research components to devise a framework for integrating additional functions within the new risk standards. Based on schemes prepared by Richard Marijnissen.

effects of dike reinforcements that include salt marsh development as a nature-based adaptation measure for sea-level rise (**Figure 3, top-right**).

I am applying the concepts of this framework into two more case studies (**Figure 3, bottom schemes**): the Wide Green Dike, and the Double Dike. How are the dike designs adapted for additional functions such as clay mining and salt marsh development? Moreover, what are the synergies and risks these functions provide to dike safety? The final step synthesises insights from developing the extended framework, and the application cases. Thereby, I can provide some recommendations for assessing the effects of other (nature-based) functions within the new flood risk standards.

Relevant for whom and where?

The results are beneficial for users involved in designing, maintaining, assessing and drafting policies for flood defences within the new risk-based approach. All-Risk is supported by the regional water authorities in the north of the Netherlands, who are keen to integrate the results into current and future dike reinforcement projects.

Progress and practical application

Conservative estimates of failure probabilities for flood defences with multiple functions lead to a systematic underestimation of the reliability of these dikes. Instead, the extended approach incorporates the probability of different scenarios in which elements such as houses and trees affect the flood defence to evaluate its safety. In some situations, the probability of a dike failure may turn out to be 100 times stronger than would conservatively be estimated. For traditional functions and nature-based functions, the framework can be more adaptable. Natural foreshores can expand over time and partially mitigate the effects of future sea-level rise on the flood defence. Moreover, the deposited sediments may provide a source of material for future reinforcements. Recognising the potential of multiple functions is vital to strengthen the Dutch flood defences for the future efficiently. **Check the key project outputs below** for a detailed description of the findings.

Recommendations for practice

- Incorporate scenarios or transmission of shared-use whenever feasible.
- Shared-use affects flood risk proportional to the safety level of the flood defence.
- Consider sediment management along muddy coasts within the vegetated foreshore of coastal dikes.
- Consider short-term and future flood protection benefits in concepts like the Double Dike.

Key project outputs

Marijnissen, R., Esselink P., Kok, M., Kroeze, C., van Loon-Steensma, J.M. (2020). How natural processes contribute to flood protection – A sustainable adaptation scheme for a Wide Green Dike.
Doi: 10.1016/j.scitotenv.2020.139698

Marijnissen, R., Kok, M., Kroeze, C., & van Loon-Steensma, J. (2020). Flood risk reduction by parallel flood defences – Case-study of a coastal multifunctional flood protection zone.
Doi: 10.1016/j.coastaleng.2021.103903

Marijnissen, R., Kok, M., Kroeze, C., and van Loon-Steensma, J. (2019). Re-evaluating safety risks of multifunctional dikes with a probabilistic risk framework.
Doi: 10.5194/nhess-19-737-2019

The research components are applied into two innovative projects for dike reinforcement located in the north of the Netherlands and in the River Area.

Double Dike. Photo by Waterschap Noorderzijlvest.

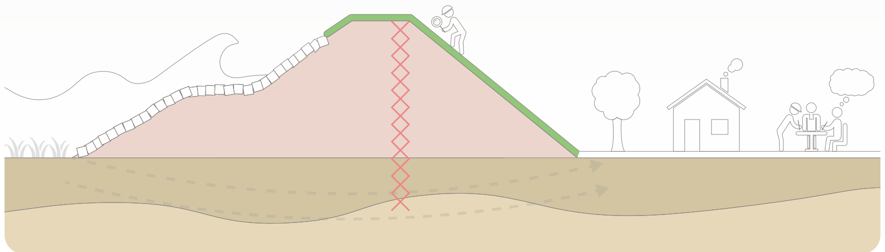
Project Summary

A3 - Dike reliability analysis

Better methods for the assessment and design of dike systems

By Wim Kanning
Delft University of Technology

Project start: 09/2017 (Part-time)
Project end: 09/2021



Outcome

This project developed better methods to assess the strength and performance of dikes using data from past events and experiments for optimising the design of flood defences. With the improved methods from MSc and PhD research, we focus more on what is in the subsoil and how this affects dike performance. Dikes will not necessarily fail if budgets for the different failure mechanisms are not allocated perfectly but may fail if subsoil properties investigation, inspection and maintenance are not carried out properly. Overall, we concluded that it is important to look beyond models and get a wider view of what makes the dike perform better.

Figure 1: Dike failure in Breitenhagen, Germany. Photo by Weichel (2013).

Motivation and practical challenge

Seeing the aftermath of the New Orleans flood in 2005 motivated me to work on dike reliability modelling (**Figure 2, bottom-right photo**). The flood consequences were grave and very impressive (**Figure 2, top and bottom-left photo**). That event made me realise the difficulties in predicting dike reliability first-hand and the need to reduce modelling uncertainties abroad and in the Netherlands.

On the one hand, it showed me failure mechanisms that are rarely observed in the Netherlands outside books and laboratories. On the other hand, it showed that modelling these failures involves much more than applying well-known calculation rules. Very uncertain subsoil conditions determine the strength of the dike. For example, very small weak zones in the soil proved critical for slope stability. Hence, modellers and designers of dikes should better account for the uncertain factors influencing the dike strength as much as possible.

Research challenge

To improve the modelling of failure mechanisms of flood defences, I explore together with MSc and PhD students from All-Risk and SAFELevee projects how uncertainties in dike performance can be accounted for and best mitigated.

Innovative components

Our research helps in better understanding failure mechanisms for optimising the design of flood defences to better comply with the new flood protection standard. Some of the unique topics that I'm working on as a daily supervisor of the following PhD researchers are (related projects):

Figure 2: **Top and bottom-left:** Floodwall failure on 17th Street Canal from Hurricane Katrina in New Orleans (photos by U.S. Army Corps of Engineers and IPET, 2005). **Bottom-right**: Rebuilt New Orleans floodwall in 2013 (Photo by Bianca Hardeman).

- **The temporal development of failure mechanisms.** Together with Joost Pol (Project D3), we look at the progression rate of piping using full scale and small-scale experiments. This temporal development shows how long piping needs to occur to result in flooding along the coast and on riverine areas.
- **Method to derive the most likely causes of failure of past breach events.** Together with Job Kool (part of the SAFELevee project), we improve the

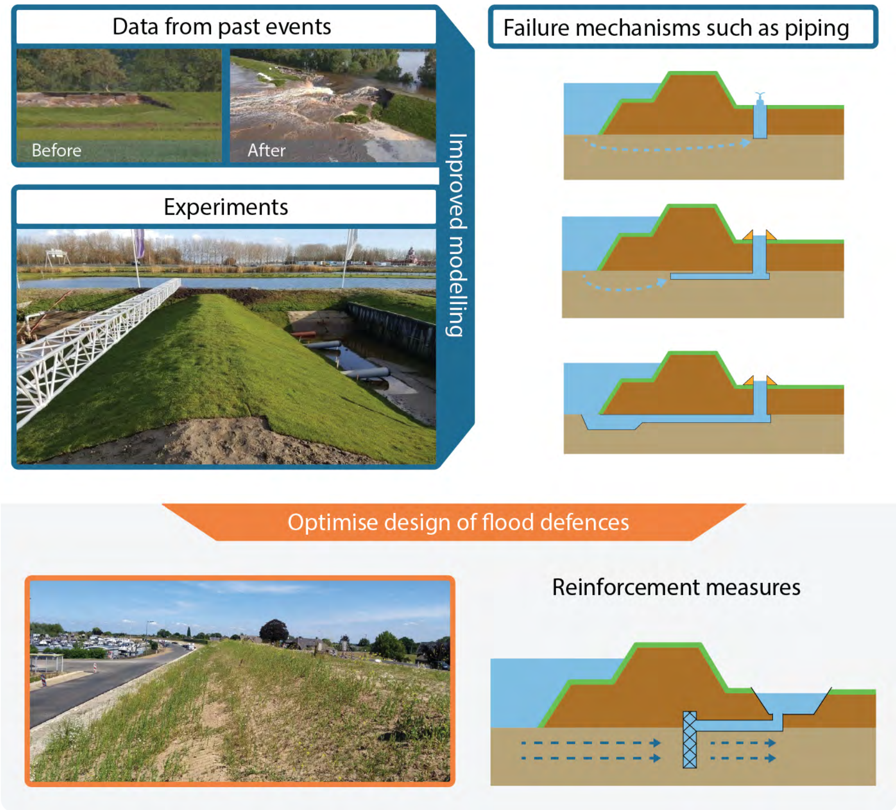


Figure 3: Components include data from **top:** the dike failure in Breitenhagen, Germany (source: Weichel, 2013); **middle:** the Flood Proof Holland backward erosion piping experiment (source: Pol, Kanning & Jonkman, 2021), and **bottom:** reconstructions around Kinderdijk in South Holland (source: TU Delft [SAFELevee], 2021). The piping and reinforcement schemes were adapted from van Beek (2015).

modelling of failure mechanisms via the structured deduction of failure scenarios from before and after data. We tested this approach to find the most likely cause of the failure of the Breitenhagen dike in Germany (Figure 1). The method is generically applicable to other locations.

- **Optimisation of dike reinforcements.** With Wouter Jan Klerk (Project A1), we look at various measures to, for example, reduce uncertainties on the soil parametres and implement reinforcement techniques.

Relevant for whom and where?

Other researchers interested in the probabilistic analysis and failure mechanisms modelling. Organisations planning the reinforcement of dikes and authorities setting the design requirements.

Progress and practical application

For a detailed description of each finding, please **see the key project outputs on the next page**. The analysis of the 2013 failure on the Breitenhagen dike in Germany shows that the slope instability most likely occurred as the result of an old breach. This old breach probably eroded the soil in front of the reconstructed dike, creating a direct connection between river and aquifer, thereby increasing pore water pressures.

By including temporal progression rates in the failure probability assessment due to piping, the improvements on the dike safety are small for riverine cases, which have long-lasting high water levels. However, the improvements are much larger for the coastal cases, which have short-lasting high water levels resulting in insufficient time for piping to develop fully. There is still a considerable delay of several days in the expected time of piping development in the riverine cases, which is beneficial for emergency interventions. Instead, piping is less likely to occur with floods of low duration for coastal cases.

Finally, our application example for five dike sections along the river Lek in the Netherlands shows that additional monitoring information is only valuable if the expected reinforcement decision is likely to be different.

Recommendations for practice

- Look beyond the models by considering more the dike subsoil history and other sources of information such as the analysis of past dike breaches to understand dike performance better.
- Old dike breaches and former river meanders are the most critical dike sections.
- Take inspections more seriously.
- Put more effort into understanding piping.
- Case studies should be more central in the development of dike assessment tools.

The research include key locations in the Netherlands and abroad to use data from past events and experiments in the optimisation of flood defences.

Photos by Waterschap Rivierenland.

Key project outputs

Kanning, W., Schweckendiek, T. (2019). Bayesian inference of piping model uncertainties based on field observations.
Doi: 10.3850/978-981-11-2725-0_IS4-9-cd

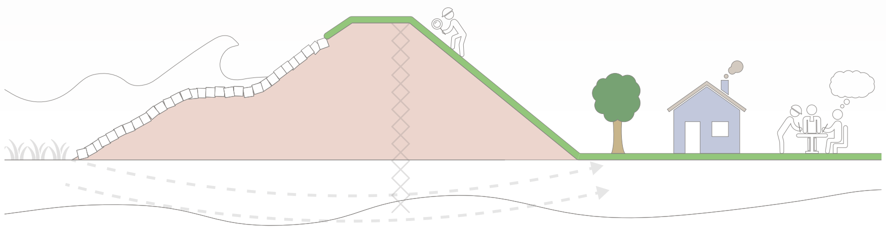
Jongejan, R.B., Diermanse, F., Kanning, W., Bottemad, M. (2020) Reliability-based partial factors for flood defenses.
Doi: 10.1016/j.ress.2019.106589

Kool, J.J., Kanning, W., Jommi, C., Jonkman S.N. (2020). A Bayesian hindcasting method of levee failures: The Breitenhagen case. Doi: 10.1080/17499518.2020.1815213

Project Summary

A4 - Spatial adaptation in coastal environments

New possible synergies between flood protection infrastructure and urban landscape design

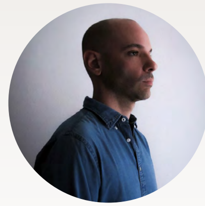


By Luca Iuorio

Delft University of Technology

Project start: 09/2020

Project end: 09/2022



Contributors

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Prof. dr. ir. M. Kok

Delft University of Technology

Outcome

The current flood risk-related challenges induced by climate change place pressure on designing urban areas where natural and man-made conditions can be imbalanced. Today, flood risk is mostly managed to reduce the probability of flood events. However, the engineered probability approach to flood risk management might not always result in a well-designed landscape; especially in floodplain and coastal areas, water defence infrastructures significantly impact the urban structure. This project output highlights new possible synergies between flood protection infrastructure and urban landscape through integrated design. Designing, indeed, is the fundamental act to explore the spatial challenge of climate change in its complexity.

Figure 1: Ems bay seen from Delfzijl beach, Dutch Wadden Sea. Photo by Luca Iuorio.

Motivation and practical challenge

Especially in the Dutch context, awareness increases that design and engineering are two sides of the same coin. In the last decades, this awareness gave birth to several experimental programmes in which flood risk management measures increasingly demand to overcome the division and practical silos between urban planning and flood management. Making space for water has become one of the hallmarks of a new generation of flood management plans and strategies that address a renovated attitude in living closer with water. However, living with water includes the discipline of spatial design more than the dominant engineering-based risk paradigm. Spatial development is a part of the risk approach, and engineering is a part of the spatial design. Therefore, by better considering the history, dynamics, and transitional aspects of urbanised areas, it is possible to envision alternative ways to adapt to climate change and the environmental crisis through the means of the design, in its infrastructural and spatial features.

Figure 2: Family swimming in the Wadden Sea, Eemshaven, August 2021. Photo by Luca Iuorio.

Research challenge

The main question of the research is how to translate the risk approach (a product of the probability of flooding and its societal and economic consequences) into its spatial aspects. By better considering citizens' attitudes of perceiving and experiencing cities, landscapes and places, new possible perspectives in the flood defence system emerge to integrate spatial dimensions of protected areas to reduce the overall risk.

Innovative components

The research explores the possibility to further demonstrate that flood defence infrastructures can be developed within a spatial approach. We recognised that flood defences are physical manufactures integrated into the urban landscape that impact urban development and the way people interact with water (and water-related risks) through the flood defences. This research explores alternative models of coastal management by integrating spatial planning and design. The spatial integration into the landscape of the traditional dikes and innovative nature-based measures, accepting water overtopping, implementing temporary dikes, and land-use change are developed as the main actions to reduce the overall flood risk of the Dutch coastal urban environments. Through this exploration, we produce future visions to show how including whole urban areas in the design of water protection systems can establish more complex and resilient flood management through spatial measures.

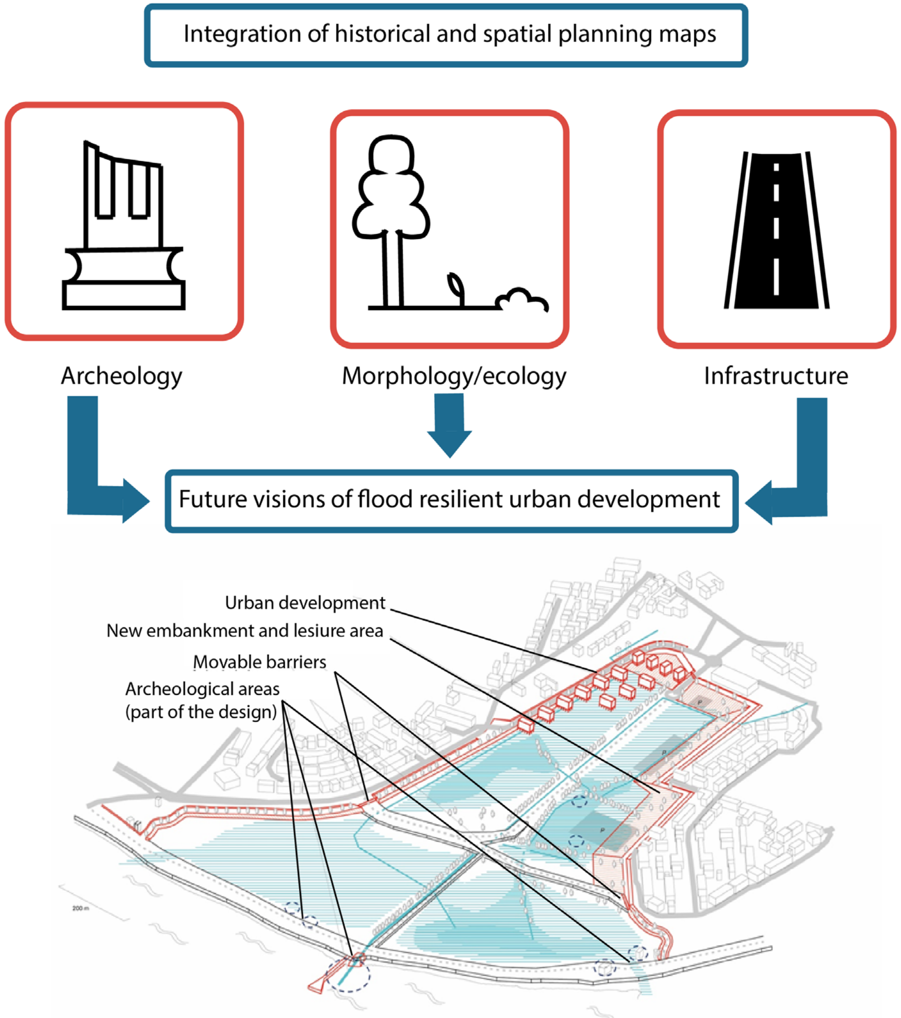


Figure 3: Schematic representation of the innovative components. Future vision examples for Southend-on-Sea drawn by Andrea Bortolotti and Luca Iuorio.

Relevant for whom and where?

This project is relevant for both flood risk and spatial planners. The research deals with the big physical inheritance of the coastal built environment where changes in building and planning infrastructures by specialists may also impact the attitude of perceiving and experiencing cities, landscape and places by citizens.

Findings and practical application

Referring to the Vlissingen (NL) and Southend-on-Sea (UK) Interreg SARCC project locations (see https://www.interreg2seas.eu/en/SARCC), we proposed accepting wave overtopping and building a secondary defence line instead of heightening the existing primary defence line. In such a way, we adapted specific zones to function as a retention basin for excess water in the case of extreme events while using the existing and enhanced drainage network that drains the area at the end of the storm. The visions for these urban areas into floodable parks better integrate the flood defences with new developments, enhance public spaces, and consider recreational functions. Moreover, we designed the new urban development inside the area to be flood-proofed (e.g., raised on piles or alternative ground floor functions, such as car parks). The resulting spatial interventions help stand a flood event in the future by reducing its impacts. The dike continues shaping the city as a fundamental part of it but represents only an element of the complex and broader territorial design. In contrast, the storage areas – where water once overtopped the dike and that can now store water – are an active part of the urban environment; the seasonal controlled floods change the configuration of the open spaces, adapting urban fabric to the storm events. For a detailed description of the findings, **check the project outputs on the next page**.

Recommendations for practice

- Design flood defences by also coming to terms with the spatial form of the cultural landscapes and the technical construction of urbanised areas.
- Try to develop flood defence innovations by reducing the probabilities and the consequences of flood risk.

Key project outputs

Iuorio, L. & Bortolotti, A. (2021). Integrated coastal flood design: changing paradigm in flood risk management
Doi: 10.24404/616051311d74bb0008d549ca

The research includes pilot locations in the Netherlands but also in the UK and Italy. Note: The designs for Vlissingen and Southend-on-Sea have been developed within the context of the Interreg SARCC Project.

Double Dike. Photo by Waterschap Noorderzijlvest.

Storyline

A wide green perspective on dikes

How the salt marsh and borrow pit help to counter the effects of sea-level rise

By Richard Marijnissen
Wageningen University & Research

We Dutch take great pride in our massive dikes and delta works which have kept the sea at bay for centuries. Being a hydraulic engineer myself, I naturally considered flood defences to remain at the forefront of future climate adaptation. However, in my PhD research at the University of Wageningen, I realised that strategically using the areas next to the flood defences may help to adapt more effectively to sea-level rise. Such is the case of the 'Wide Green Dike', a pilot to strengthen the dikes with the clay trapped by the salt marsh plants growing along the northern Dutch coast. This storyline is about my research into the safety of a Wide Green Dike, and the lessons learned that might help more regions adapt to sea-level rise.

The challenge

“How could flood protection and nature be combined into one integrated dike design?”

Dike reinforcement is of utmost importance in the Netherlands, a low-lying country whose primary flood defences should now comply with more strict safety standards to better prepare for a changing climate. However, the coastal areas next to these dikes also need to be preserved to maintain their ecological value. Two different uses, flood protection on the one hand, nature values, on the other hand, both competing for space, and both

Cover photo: The 'Wide Green Dike'. Photo by Waterschap Hunze en Aa's.

negatively affected by sea-level rise. The Wide Green Dike pilot aims to combine the two, and hence I investigated it as a case-study in my PhD.

THE DIKES AT THE NORTH-EASTERN DUTCH COAST

The Ems-Dollard bay

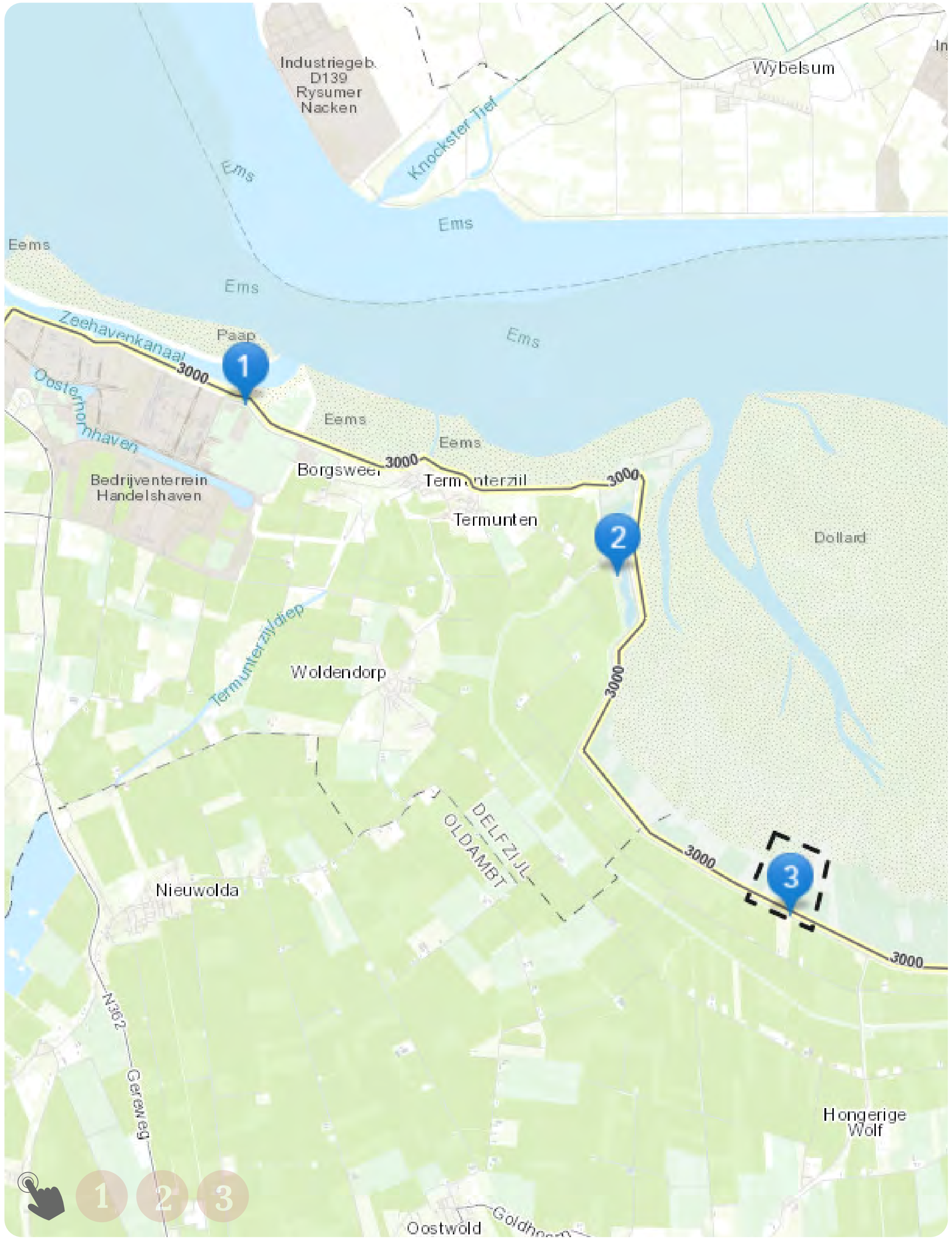
In the north-eastern corner of the Netherlands, draining into the Wadden Sea is the Ems river estuary. Located within is the 100 square kilometres Dollard bay, which harbours typical salt marsh or salt-tolerant plant species and is a bird refuge of global significance. Nevertheless, the ecosystem is threatened by increasingly high sediment concentrations blocking sunlight from penetrating into the water. The centuries of intertidal area being converted to polders, deepening of the estuary for navigation and ongoing natural sedimentary processes in the bay, have all been linked to increasingly high turbidity in the estuary today.

Combining two worlds

Inspired by the wide grass dikes in Germany, the Regional Water Authority Hunze en Aa's in the Netherlands, started a pilot to combine the needs for nature and flood protection. The so-called 'Wide Green Dike' pilot is a wide and gradually sloping dike that merges smoothly into the salt marsh without additional asphalt protection at the seaward side of the dike. Most importantly, the dike will be reinforced over time with the excess sediment from the Dollard. Clay is extracted from the three locations shown in the map on the right: (1) at the harbour of Delfzijl, (2) within polder Breebaart, and (3) from a borrow pit at the Wide Green Dike pilot site itself.

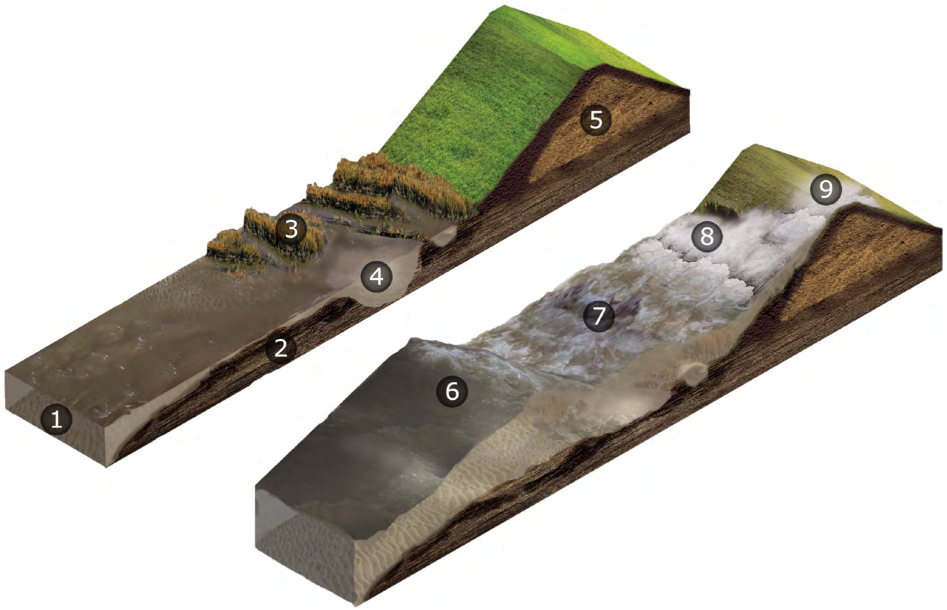
The Wide Green Dike pilot

The Wide Green Dike pilot started in 2018 by digging a clay pit. The borrow pit is approximately four hectares with an average depth of over one



Map imagery by Esri, HERE, Garmin, NOAA FAO, USGS, NGA. Flood map data by National Georegister.

The Wide Green Dike section from above. Photo by the Regional Water Authority Hunze en Aa's.



The most essential processes in the salt marsh, the pit and the dike. See the text to read what each number is about. Illustration by Richard Marijnissen.

and a half metres and a breeding island for birds in the middle. The extracted marine clay was deposited more than a year ago on dewatering sections next to the pilot site to get the necessary clay.

The research question

For my research, I estimated how much clay is captured by the pits and the salt marsh versus how much clay is needed to reinforce the dike under various sea-level rise scenarios. The main question:

"Is reinforcing a dike with clay captured in the pits and salt marshes actually feasible to combat sea-level rise?"

The salt marsh, the pit and the dike

Wrapping all these complicated processes into manageable model calculations was perhaps the most challenging step of my research. I focused on the nine most essential ones, rather than aiming to fully represent all processes.

Calm conditions

Each tide water from the Dollard brings in sediment suspended in the water **(1)**. The high tides occasionally flood the salt marsh and deposit sediment **(2)**. The accumulation of silt and mud form a tidal flat where salt-tolerant plants grow overtime on the upper parts **(3)**. Whenever the deposited clay is excavated **(4)**, the borrow pit acts as a sink for the sediment that the next high tide may bring. The sediment settles in the pit and thus a new clay layer forms over the years so that clay can be extracted to reinforce the adjacent dikes **(5)**.

Storm conditions

Only at elevated water levels during stormy conditions (at most a few dozen times a year) will the waves reach the dike **(6)**. The high waves will typically dissipate the energy along the tidal flat **(7)** but very strong waves may damage **(8)** and eventually overtop the dike **(9)**.

WHAT DO THE MODELS PREDICT?

The pit

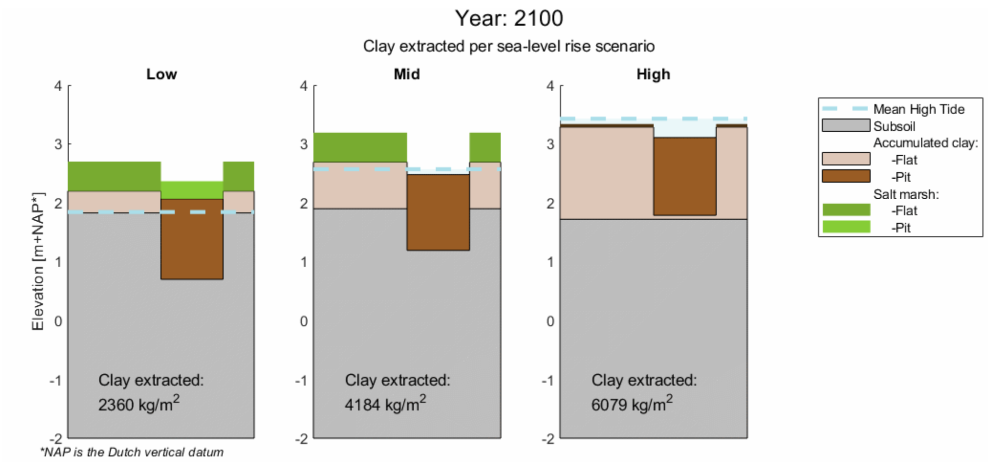
The pit is already filling up with clay nicely and is projected to be refilled within 22 years (around the year 2040). As the sea-level rise accelerates in the future, the pit is flooded more frequently and more clay is trapped in the pit. As a result, the pit will keep filling up faster in the high sea-level rise scenarios. In any case, my modelling results also show that 75% of the infilling takes place during the first ten years after the excavation of the borrow pit. Given that a deeper pit is more efficient in settling sediment, the remaining infilling will take longer with the increasing elevation of the bottom of the pit.

The dike by 2100

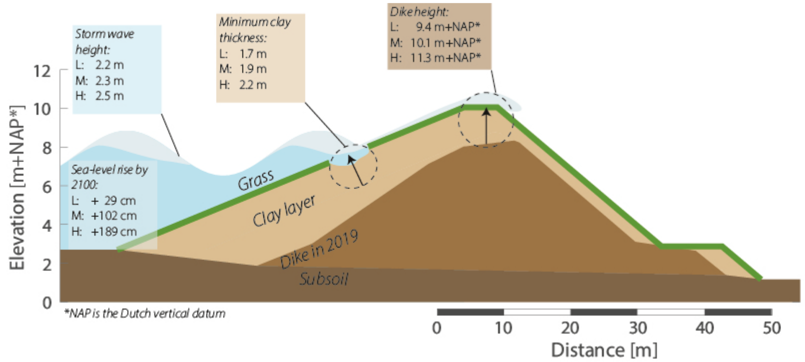
As long as the sea-level rise doesn't accelerate too much the pit and salt marsh can accumulate enough sediment not to drown. However, in the highest sea-level rise scenario, the sea-level rises too fast for the salt marsh to keep up and the marsh drowns eventually. Waves break in shallow water, thus as the salt marsh lowers relative to the sea level, the dike has to repel stronger waves. Preventing the salt marsh from drowning in high sea-level rise scenarios is necessary to limit the reinforcement needed of the Wide Green Dike.

BALANCING THE AMBITIONS

While the pit in the salt marsh will refill with clay, the clay in it will not have compacted as much as the clay deposited over decades inside the marsh. As a result, the amount of clay gathered from re-excavating a pit will always be lower.



Predicted filling of the pit with clay until 2100. Illustration by Richard Marijnissen.



According to the model simulations, this is what the Wide Green Dike should look like during a critical storm in 2100 for a low (L), medium (M) and high (H) sea-level rise scenario.

(The dike shown here is for the high scenario.)

The dike by 2100. Illustration by Richard Marijnissen.

"Should new clay be retrieved somewhere else in the salt marsh, or could the remaining salt marsh stay undisturbed by re-excavating the same pit over and over again?"

Under a low sea-level rise scenario, re-excavating the pit is not effective. The infilling is not fast enough to re-excavate the pit over three times this century. For a high sea-level rise scenario, (re-)excavating one pit is much more efficient considering that the clay infilling rate will accelerate with the sea-level rise. This allows for many more re-excavations, but also more clay for dike reinforcement will be needed.

There should be a balance with the intended natural values. For optimal sediment capture deep pits that are extracted often would be needed, but to allow new natural marshes to emerge, shallow pits that are extracted infrequently might be more preferable.

LESSONS LEARNED

Reinforcing flood protection against sea-level rise to maintain safety against flooding remains one of the major challenges this century. Dikes are and will always be an integral part, but a wider green perspective will help cope with the challenge more effectively. In essence, we need to recognise and employ nature's engineers, the salt marshes, to reinforce coastal protection.

The Wide Green Dike pilot is a good example of an integrated solution. The process of clay accumulation in the pits both aids in reducing turbidity in the estuary, and provides sufficient material for dike reinforcements in the future. Nevertheless, challenges remain to balance nature and flood protection values.

Moving forward

In my PhD research, I only scratched the surface of all the details needed to make this pilot a success. There are still many more questions to be addressed. For example:

- How much clay is needed on the Wide Green Dike *exactly*, taking into account everything from multiple storms to cows walking on the dike's slope?
- How much clay is actually accumulating inside the pit of the pilot?
- What does it take to turn the sediment from Dollard into clay suitable for a dike?
- and so much more.

While many questions remain, the general scientific insights my studies found about the Wide Green Dike pilot will help the real implementation in the Dollard, and possibly elsewhere.

Interested to read more?
Click or scan the QR Code to view the online version of this storyline.

This storyline is based on the following open access publications:

- Marijnissen, R., Kok, M., Kroeze, C., & van Loon-Steensma, J. (2020). The Sensitivity of a Dike-Marsh System to Sea-Level Rise—A Model-Based Exploration. *Journal of Marine Science and Engineering*, 8(1), 42. Doi: 10.3390/jmse8010042
- Marijnissen, R., Esselink, P., Kok, M., Kroeze, C., van Loon-Steensma, J.M. (2020). How natural processes contribute to flood protection – A sustainable adaptation scheme for a Wide Green Dike. *Science of The Total Environment* 739, 139698. Doi: 10.1016/j.scitotenv.2020.139698

Acknowledgements
This work is part of the Perspectief research programme All-Risk with project number P15-21, which is financed by NWO Domain Applied and Engineering Sciences. I thank Erik Jolink and Cora Kuiper of the Hunze & Aa's regional water authority, colleagues at the Wageningen University, and Juliette Cortes from the All-Risk editorial team for their input on this storyline.

Storyline

Proof loading and monitoring to optimise flood defence asset management

By Mark van der Krogt and Wouter Jan Klerk
Delft University of Technology

Estimates of the failure probabilities of flood defences are influenced by many different uncertainties. Uncertainties about, for example, the strength of the subsoil or the response of the water pressures to high water, often lead to improvement of flood defences with large stability berms.

Although reducing those uncertainties always sounds very promising, application is often difficult in practice and does not always lead to the expected or desired result. For example, if pore pressures are only measured for a short period of time, the probability of a relevant high water passing by during that period is rather small. 'Other' uncertainties may also suddenly appear, which were not yet in sight when monitoring was started. However, these can have a major influence on the probability of failure. Consider, for example, the water pressures in the dike body, while the measurement campaign focused only on the water pressures in the aquifer. Then you have learned something, but not the information that is really needed.

"If only we'd have known that..."

In recent months, we have been working on a method to consider in advance whether and which uncertainty reduction method will lead to the highest expected profit. We explain it below.

Cover photo: Proof loading by infiltration of the Hollandse IJsseldijk. Photo by Michiel van der Ruyt.

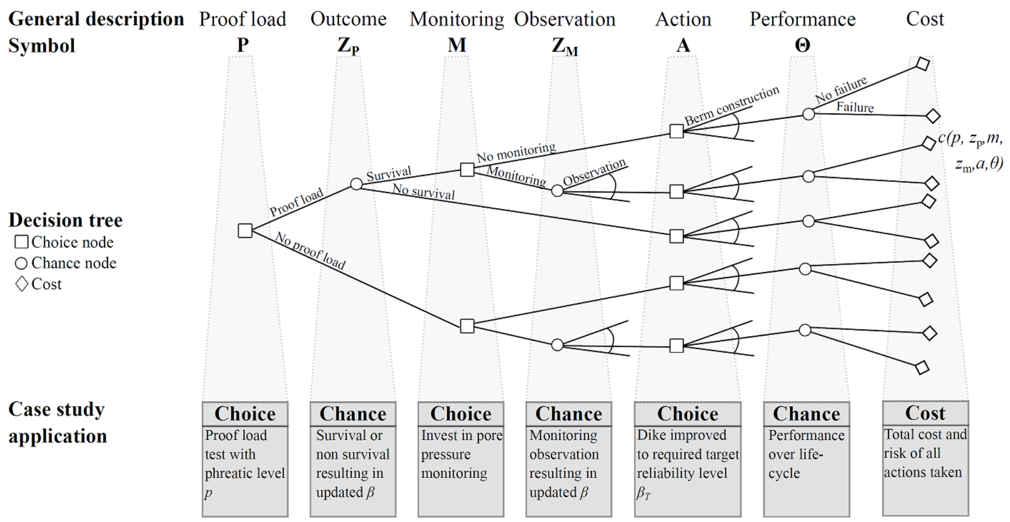


Figure 1: Decision tree for flood defence asset management. Source: van der Krogt et al. (2020, Figure 1).

Influential factors	**Positive impact**	**Remark**
Proof load level	Higher proof load, more uncertainty reduction.	The increased risk of failure does not always outweigh the potential benefits, especially if consequential damage is high.
Larger geotechnical uncertainty	Proof loading is more effective	Pore pressure monitoring might become attractive only after reducing geotechnical uncertainty. It is recommended to determine the sequence of measures based on their relative uncertainty contribution and consider other methods (e.g., site investigation).
Higher construction cost of stability berms	Uncertainty reduction methods are more attractive as the benefits are larger.	Other methods for reinforcement might be more effective.

Table 1: specific factors that play a role in the decision to monitor pore pressures or to apply a proof load test. Source: van der Krogt et al. (2020, Table 4).

In the average of 5 years typically available between rejection (i.e., we do not meet the required safety level anymore) and reinforcement of a dike, valuable time is available for additional research. We consider two ways:

1. Doing a proof load test by artificially raising the phreatic level
2. Monitoring of pore pressures to improve insight in the response of the phreatic line to high water levels.

In our method, we calculate the value of the extra information that we expect as a result of proof load tests and monitoring. The additional information improves failure probability estimates for slope stability. In most cases, just the uncertainty reduction is not sufficient to meet the failure probability, but a much smaller berm can be constructed. Bottom line, the extra information leads on average to a lower flood risk and cheaper dike improvements.

We compare the costs and benefits of various combinations of proof load testing and monitoring with the 'basic strategy' of simply constructing a stability berm. We also include the possible additional costs such as the risk of damage in the event of a failed test load. We call the lower costs compared to 'doing nothing' the Value of Information, or VoI. A positive VoI therefore indicates that a strategy is on average a good choice.

The calculations show which factors and conditions determine whether an asset manager should monitor pore pressures or opt for proof loading. A very clear outcome is that it is very important to focus the uncertainty reduction on the uncertainties that are most dominant for the failure probability. A probabilistic analysis provides valuable clues to determine which those are.

"Focus on the uncertainties that are most dominant for the probability of failure"

Other specific factors that play a role in the decision to monitor pore pressures or to apply a proof load test are listed in table 1.

The results show that it is essential to carefully consider how and which uncertainties can be reduced in order to achieve efficient management of flood defences. And it can be slightly different for each flood defence.

Interested to read more?
Click or scan the QR Code to view the online version of this storyline.

Are you curious about which additional factors and circumstances are decisive for the decision to monitor water pressures or to test loads? Read it for yourself in our article:

van der Krogt, M.G., Klerk, W.J., Kanning, W., Schweckendik, T., Kok, M. (2020). Value of information of combinations of proof loading and pore pressure monitoring for flood defences. *Structure and Infrastructure Engineering*. Doi: 10.1080/15732479.2020.1857794

About the Authors
Mark van der Krogt and Wouter Jan Klerk are PhD candidates at TU Delft and researchers at Deltares. Thanks to Wim Kanning, Timo Schweckendiek and Matthijs Kok, for the help in the realisation of the research and the article. We thank everyone involved in COST Action TU1402 for the nice collaboration and interaction in the past years.

Reflection

Double dikes: twice the protection with twice the responsibility?

Webinar team

Moderator

Marleen van Rijswick

Utrecht University

Introduction

Kees de Jong

Noorderzijlvest

Speakers

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Willemijn van Doorn-Hoekveld

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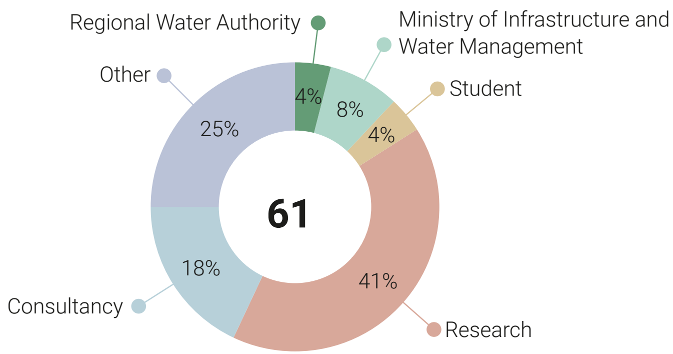
Participants



Artist impression of the Double Dike design. Image by Waterschap Noorderzijlvest.

The double dike case:

The double dike system in the province of Groningen in the north of the Netherlands is a concept where two parallel dikes together provide the required safety for the hinterland during storms. In the area in between, seawater can flow in and out, which offers opportunities for new land use. Think, for example, of aquaculture, saline cultivation, recovery of salt marshes and clay extraction. During the All-Risk webinar, the questions were discussed on how a double (twin) dike can contribute to flood risk protection, and what the division of water management responsibilities between governments is regarding this concept. In the review below you will find what has emerged from the discussion between science and practice.

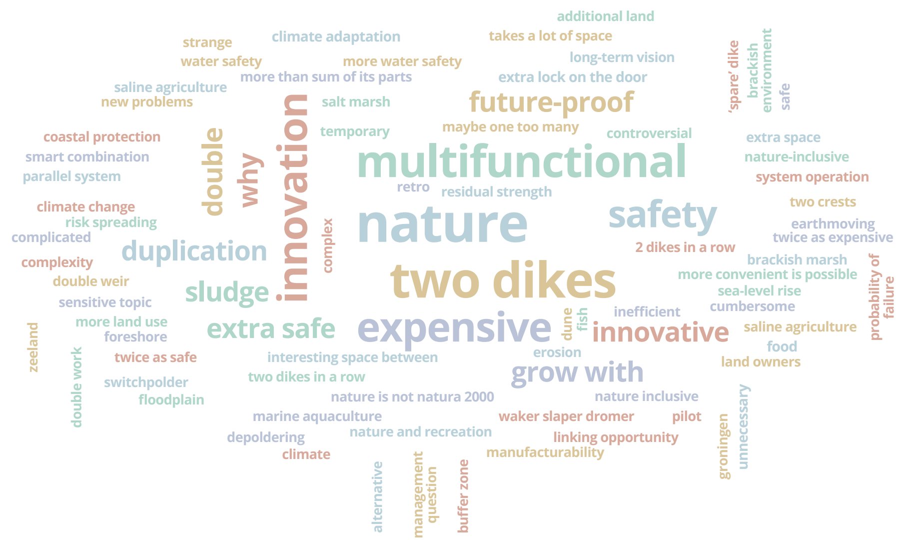
Would you like to see the presentations of the researchers? You can view them by **clicking or scanning the QR Code**.

This reflection emerged from the discussion between researchers and participants during the All-Risk webinar organised on May 17, 2021.

The discussion

During the webinar it became clear that there is some controversy regarding the concept of double dikes. On the one hand, the concept offers interesting additional functions (saline cultivation, aquaculture, nature restoration, clay mining). On the other hand, the question arises whether the second dike contributes to flood risk management and how this relates to the costs. During the discussion it appeared that the final words have not yet been spoken on this matter. Reference is made to various applications of double dikes: from a low outer and a high inner dike (or vice versa) to sandy coastal applications such as on the northeast islands of Vlieland and Terschelling (also in the province of Groningen), with the foredune as the outer barrier and as the inner barrier the inland boundary profile including the intermediate barrier dune valleys. There are also several options to make use of the intermediate area (for example, space for floating homes/recreational homes such as in Zeeland/Waterdunen in the southwest of the Netherlands).

First, it is important to consider what the intended goal is and what added value is created with a double dike. Then it can be considered which

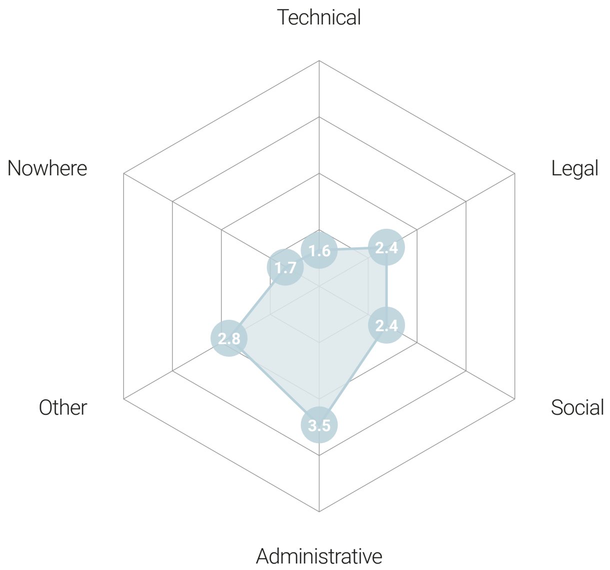


What words come to mind when you think of the concept of a Double Dike?

dike – the inner dike, the outer dike or both dikes together – can best be regarded as a primary defence, technically and legally. Theoretically only the inner defence must comply with safety norm. Participants prefer to classify both dikes in the double dike system as primary defences. However, in practice, it may be most convenient to assess the defence realising the largest reduction in flood risk as the primary defence.

What is the biggest challenge for implementing a double dike?

Participants indicated that the question of which flood defence should be the primary flood defence should also be placed in time. For example,



What is the biggest challenge for implementing a double dike?

accretion of the intermediate area could cause a shift: from an inner primary barrier to an outer primary barrier. The question remains how such a dynamic (eco)system can be regulated legally.

If one of the two defences contributes relatively little to flood risk management, it can be included in the assessment until it is removed. From a legal point of view, it can then be decided not to designate it as a primary flood defence and to regulate activities on this flood defence in the regulation of the Water Authority (Keur). If the construction of the double dike is not for flood risk management reasons, funding from the Flood Protection Programme (HWBP) will not be possible in advance. In case reinforcing only one flood defence is more cost effective, the idea of a double dike could be undermined in the long run. If you only look at the short term, a double dike is not always an obvious choice. From a long-term perspective, a double dike can have an added value regarding flood risk management in a broader perspective.

A perspective for the future?

Participants also pointed out that the added value of a double dike in the short term can differ from the added value in the long term. This gives rise to follow-up questions about the value of this concept in a scenario in which an accelerated sea-level rise becomes a reality. Can the accretion of the hinterland decrease the probability of flooding in the long term and can this process keep up with sea-level rise? It is also suggested that perhaps two safety standards can be used: one for the intermediate area in which a lower level of safety is offered, and one for the area behind the inner dike (to protect large numbers of victims and capital intensive investments). An example is a scenario in which it is decided to keep the Western Scheldt permanently open for the accessibility of the port of Antwerp. In the back of the Western Scheldt, along the neck of Zuid-Beverland, a floodable outer dike could be realised with an interdike area in which agricultural use will be possible for a long time. The inner dike then serves to protect the hinterland. Another example: for the Wide Green Dike it has already been estimated that accretion can be used to arm the dike against rising sea levels (see https://doi.org/10.1016/j.scitotenv.2020.139698).

It is noted that dike improvements can be looked at more broadly: they can act as a driver for area developments. Consider, for example, climate-proof landscapes where the intermediate area offers a buffer for the lower-lying hinterland (with a broad defence zone). It would be of added value to follow this broad and long-term oriented evaluation and monitoring approach. The big key question remains who is responsible for allowing it to silt up in the long term and at the same time guaranteeing safety in the short term. Participants noted that the prospect of preserving the value of the land and water safety in the long term is not yet widely prevalent among governments. The Delta Programme could offer added value in this regard.

Trust between governments will be necessary before this long-term perspective can get off the ground in administrative and organisational terms. When asked whether the division of responsibilities between governments could stand in the way of an innovative concept such as the Double Dike, three quarters of the respondents affirmed this. According to participants, the answers to this question illustrate how difficult plurality is in our world of thoughts and policy. The outcome touches upon the relationship between the governments of the general democracy with regard to the spatial planning of an area (municipalities, provinces, national government) and water authorities as functional management, with their focus on functional flood risk management. However, there are also positive voices: participants indicate that a lot can be done with the twelve-yearly assessment and evaluation. A clear story about "why do we do something and how do we do it" and clearly stating what management entails can bring a lot of peace and space for future-oriented discussion and solutions, and… where there is a will, there is often a way.

All-Risk recommendations:

- First, look at the intended goal and for which aspects the double dike creates an added value.
- Then consider which dike – the inner dike, the outer dike or both dikes together – can legally and technically best be regarded as primary flood defence.
- From a technical-theoretical point of view, we recommend considering the inner dike as the primary flood defence to calculate whether it meets the safety standard.*
- From a legal point of view, depending on the importance of the outer dike for water safety, this dike could – in addition to the inner dike – also be designated as primary flood defence or be actively regulated as a flood defence object (or foreshore) in the regulations of the Water Authority.*

**The participants indicate to designate both barriers as primary. While current practice prefers the dike with the largest contribution to the reduction of the probability of flooding.*

Aerial photo of the outer and inner dike of the double dike system. Photo by Waterschap Noorderzijlvest.

Examples of asset management activities for dikes. Photo by Wouter Jan Klerk.

The theme:

Safety standards of flood defences are based on probabilities of flooding. Using a variety of failure models and statistical methods, we try to assess these probabilities as well as possible, in order to take effective measures for flood risk reduction. The question is how well we actually have insight into the flooding probability, and whether we take all relevant factors into account.

In this webinar, we consider two aspects that have not been explicitly accounted for in flood probability estimates: influence damage of the revetment due burrowing and interactions between failure mechanisms leading to failure behaviour that deviates from currently considered behaviour. How can we account for these effects? And how does it influence the practical action perspective?

Would you like to see the presentations of the researchers? You can view them by **clicking or scanning the QR Code**.

Reflection

Risk-based inspection and interactions between failure mechanisms

Webinar team

Moderator

Matthijs Kok

Delft University of Technology

Speakers

Wouter Jan Klerk

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Introduction

Oscar van Dam

Hoogheemraadschap van Delfland

Joost Pol

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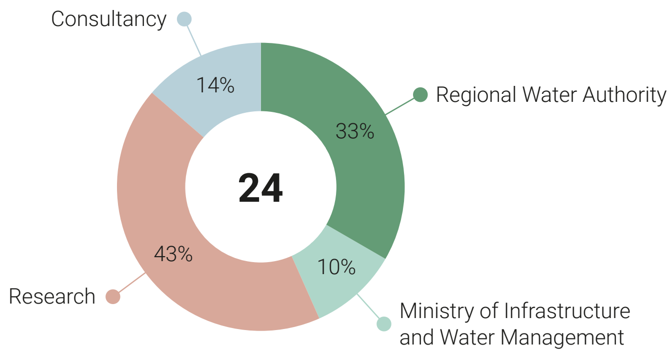
Participants



This reflection emerged from the discussion between researchers and participants during the All-Risk webinar organised on October 4, 2021.

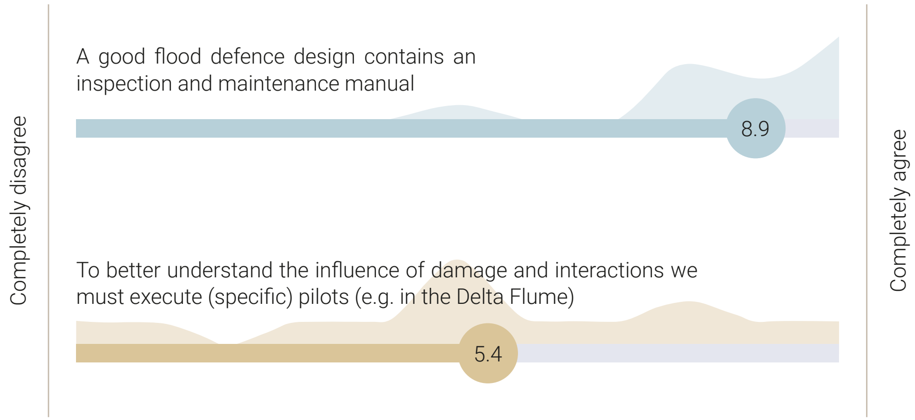
The discussion

The presentation discussed the accuracy of flood defence inspections, which has been quantified in a field test with inspectors from the Rivierenland Water Authority. This test clearly shows that not all damages are observed in inspections and that these omissions have to be accounted for when estimating failure probabilities of flood defences. In the considered case, the influence of damage on the system failure probability was quantified: this results in a significant increase and demonstrates that existing inspection policies are often insufficient to meet the requirements. With targeted interventions, the influence of damage on flood defence reliability can be reduced significantly. This reduction has been substantiated using a multi-objective analysis of total cost and structural robustness. The latter is a new and useful indicator to quantify how design, inspection and maintenance influence the impact of damage of revetments on flood defence reliability.

What comes to your mind when you think about inspections?

It is widely recognised that there is not much knowledge on the influence of damage to flood defences. There was also a broad agreement among participants on the importance of accounting for damage to flood defences into the design considerations, although this is often difficult. The proposition that every flood defence design has a (risk-based) inspection and maintenance manual has broad support, although it is not yet clear what such a manual should contain exactly. Amongst otheres there are important uncertainties, on the exact influence of damage on strength. The proposition on doing physical tests (e.g., in the Delta flume) gained mixed support,

What comes to your mind when you think about inspections?

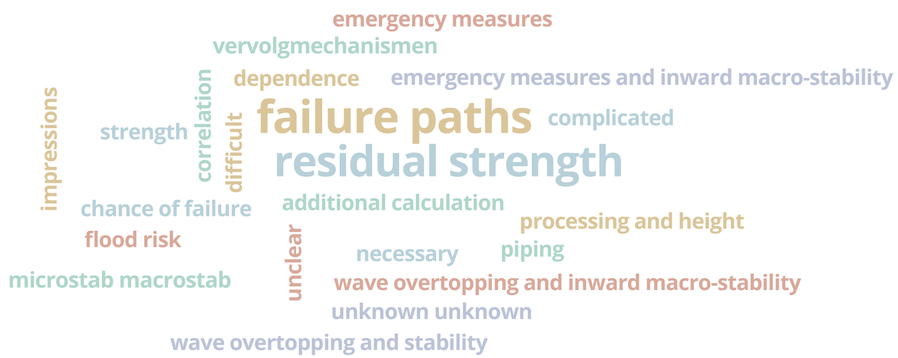


primarily because the starting point should be the risk contribution of the uncertainties and not the physical unknowns.

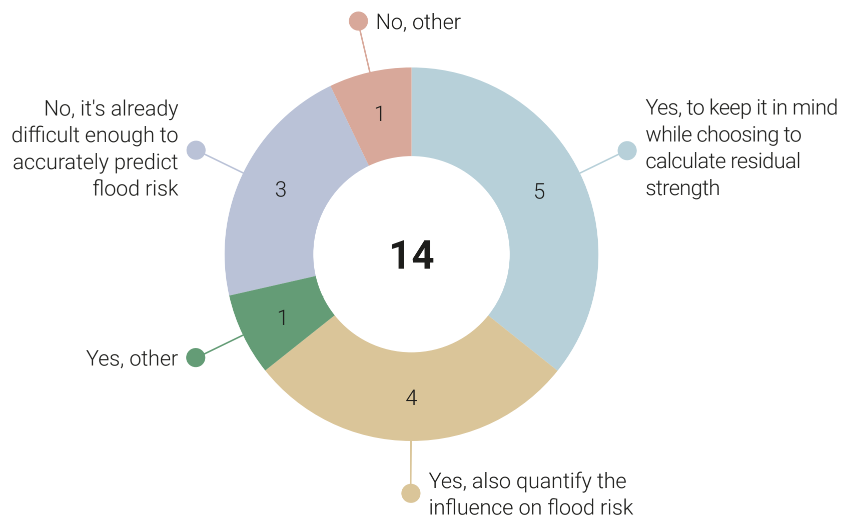
Future research on the impact of damage should primarily focus on large-scale burrowing related to internal erosion and slope instability and damage to grass revetments. The key reason is that these damages are relevant for a very large part of the flood defences, which makes the potential implications on a national scale very large. Similar reasons hold for pattern-placed revetments, which are also seen as important. The relatively small portfolio of asphalt revetments and toe structures leads to a lower priority for research.

What about the interactions between failure mechanisms?

The presentation first explained what interactions between failure mechanisms are, and in which cases they may affect the flooding probability. This is mainly the case when the residual resistance is eliminated (or reduced) by the occurrence of a more frequent initial failure process. Thus research on interactions appears to be related to research on so-called 'residual resistance' or 'residual strength', a strength that is not yet taken into account. An analysis of residual resistance (and thus interactions) is always tailored, for instance using failure scenarios or integral reliability analysis.



What comes to your mind when you think about the interactions between failure mechanisms?



Would you like to do something with interactions in the assessment of flood defences?

During the discussion, participants recognised that this kind of analysis should move from somewhat conservative analyses based on failure initiation towards more accurate reliability estimates. About 2/3 of the participants want to work with interactions; from keeping it in mind during residual resistance analyses to a full quantification. On the other hand, participants noted that it involves more work than standard analyses and that there is still much unknown about the underlying processes.

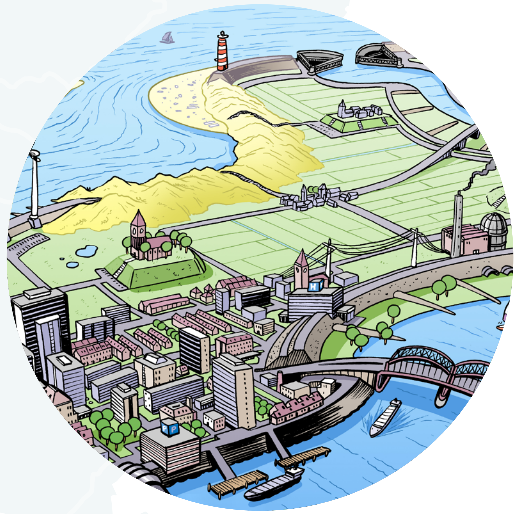
Therefore, there is a particular need for research on how these interactions work. That is difficult to imagine as few such cases have been reported in detail. It would be useful to describe failure cases in practice where multiple mechanisms play a role. In addition, part of the participants were also in favour of a practical guide or calculation examples.

All-Risk recommendations:

- Explicitly take into account the accuracy of inspections and maintenance in design (choices).
- Further research into the effect of, for example, damage to the grass cover must be risk-based: only when significant risk reduction is expected, experimental research (e.g. in the Delta flume) make sense.
- An important part of the above risk reduction is the size of the area affected by the damage: it is therefore recommended to look primarily at the consequences of large burrows and damage to grass and revetments.
- Take interactions into account when applying residual strength, quantitatively or to inform decisions to which degree residual resistance should be included.
- Further knowledge development is needed in the form of case descriptions of breaches (e.g. via TU Delft ILPD data base, https://leveefailures.tudelft.nl), knowledge of failure processes after initiation, and quantification of the effect of interactions on the failure probability for several practical cases.

Measurement of beach wrack on the dikes after a storm, as a measure for wave run-up. Photo by Beatriz Marin-Diaz.

Chapter 3
Dynamics in Hydraulic Loads



Introduction

By Tjeerd Bouma

Being able to design dikes along ‘muddy’ coasts (Waddensea, Scheldt estuary, etc.) and the many cross-connected branching rivers that have shaped our Delta starts with being able to predict the hydraulic load that these dikes may experience during extreme conditions: i.e., storms and storm surges hitting our ‘muddy’ coasts versus extreme river discharges flushing through our rivers. Although these hydraulic loads have been studied for a very long time, recent insights revealed that three urgent issues remain to be resolved:

1. Do we truly understand how marshes attenuate waves across various landscape settings, under which conditions they can grow, and how to construct and manage them for flood safety?

2. Do we properly account for the full spectrum of wave-loading that can reach a sea wall and its vegetated foreshore?
3. To which extent does our ability to correctly predict river water levels during peak discharges depend on our ability to predict the water distribution at river-branching points?

Although it has been shown that salt marshes effectively reduce wave loading on dikes during extreme storms (Möller et al., 2014; Vuik et al., 2016; Willemsen et al., 2020) and reduce the depth of a dike breach in case of dike failure (Zhu et al., 2020), practical implication remains limited. To further application, in the project "Foreshore ecosystem management" (B1), **Beatriz Marin Diaz** used a combination of different techniques to get insights in

1. how tidal flats and marshes affect wave run-up across different landscape settings,
2. what drives where marshes can develop,
3. which sediments to use when constructing a marsh that can reduce the breach growth during dike failure,
4. how to optimise grazing management to maximise erosion resistance of marsh cliffs and,
5. how to facilitate marsh expansion by management measures on the tidal flat.

In addition, **Chris Lashley** investigated in the project "Wave propagation over foreshores" (B2) how infragravity (IG) waves alter the risk of wave overtopping at coastal structures with different types of shallow foreshores. In his research he focused on developing practically applicable empirical methods, to test the effect of these very long infragravity waves, that increase in height when approaching shallow areas, on sea walls. Using existing physical model tests and new numerical data, he developed empirical modelling as alternative to computationally expensive numerical modelling.

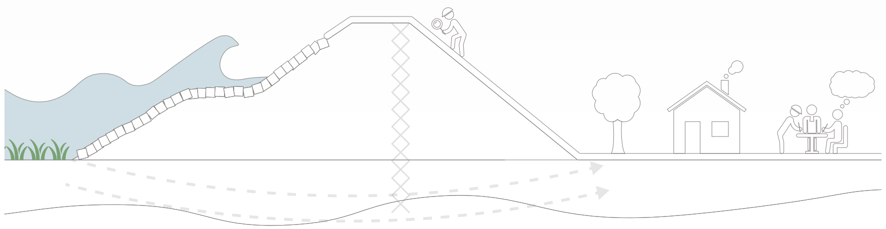
Measurements of extreme water levels during peak discharge events have taught us that it is complex to predict these water levels accurately. The uncertainty in predictions will increase, now that many parts of the rivers have been reshaped and widened, in the Room for the River programme. In the project "Large-scale uncertainty in river water levels" (B3), **Matthijs Gensen** aims to quantify and possibly reduce uncertainties in river-water level predictions. For this, he reanalysed historical data of discharges and used 1D models to quantify and explore the sensitivity of water levels to hydraulic channel roughness and to discharge distributions at bifurcations.

We highlight three key recommendations for practice. Firstly, to use marshes for flood defence, we should stimulate net sediment accretion at the fronting tidal flats, use fine sediments when "building" marshes and apply extensive grazing on marshes. Secondly, using the empirical relationship to test the effect of infragravity waves on coastal protection will provide more credible assessments. Thirdly, explicitly considering river bifurcations has shown to significantly improve the accuracy of the water level and discharge uncertainty estimates.

Project Summary

B1 - Foreshore ecosystems management

Insights in coastal ecosystem dynamics for their application in coastal protection



By Beatriz Marin-Diaz

NIOZ – Royal Netherlands Institute for Sea Research

Project start: 09/2017

Project end: 11/2021

Promotors

Prof. dr. T.J. Bouma
NIOZ

Dr. L.L. Govers
University of Groningen

Prof. dr. H. Olff
University of Groningen

Prof. dr. D. van der Wal
NIOZ

Outcome

This project highlights the value of natural coastal ecosystems in lowering the wave loads on dikes and providing erosion-resistant elevated soil fronting the dikes (**Figure 1**). More specifically, we provide insight on (1) the importance of elevation and width of both tidal flats and marshes for wave run-up onto the dikes, (2) the importance of tidal flat elevation (changes) on the long-term marsh development, (3) the use of 'green' management measures to stabilise tidal flats and thereby facilitate marsh expansion, (4) the topsoil erosion resistance of marshes compared to bare mudflats under fast water flow, as would occur during a dike breach and (5) the erosion resistance of marsh cliffs in relation to grazing management and sediment type, as this drives the marsh width in front of a dike.

Figure 1: A dike protected by a salt marsh in the Dutch Wadden Sea.
Photo by Beatriz Marin-Diaz.

Motivation and practical challenge

From the coastal areas near my home in Barcelona to the Dutch coast that I now study, I acknowledge that hard engineering measures such as dikes are at many places needed for flood protection (**Figure 2 top-left**). However, the required engineering measures may become less intrusive if we know how to combine them with natural foreshore ecosystems such as salt marshes, resulting in hybrid solutions (**Figure 1**). The salt- and flooding tolerant plants growing in these marshes may contribute to coastal protection by stabilising the soil and reducing waves, in addition to providing other important ecosystem services like water quality improvement, carbon sequestration and habitat for biodiversity (**Figure 2 top-right**). This contribution is highly promising. For example, by preserving and restoring natural ecosystems like salt marshes and mudflats, about 100 km of dikes along the Wadden Sea may, in theory, convert their safety status from insufficient to safe. To date, uncertainties about the actual effectiveness still hamper the practical implementation of these ecosystem-based measures. Hence, as an environmental biologist, I am highly motivated to generate knowledge enabling the implementation of ecosystem-based coastal defences and thereby protecting and restoring declining coastal ecosystems.

Research Challenge

In this project, I address key knowledge gaps about the functioning of natural coastal ecosystems such as salt marshes and mudflats for flood defence and how their management may benefit both flood protection and ecological value.

Innovative components

1. The role of tidal flats and salt marshes on wave attenuation and reduction of wave run-up on sea dikes was quantified by three-year-long measurements along the Wadden Sea coast (**Figure 2 top-left and map**).
2. By analysing a 20-year time series of aerial images and elevation maps, I identified which factors drive salt marshes development at several locations in the Wadden Sea.
3. The potential of utilising artificial reefs for salt marsh expansion by accreting the fronting mudflats was experimentally explored by creating, with many colleagues, a unique artificial reef experiment (**see location on the map on page 74**). I focused on the wave attenuation and elevational effects (**Figure 2 bottom-left**).
4. The topsoil erosion mechanisms of salt marshes and mudflats, important for minimising the depth of dike breaches. With a fast-flow

Figure 2: **Top-left:** measurement of beach wrack on the dikes after a storm, as a measure for wave run-up. **Top-right:** salt marsh edge. **Bottom-left:** biodegradable artificial reefs deployed in the tidal flats of Griend. **Bottom-right:** cattle grazing in a salt marsh. Photos by Beatriz Marin-Diaz.

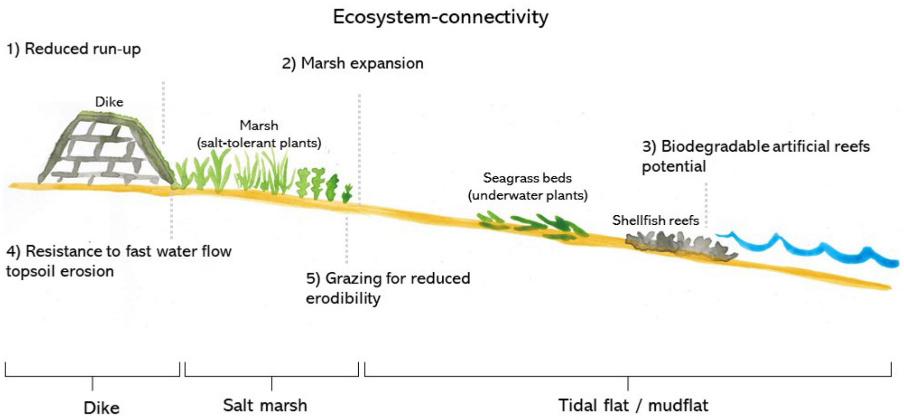


Figure 3: Illustration summarising the findings and the importance of the ecosystem connectivity. For example, shellfish reefs may reduce waves and trap sediment, which may be beneficial for the salt marsh expansion. In return, salt marshes protect the dike by providing erosion resistant soils in front of the dikes and by reducing wave run-up during storms. Illustration by Beatriz Marin-Diaz.

flume, I studied the resistance of salt marshes and tidal flats with different soil and vegetation properties to fast-flow induced erosion, as could occur during a dike breach.

5. The effect of grazing management on lateral erosion resistance, which is important for understanding its effect on marsh width. With wave flumes, I tested the lateral erodibility of marsh soils collected in areas with different grazing management, marsh age and marsh elevation (**Figure 2 bottom-right**).

Relevant for whom and where?

All authorities involved in the design of ecosystem-based coastal defence, like water-boards, nature managers, and NGOs.

Progress and practical application

Figure 3 summarises the main findings on coastal ecosystem dynamics related to coastal protection in an illustration highlighting the importance of the connectivity between all ecosystems occurring in front of a dike.

Referring to **Figure 3,** below you find a brief summary of the findings (for details, see the **project outputs** on the next page):

1. **Reduced run-up:** Salt marshes (even with short vegetation) always reduced the wave run-up compared to bare tidal mudflats (and the absence of mudflats).
2. **Marsh expansion:** Marsh expansion is related to an increase in elevation of the fronting tidal flats. Marsh formation at locations with low sediment deposition may only be achieved by engineering measures.
3. **Biodegradable artificial reefs potential:** The experiment shows the potential to change tidal flat morphology. However, the reef's dimensions should be larger, and the selection of the material should match the hydrodynamic exposure.
4. **Resistance to fast water flow top erosion:** The salt marsh vegetation traps fine sediment and organic matter, creating a highly resistant cohesive top layer. Only pioneer vegetation at sandy places was not erosion-resistant, but comparable to bare mudflats. Marshes for flood safety should not be built with only sand as these can be sensitive to lateral erosion.
5. **Grazing for reduced erodibility:** Both small (e.g. hares, geese) and large herbivores's (i.e. cattle) grazing reduce saltmarsh lateral erodibility on fine-grained soils. However, intensive cattle grazing may compact the soil, which may negatively impact the marsh resilience to sea-level rise in areas with low sediment supply.

Recommendations for practice

- We recommend preserving existing marshes because they provide stable soil and wave run-up reduction onto the dikes independently of the season, vegetation state or grazing management. To prevent marsh erosion and create new marshes, focus on managing the elevation of the fronting tidal flats and stimulate their net sediment accretion. This may be realised by improving the ecosystem connectivity.
- For future marsh restorations, using fine-grained sediments or silt are recommended rather than using only coarse sand, which makes marshes sensitive to erosion or may take very long to become erosion resistant.
- High-intensity grazing by cattle should be avoided as it is negative for biodiversity and may lower the soil elevation. However, we recommend low-intensity grazing by cattle and preserving small herbivores such as hares and geese in the low salt marshes as they may limit erosion and enhance biodiversity without any potentially negative side effects.

Locations studied near the north and south Dutch coast and the artificial experiment in the north Island of Griend.

Photo by Beatriz Marin-Diaz.

Key project outputs

Marin-Diaz, B. et al. (2021). On the use of large-scale biodegradable artificial reefs for intertidal foreshore stabilization.
Doi: 10.1016/j.ecoleng.2021.106354

Marin-Diaz, B., Govers, L.L., van der Wal, D., Olff, H., Bouma, T.J. (2021). How grazing management can maximize erosion resistance of salt marshes. Doi: 10.1111/1365-2664.13888

Marin-Diaz, B., Govers, L.L., van der Wal, D., Olff, H., & Bouma, T.J. (2022). The importance of marshes providing soil stabilisation to resist fast-flow erosion in case of a dike breach.
Doi: 10.1002/EAP.2622

Project Summary

B2 - Wave propagation over foreshores

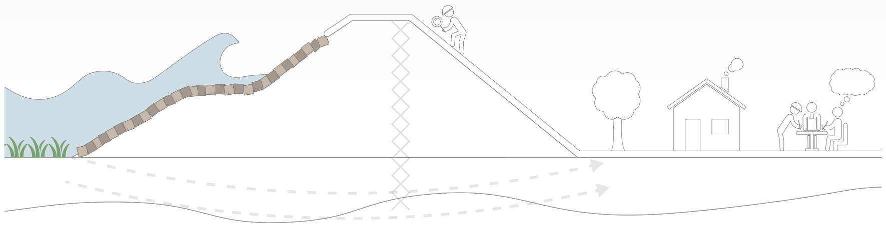
The influence of infragravity waves on overtopping at coastal structures with shallow foreshores

By Christopher Lashley

Delft University of Technology

Project start: 09/2017

Project end: 09/2021



Promotors

Prof. J.W. van der Meer
IHE-Delft

Dr. J.D. Bricker
Delft University of Technology

Prof. dr. ir. S.N. Jonkman
Delft University of Technology

Outcome

This project developed new empirical methods to estimate the relative magnitude or significance of infragravity waves and the mean overtopping discharge at coastal defences with shallow foreshores. For wave overtopping, two methods were proposed: the first augments the traditional approach where phase-averaged numerical modelling is first used to estimate wave parameters at the toe, followed by an empirical estimate of the wave overtopping. The second approach is fully empirical and uses deep-water wave parameters as input and directly account for infragravity waves. These approaches were then assembled into a probabilistic framework capable of quantifying the impact of infragravity waves on safety along the Dutch Wadden Sea coast.

Figure 1: Dike partially covered by asphalt and partially by grass, fronted by a shallow, mildly-sloping mudflat along the Dutch Wadden Sea coast. Photo by Jaap van Duin.

Motivation and practical challenge

To incorporate nature-based measures, such as the effect of salt marshes and mudflats, in the design and assessment of sea dikes, we must fully understand their impact on waves and the likelihood of flooding during extreme storms. While the influence of such shallow environments on short-period wind waves (periods less than 25 seconds) is well understood and accounted for, what happens to longer-period infragravity waves (periods of minutes) is still not fully understood. During extreme storms, these waves typically propagate, reaching up to coastal dikes. Despite their importance for flood safety and coastal dynamics, the current approaches neglect or only indirectly consider the IG waves in the analysis. In the Netherlands, this challenge presents itself in the Wadden Sea, which is quite shallow for kilometres and experiences waves generated locally and in the North Sea. The improved understanding of these waves propagating over the foreshores is also useful for building with nature in other coastal areas such as the Caribbean Islands where I am from.

Figure 2: Recent field campaign to measure waves and currents during the yearly winter storms in the same location. Photos by Pieter van der Gaag.

Research Challenge

The research seeks to answer: under what conditions are these infragravity waves significant at the structure toe, and given that they are significant, what is their impact on flood safety?

Innovative components

The following methods were applied and validated as much as possible with field measurement campaigns to answer the above questions:

- **Numerical modelling:** while field measurements and physical model tests are often difficult and expensive to implement, numerical models may be used to understand better the interaction between waves and the foreshore in a timely and cost-effective manner. This research applied state-of-the-art numerical modelling tools such as SWAN, SWASH, XBeach and OpenFOAM to estimate the nearshore wave heights and the volumes of waves overtopping the dike.
- **Empirical modelling:** Using existing physical model tests and new numerical data, the relationship between the foreshore, nearshore waves and the volume of water that may overtop the dike were captured in simple empirical relations. These relations may then guide coastal advisors towards more accurate dike designs and flood risk assessments. Thereby, they can estimate the influence of infragravity waves that are often enhanced due to shallow waters according to: (1) the magnitude of the offshore waves; (2) the foreshore characteristics such as the slope and vegetation coverage; and (3) the slope of the dike.

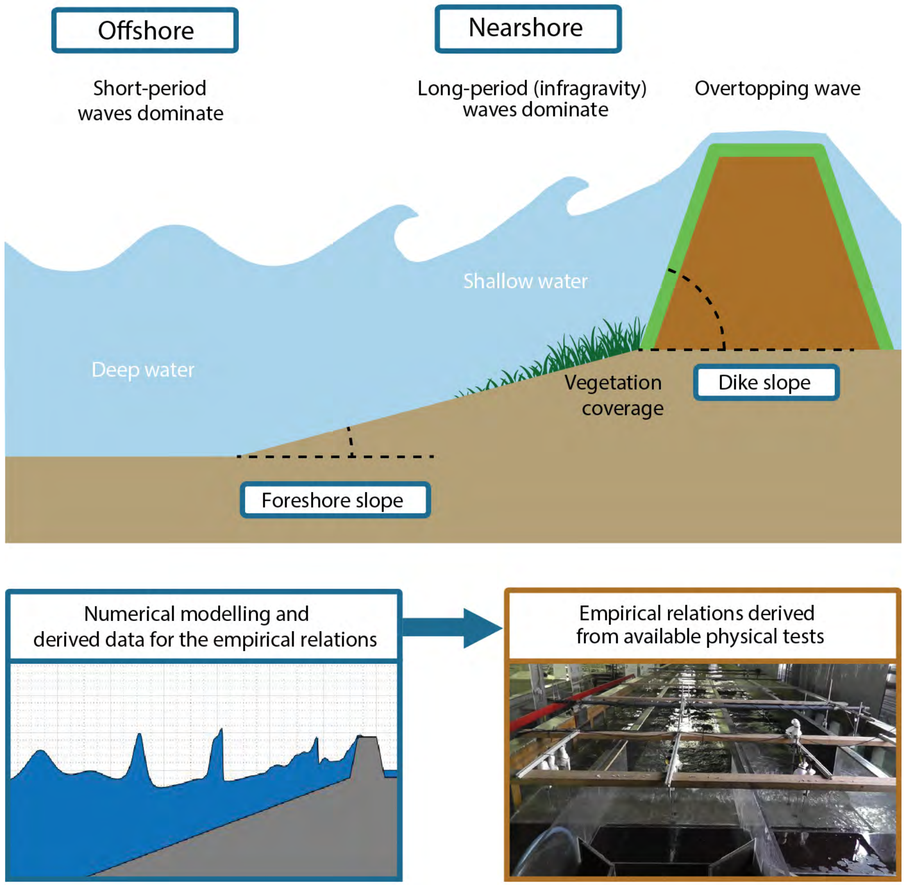


Figure 3: Components of the research to estimate the influence of nearshore waves according to the offshore and dike characteristics for more accurate dike designs and flood risk assessments. Based on schemes from Christopher Lashley. Physical model tests photo by: Corrado Altomare and Tomohiro Suzuki (Flanders Hydraulics Research, Belgium).

Relevant for whom and where?

The improved understanding of wave propagation over shallow foreshores is useful for coastal engineers, researchers, ecologists and flood risk advisors.

Progress and practical application

Findings indicate that infragravity waves become significant at locations exposed to high offshore swell with shallow, mildly sloping foreshores and reduced vegetated cover. Additionally, the numerical model comparison highlighted that more computationally-demanding models do not guarantee improved accuracy in predicting nearshore wave parameters or overtopping discharge.

The influence of infragravity waves in the nearshore is further significant for shallower water depths, milder foreshore slopes, reduced vegetated cover, and milder dike slopes. Moreover, with empirical adjustments, phase-averaged models like SWAN —which on their own do not model infragravity waves— can be used to estimate infragravity waves. For further details about each finding, see the **project outputs** on the next page.

Recommendations for practice

- Even when the infragravity wave height at the structure is minor, their influence on the wave period — and, by relation, wave overtopping — can be significant.
- The influence of infragravity waves is highly dependent on local bathymetric and forcing conditions. It is recommended that a quick check for the expected magnitude of the infragravity waves always is carried out using the tools developed here.
- It is important to assess not only wave attenuation but also the evolution of the mean wave period over the foreshore.

The research components are applied into a case study located in the north of the Netherlands.

Photo by Beatriz Marin-Diaz.

Key project outputs

Lashley, C.H., Jonkman, S.N., Van der Meer, J.W., Bricker, D.J. & Vuik, V. (2021). The Influence of Infragravity Waves on the Safety of Coastal Defences: A Case Study of the Dutch Wadden Sea
Doi: 10.5194/nhess-2021-211

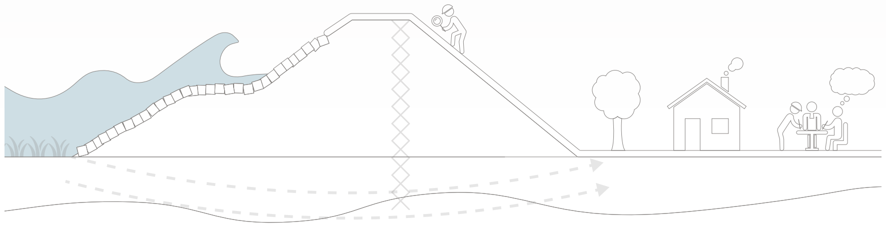
Lashley, C.H., Van der Meer, J.W., Bricker, D.J. & Altomare, C. (2021). Formulating Wave Overtopping at Vertical and Sloping Structures with Shallow Foreshores Using Deep-Water Wave Characteristics.
Doi: 10.1061/(ASCE)WW.1943-5460.0000675

Lashley, C.H., Bricker, D.J., Van der Meer, J.W., Altomare, C. & Suzuki, T. (2021). Relative Magnitude of Infragravity Waves at Coastal Dikes with Shallow Foreshores: A Prediction Tool.
Doi: 10.1061/(ASCE)WW.1943-5460.0000576

Project Summary

B3 - Large-scale uncertainty in river water levels

Accounting for the entire river system and the range of discharge conditions for the design of river interventions in a bifurcating river



By Matthijs Gensen

University of Twente

Project start: 09/2017
Project end: 09/2021

Promotors

Prof. dr. S.J.M.H. Hulscher
University of Twente

Dr. J.J. Warmink
University of Twente

Dr. F. Huthoff
University of Twente

Outcome

Our research has given insight into the functioning of a bifurcating river. We have shown that the largest downstream branch in a bifurcating river dominates the water levels throughout the entire system by steering the discharge distribution at the bifurcation. The bifurcation also strongly affects the impact of human interventions. Specific intervention design is necessary to avoid unwanted water level increases. We have also shown that the water balance of discharges at a bifurcation is not necessarily closed when estimating discharges from available water level observations. Discharge and water level estimation can be improved by explicitly accounting for water balance.

Figure 1: Rhine bifurcation at Pannerden. Photo by Rijkswaterstaat.

Motivation and practical challenge

In the past decade, the Dutch government carried out the Room for the River programme. Under this programme, several large-scale interventions such as dike relocation or floodplain excavation were implemented to reduce the water levels along the main Dutch rivers. As a hydraulic engineer, I expect that these interventions may also influence the discharge distribution within the river branches when carried out in the vicinity of a bifurcation. The discharge distribution at the main bifurcations of the Dutch Rhine (**see Figure 2**) has a dominant influence on the downstream water levels. These water levels are the driving hydraulic load, determining the required height and strength of the 1,430 km river dikes in the Netherlands. I expect that the roughness of the river bed and the effect of river interventions have a dominant influence on the uncertainty in water levels and the discharge distribution.

Figure 2: Rhine bifurcation at Pannerden where the discharge of the Rhine river is distributed approximately into 2/3 to the Waal river and 1/3 towards the Nederrijn and IJssel rivers. Photo by Rijkswaterstaat, beeldbank.rws.nl / Joop van Houdt.

Research challenge

To support a more accurate and robust dike design, I aim to quantify and possibly reduce uncertainties in river water levels related to an uncertain discharge distribution.

Innovative components

The distribution of discharge over the river branches has a dominant influence on the design water levels, which respond very differently to changing conditions in a bifurcating river compared to a single branch river. Focusing on the bifurcating Dutch river Rhine system and its three main branches (**Figure 3, top-right**), new components of my research quantify:

1. Water levels in the three branches as a result of uncertainties in the hydraulic roughness of the main channel. Using a 1D model, I estimated the sensitivity of water levels to various combinations of low and high roughness values for the river branches (**see Figure 3, top-left**).
2. Changes in the water levels due to a dike relocation intervention on the upper reach of the Waal River. I used a simplified 1D schematisation to model these changes under both a free discharge distribution and a hypothetical fixed discharge distribution at the bifurcation (**see Figure 3, bottom-left**).
3. Water level changes by considering the water balance closure of discharges at a river bifurcation (**Figure 3, bottom-right**).

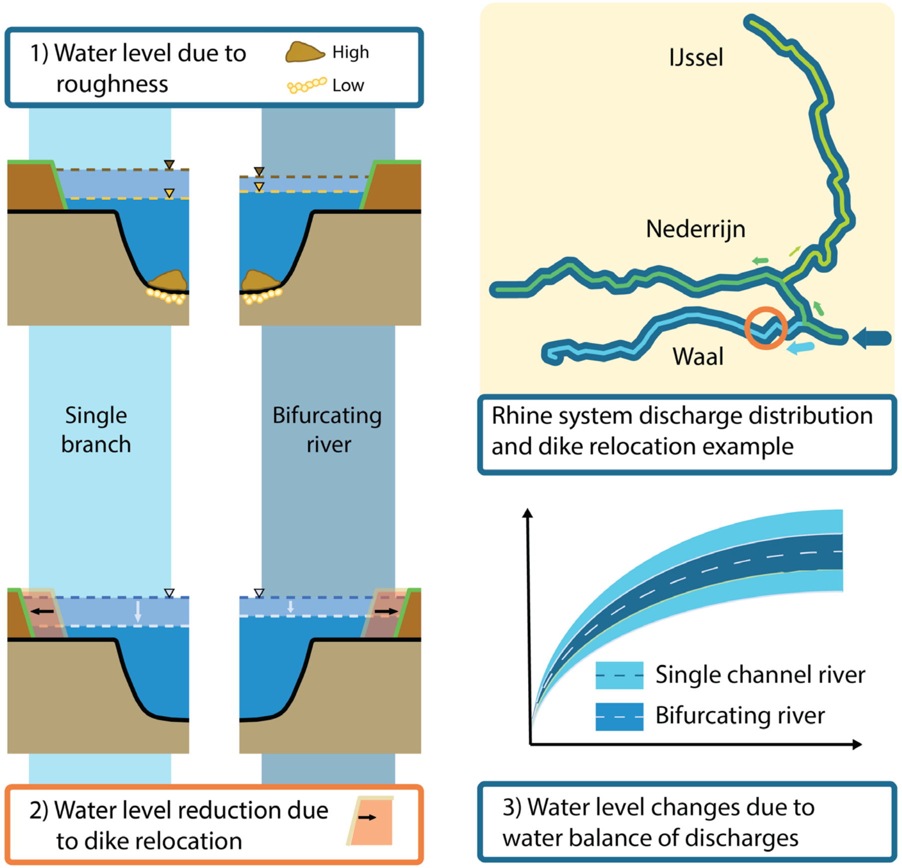


Figure 3: Three main components of my research related to the interaction between water levels and discharge distribution. Based on schemes from Matthijs Gensen.

Relevant for whom and where?

Contributors to the project, researchers and others who are involved with overarching design and planning of river interventions.

Progress and practical application

Taking into account the interaction between the river water levels and the discharge distribution at the bifurcations strongly reduce the uncertainties in river water levels throughout the entire bifurcating system. For example, these interactions cause a high water level in a branch to be counteracted by a decrease in discharge towards this branch. These counteracting effects strongly depend on the size of the downstream branches. Conditions in the Waal branch, which carries the largest portion of discharge, dominate the uncertainties in water levels throughout the entire Rhine system. The other branches, particularly the IJssel branch, have little to no influence. Furthermore, our findings for a dike relocation intervention show that the counteracting effect between water levels and discharge distribution must be accounted for in future planning of human river interventions. A second intervention aimed at balancing the discharge distribution is ideally of the same type, e.g. two floodplain excavations. Otherwise, large deviations in the discharge distribution can occur for medium-high or extreme discharges. For details about findings **see the project outputs** on the next page.

Recommendations for practice

- Explicitly consider the bifurcating river as one interconnected system in which water levels and discharges are interdependent.
- Consider water balance closure in the derivation of rating curves (Qh-relations).
- Measure discharges in multiple branches on the same day to consider the water balance and assess the accuracy of the measurements.
- Assess the effect of discharge distribution uncertainty on system-wide flood risk.

Key project outputs

Gensen, M.R.A., Warmink, J.J., Huthoff, F., Hulscher, S.J.M.H. (2020). Feedback mechanism in bifurcating river systems: the effect on water-level sensitivity.
Doi: 10.3390/w12071915

Gensen, M.R.A., Warmink, J.J., Huthoff, F., Hulscher, S.J.M.H. (2021). Human interventions in a bifurcating river system: Numerical investigation and uncertainty assessment.
Doi: 10.1111/jfr3.12762

Berends, K.D., Gensen, M.R.A., Warmink, J.J., Hulscher, S.J.M.H. (2021). Multidecadal Analysis of an Engineered River System Reveals Challenges for Model-Based Design of Human Interventions. Doi: 10.3390/civileng2030032

Rhine river and its branches pointing out the main bifurcations at Pannerdensche Kop and IJsselkop.

Photos by Rijkswaterstaat, beeldbank.rws.nl

Storyline

Cooperating with the river bifurcations

On the possibility of allowing more management freedom around the river bifurcations

By Matthijs Gensen
University of Twente

A river bifurcation balances out the water level variations from downstream changes in the river. In the Dutch Rhine river, the conditions nearby the bifurcation along the Waal branch drive the water level variations throughout all the Rhine branches. The conditions in the Nederrijn and IJssel drive only minor water level variations, and therefore, we may allow for more management freedom in the Nederrijn and IJssel, for instance, in nature development.

The bifurcating Dutch Rhine river

Soon after the Rhine river (locally known as Bovenrijn) enters into the Netherlands it splits into three downstream branches: The Waal, the Nederrijn and the IJssel. At the bifurcation, discharge and the related flood risks are distributed over the three branches. Like many other rivers around the world, these branches of the Dutch Rhine are under constant change driven by both natural river dynamics and human interventions. Change should not necessarily be a problem if we try to adapt by creating new opportunities. Over the last 20 years, we have adapted our traditional management approach by giving more space to the river while also allowing recreation and nature development. Opportunities for adapting river management continue. For instance, with the Flood Protection Programme, the government is reinforcing the primary dikes to the changing climate.

Cover photo: Bifurcation at Pannerden. Photo by Rijkswaterstaat, beeldbank.rws.nl / Joop van Houdt.

Thereby, river managers at the national and regional water authorities are considering options to strengthen the dike sections while strategically developing the surrounding area.

A strict discharge distribution

Despite the opened-up opportunities, there is one element that we remain strict about: the discharge distribution over the three branches of the Dutch Rhine. In Dutch policy, the amount of discharge that every branch should receive is specified very precisely. This policy discharge distribution is set for a Bovenrijn discharge of 16,000 m^3/s with a precision of 1 m^3/s. Each year, river managers have to check if the current situation around the bifurcation would result in the exact policy discharge distribution.

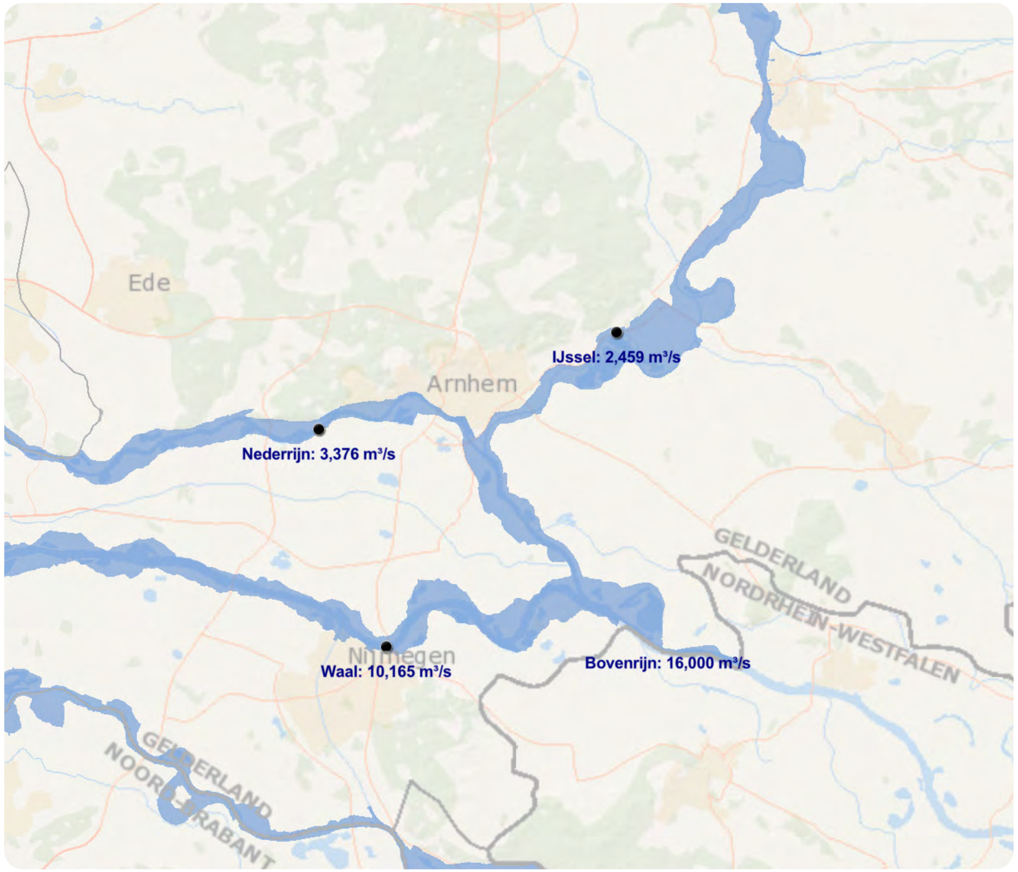
Limited freedom for river managers

The policy also specifies that, throughout the year, any human intervention around the bifurcation points cannot lead to deviations in the discharge distribution of over 5 m^3/s. If an intervention would exceed this limit, additional measures should be taken to avoid deviations. Such strict policy strongly limits the freedom of river managers. The riverine conditions around the bifurcation should remain as much as possible, otherwise, large deviations from the policy discharge distribution could occur. Therefore, for instance, vegetation in the surroundings of the river bifurcations is strictly managed, not allowing for the natural development of the area.

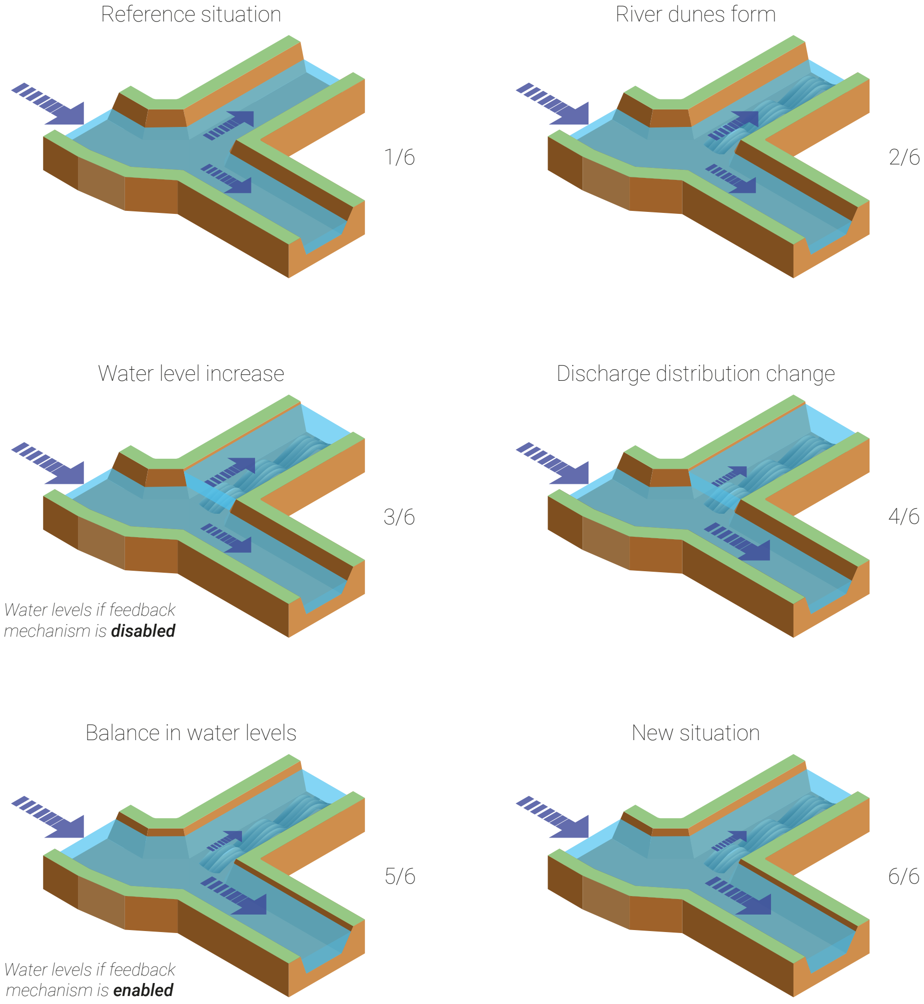
The feedback mechanism between discharge distribution and water levels

At a river bifurcation, the discharge is distributed over the downstream branches. At high discharges, the Rhine river is free-flowing, whereby the water levels in the downstream branches determine the discharge distribution at the bifurcation points. However, the amount of discharge in each branch also determines the water level along with several riverine

Location of a future dike reinforcement project along the river Waal. Photo via dijkversterkingwolferensprok.nl.



Discharge distribution in Rhine river branches. Map imagery by Esri, DeLorme, NaturalVue, NOAA OCS, geonames.org.



The effects of the feedback mechanism from a reference situation without river dunes, to a new situation with river dunes present in one of the branches. Based on schemes from Matthijs Gensen.

conditions. The most important riverine conditions include: (1) the geometry of the river cross-section, (2) the flow resistance or roughness of the river bed caused by the natural formation of river dunes on the river bed, and (3) the roughness caused by the vegetation on the floodplains.

Quantifying the water level variations due to changing conditions

As a researcher at the University of Twente, one of the aspects that I have explored as part of my work in the All-Risk programme is how the feedback mechanism at river bifurcations affects water level variations. I used a hydraulic model to estimate the variation in water levels that are caused by a change in the roughness of the river bed in one of the branches. I used two modelling approaches: a "single branch" and a "bifurcating river" approach. In the "single branch", only one branch is modelled, the feedback mechanism is disabled and the amount of discharge that the branch receives is equal to the policy discharge distribution. In the "bifurcating river", all branches are modelled, the feedback mechanism is enabled and the discharge distribution is let free.

Variations in the water levels

The three images on the next page show how water levels respond to changes in roughness in a "single branch" and in a "bifurcating river". Variations in water levels are reduced by the feedback mechanism due to a redistribution of discharge over the branches.

High roughness in the Waal

If high dunes form on the Waal branch, large variations in water levels occur. At Nijmegen, an increase of up to 45 cm is expected if the feedback mechanism at the bifurcation is disabled. This water level variation is halved if the feedback mechanism is enabled and we also see large increases in water levels in the IJssel and Nederrijn.

High roughness in the Nederrijn

If high dunes form on the Nederrijn branch, mild variations in water levels occur. If the feedback mechanism is disabled, an increase of 17 cm at Driel is observed, while this is reduced to just 4 cm if the feedback mechanism is enabled. In that case, IJssel water levels would increase by 9 cm.

High roughness in the IJssel

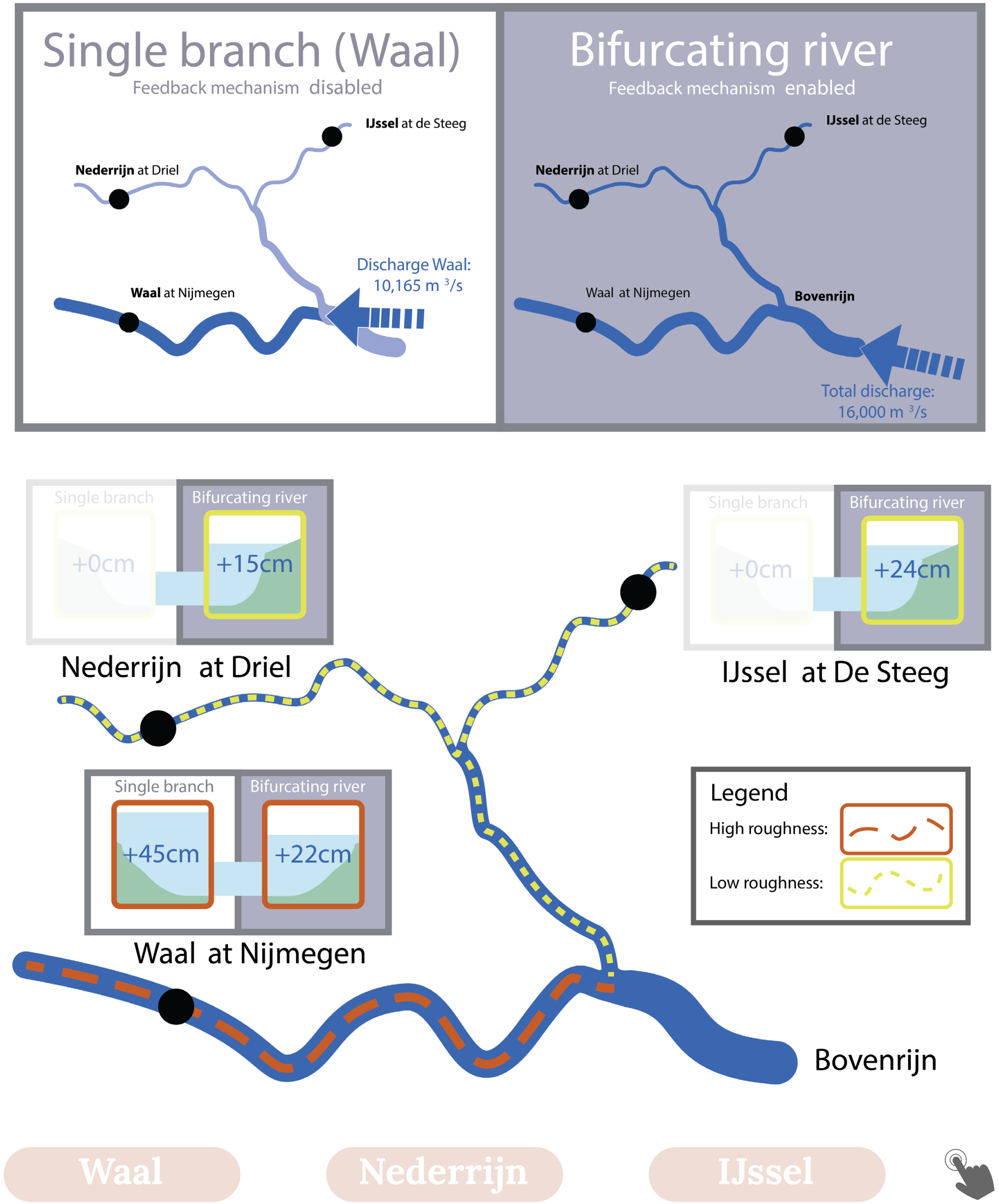
If high dunes form on the IJssel branch, slightly higher variations in water levels occur in comparison to the variations caused by the Nederrijn branch. Still, the variations are much smaller than those caused by the Waal branch. Enabling the feedback mechanism clearly diminishes the water level variations in the IJssel.

Lessons learned

The roughness of the Waal branch is a dominant driver of water level variations in all of the Rhine branches. Being the largest branch of the three branches, the Waal is better able to steer the discharge distribution than the other two branches. As such, water level variations driven by the Nederrijn or IJssel roughness are much smaller. If we consider the differences between these branches, it makes sense that we strictly manage the upper reach of the Waal. On the other hand, we may have more management freedom in the Nederrijn and IJssel, for instance, in nature development.

Two issues with the policy discharge distribution

Following my research, I think that the policy discharge distribution is too strict and that we should talk more about how more flexibility in the discharge distribution at the bifurcations can open up opportunities in both the short term (e.g. fewer restrictions on nature development) and the long term (e.g. a more cost-effective discharge distribution). I think there are two specific issues with the policy discharge distribution:



Response of water level to changes in roughness in a "single branch" and in a "bifurcating river". Based on schemes from Matthijs Gensen.

- Firstly, we should clearly acknowledge that we cannot control the discharge distribution to the precision of 1 m^3/s that we wish. Riverine conditions are unknown for the design level of the flood protection system. Therefore, large deviations from the policy discharge distribution may occur, even if we don't account for them.
- Secondly, I think that we should look at variations in the water levels instead of the deviations from the policy discharge distribution. My research showed that a deviation in the discharge distribution will result in different variations in water levels along the river branches. Currently, we do not acknowledge that the water level variations are different in each branch and we might miss opportunities for improving the river management as a result. As long as the variations in the water levels remain low, we may allow some deviations in the discharge distribution to occur.

The bifurcation can be our friend

I think that we should talk more about how we can "cooperate" with the bifurcations instead of restricting it the way it is done. We should acknowledge that we cannot exactly predict water levels and discharge distribution. However, it is the bifurcation that actually helps us with reducing major variations in water levels. A bifurcation does not have to be our enemy; it can be our friend!

Interested to read more?

Click or scan the QR Code to view the online version of this storyline.

This storyline is based on the following open access publications:

- Gensen, M.R.A., Warmink, J.J., Huthoff, F., Hulscher, S.J.M.H., 2020. Feedback Mechanism in Bifurcating River Systems: the Effect on Water-Level Sensitivity. Water 12, 1915. Doi: 10.3390/w12071915
- Project summary "B3 - Large-scale uncertainty in river water levels"

Acknowledgements

This work is part of the Perspectief research programme All-Risk with project number P15-21, which is financed by NWO Domain Applied and Engineering Sciences. We thank Bert Voortman and Max Schropp of Rijkswaterstaat, colleagues at the University of Twente, Tjerk Westerduin (visual designer) and Juliette Cortes from the All-Risk editorial team for their input on this storyline.

High water level in the Waal River, 1995. Photo by Matthijs Kok.

Flood risk along the Rhine branches:
Flood risks along the major rivers continuously demand our attention. During this All-Risk webinar, we called attention to new research on the role of two mechanisms that influence flood risk: the two main bifurcations of the Rhine branches and the role of the failure mechanism piping. Can it be plausibly argued that one of the two causes is dominant?

Would you like to see the presentations of the researchers? You can view them **by clicking or scanning the QR Code.**

Reflection

The biggest flood risk in the rivers – bifurcation points or piping?

Webinar team

Moderator

Prof. dr. Matthijs Kok

Delft University of Technology

Speakers

Ir. Matthijs Gensen

University of Twente

Introduction

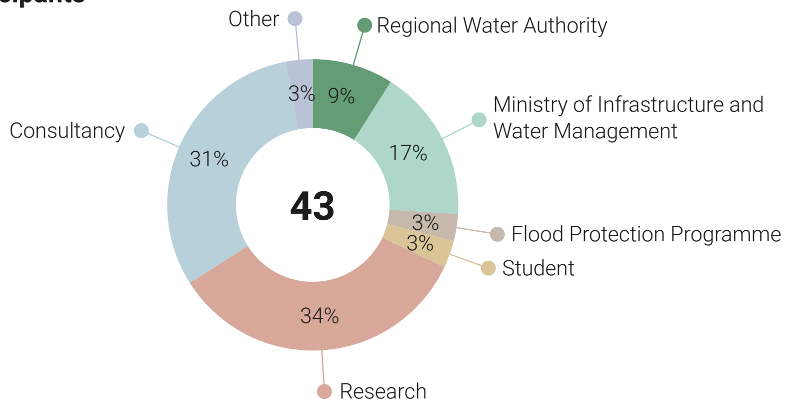
Henk van Hemert

Ministry of Infrastructure and Water Management

Ir. Joost Pol

Delft University of Technology

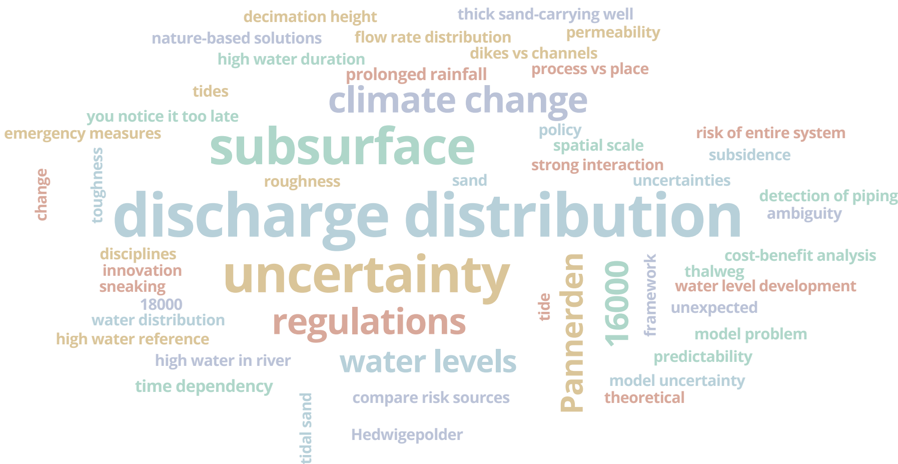
Participants



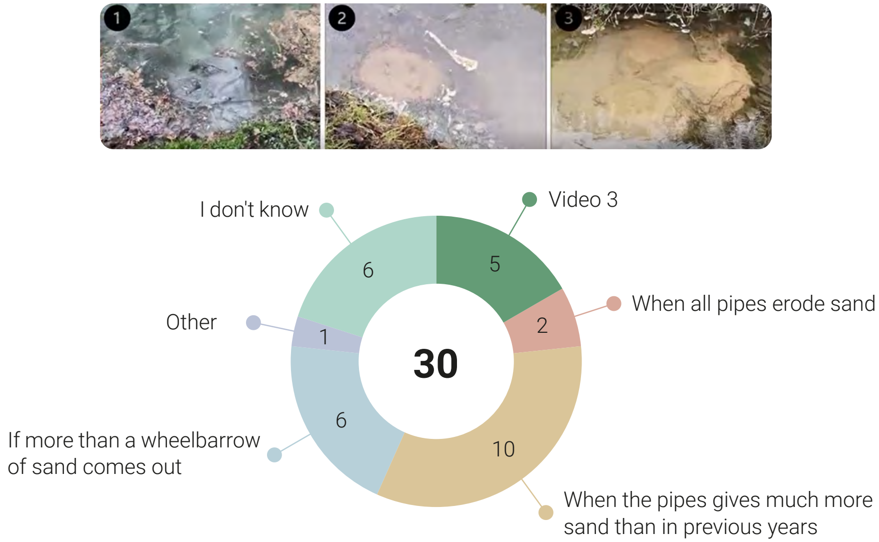
This reflection emerged from the discussion between researchers and participants during the All-Risk webinar organised on May 27, 2021.

The discussion

The overall question of this reflection became, first of all, focused on piping by asking: when does a sand erosion cause flooding? Sand erosion results in piping as a result of seepage through the subsurface. The seepage carries sand particles with it and undermines the dike. Most participants then answered from their experience: if the sand erosion due to piping gives much more sand than in past years, then it becomes critical. Others replied to the question with an absolute quantity: if the sand erosion due to piping produces more than a wheelbarrow of sand (although there was also someone who indicated in the chat that it would be more like a truck). However, the scientific knowledge is limited, and it is hardly possible to determine during a flood event, without additional measurements, whether a quantity of sand erosion due to piping is critical. The majority of the participants agreed with the statement "the effects of emergency measures (e.g. against piping) must be included in the assessment and the design of flood defences". While this consideration is currently not the common practice, it also entails a responsibility for executing the emergency measures. However, the fact that only 9% of the participants were from the Water Authorities possibly played a role in this answer. It might have caused that the practical execution of the measure is not fully addressed in the webinar discussion.

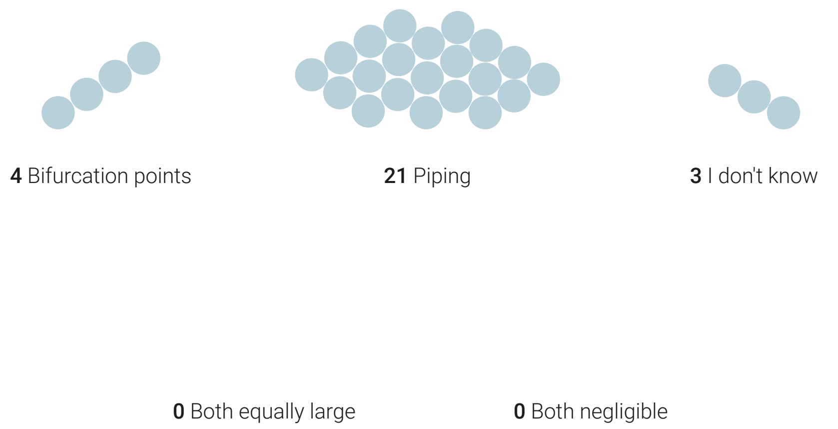


What terms come to your mind when you think about the biggest flood risk regarding piping and the bifurcation points?

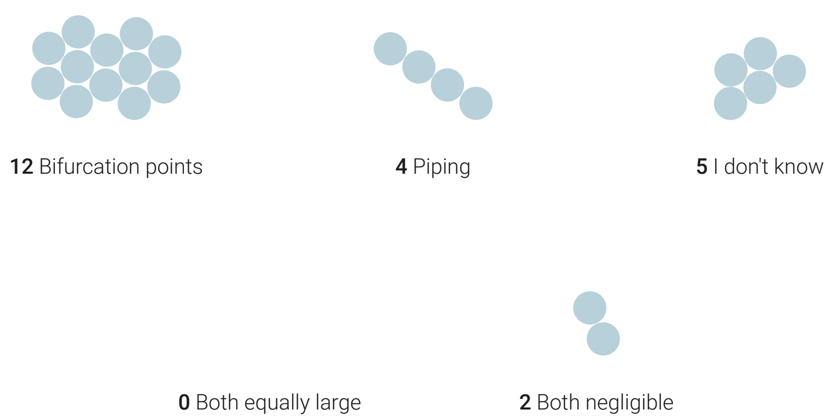


When is a sand erosion due to piping critical (real risk of flooding)? Images from videos recorded during high water field work in February 2021 by David Knops.

The participants also indicated that there are many uncertainties about the runoff behaviour at the bifurcation points and for piping, and the question arises whether the current design practices adequately cover these uncertainties. The answer to this question is different for both studies. For



Which uncertainty source makes the largest contribution to the current flood probability?



Which uncertainty source makes the largest contribution to the probability of flooding if all defences are reinforced and, therefore, meet the standard?

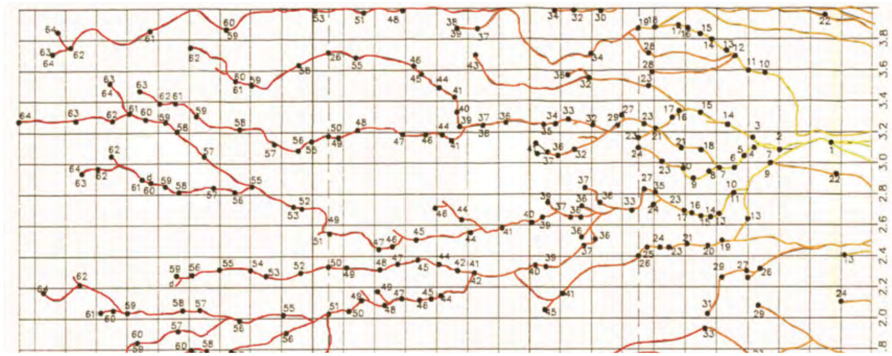
the uncertainty in the discharge distribution at the bifurcation points, it is generally assumed that the uncertainty is adequately covered. However, it is difficult to quantify how large the uncertainty is. For piping, much of the parameter uncertainty is covered by calculating probability distributions of the safety calculation values. More fundamental uncertainties about how the piping process works in practice are usually not quantified but are covered by assumptions. Moreover, the control of the discharge distribution at the main bifurcation points during high water levels generated an interesting discussion. Almost all participants indicated that the active control of the discharge distribution during a flood event could significantly reduce flood risks. Half of the participants said that the control of the discharge distribution should be considered as a measure, and a quarter of the participants said that active control is not desirable from an ethical point of view. Where are you going to send the extra runoff? And who will be responsible for that? When asked about the statement "Which strategy to cover risks and (knowledge) uncertainties is the most sensible?" none of the participants chose "Stronger dikes", which is notable: is there an anti-reinforcement sentiment? With research and measurements, the risk as we calculate it can be reduced, but even research does not always produce this desired result, and can also produce surprises.

Answer to the overall question

The webinar participants answered to whether piping or the bifurcation points pose the greatest risk when referring to sources of uncertainty to the current flood probability: five times as many people indicated that piping poses the greatest risk. Participants explained their choice by referring that piping can also cause problems with lower discharges. Those who identified the bifurcation points as the main source indicated that a different discharge distribution on an entire Rhine branch could cause problems, and influence all failure mechanisms (including piping!). For the future situation, the source of uncertainty question was assessed completely differently: participants assumed that the dike reinforcements are effective and that as a result the probability of piping then becomes so small that it no longer plays a dominant role, but that the uncertainty remains around the bifurcation point.

Piping sometimes exhibits bifurcation points at the micro-scale as well

Bifurcation points can be seen on a large scale at the Rhine branches in the Netherlands, but bifurcation points can sometimes also be seen on a microscale in piping. This is clearly shown in the figure on the right. This image is from a piping test in the Delta Flume of the Water Cycle Laboratory in 1991, and interestingly enough, the pattern of many bifurcating points can be seen before a continuous 'pipe' develops.



Results of piping test from 1991. Image from Silvis (1991, appendix 15).

All-Risk recommendations:

- Piping: Dike reinforcement combined with knowledge development is important. However, it is also important to invest in good monitoring of sand erosion due to piping, related tools for interpretation and prioritisation, and the improved execution of emergency management measures.
- With piping, it is important consider the duration of the flood wave. After all, a short-lived wave poses less risk than a long-lived load. This distinction is also important along the coast because there the duration of the flood is relatively short.
- Bifurcation points: Knowledge about the discharge distribution at high discharges is important to determine failure probabilities accurately. However, it is relevant to note that the bifurcation points effectively attenuate disruptions in water levels and thus ensure a balance in water levels along the various branches. In the future, when all dikes meet the standards, the uncertainty in discharge distribution will remain a major source of uncertainty. However, this uncertainty is considered when designing dikes along the Rhine branches.
- It is recommended to consider the uncertainty in the dike reinforcement interventions in conjunction with the uncertainty in the roughness of the river channel and its floodplains, because roughness differences may cause disruptions to the discharge distribution.

A dike protected by a salt marsh in the Dutch Wadden Sea. Photo by Beatriz Marin-Diaz.

The theme:
In the nineteenth and early twentieth centuries, salt marshes were mainly created for agriculture in the north of the Netherlands. More recently, we have reconsidered the value of these vegetated foreshores for flood safety. A recent analysis of historical major flood disasters by Zhu et al. (2020) confirmed their flood safety value. Sea walls (also referred to as dikes or levees) with salt marshes in front were not only less vulnerable to dike breaches during storms, but also had smaller breaches when dikes did fail.

Would you like to see the presentations of the researchers? You can view them **by clicking or scanning the QR Code.**

Reflection

Foreshores – useful for manageable flood safety or just beautiful nature?

Webinar team

Moderator

Tjeerd Bouma

NIOZ – Royal Netherlands Institute for Sea Research

Introduction

Jan-Willem Nieuwenhuis

Waterschap Noorderzijlvest

Speakers

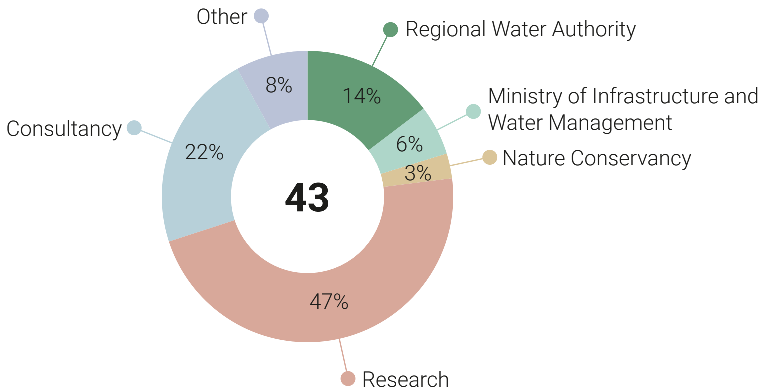
Beatriz Marin Diaz

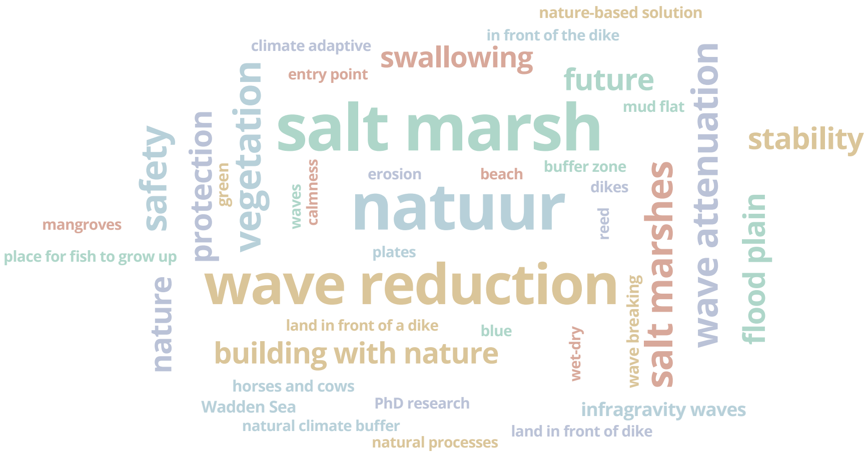
NIOZ / University of Groningen

Christopher H. Lashley

Delft University of Technology / IHE Delft

Participants





Vegetated foreshores have a double role: Nature and safety. Participant responses to the question about the role of vegetated foreshores.

This reflection emerged from the discussion between researchers and participants during the All-Risk webinar organised on June 29, 2021.

During the All-Risk webinar, we discussed (1) the effectivity of vegetated foreshores in attenuating wave run-up across the Wadden Sea region, (2) how to manage vegetated foreshores in order to reduce uncertainties in long-term stability (3) how very long waves – so-called infragravity waves – are affected by vegetated foreshores.

Are marshes a realistic tool to manage flood safety?

After the presentations, we first discussed if marshes should be restored or created at places at the most wave-exposed places. Most participants thought that marsh restoration does have an added value for nature and flood safety but that marsh restoration at exposed places would require technical means. These means may involve the creation of traditional structures to create sediment accretion and drainage, in line with traditional solutions. But mimicry may also offer a solution (Temmink et al., 2021). Overall, only a few participants thought that marshes will not survive at exposed locations and that building with nature is not realistic there.

Subsequently, we discussed that marsh creation does not always improve the quality of nature, given that the tidal flats present now can be highly valuable too. For the additional value of tidal flats, regional water authorities tend to look seaward of a dike, while nature organisations see more opportunities for solutions landward of the dike. Finally, we pointed out that high marshes in a late-successional stage are most beneficial for flood safety, while young pioneer marshes have the most value for nature. The differences emphasise the need to create wide foreshores with low and high marshes being present, as they serve both goals and are more sustainable.

Who should be the responsible manager of the marshes?

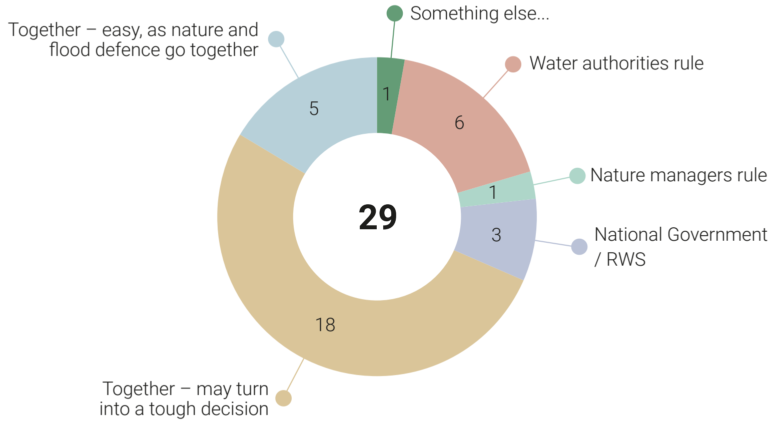
We further discussed who should be responsible for managing the foreshores. Regional water authorities would prefer to be responsible because they are also responsible for flood safety, a primary requirement for the Netherlands. The department of Rijkswaterstaat prefers responsibility at the national level because the Wadden Sea is a national heritage, and local measures may have effects that go beyond the local scale. The nature organisations prefer a joined management responsibility to ascertain that the management will serve more than flood safety. An important remark from the contractors building dikes was that the management should be shaped realistically concerning long-term (maintenance) contracts.

Nowadays, contracts are increasingly asking to offer construction and maintenance. If vegetated foreshores are part of the flood defence system, the management should allow maintenance works within the contracts.

Which kind of monitoring would be needed?

Inspired by the presentations, we discussed which monitoring strategies would be effective. Concerning the need to measure infragravity waves, opinions were split. On the one hand, participants noted that the uncertainties are small compared to the uncertainties in other dike-failure mechanisms, while the measurements are relatively expensive and with limited expertise available to interpret such infragravity wave data. The existing data sets of wave-boys should be analysed better. On the other hand, most participants like the basic concept that measuring equals knowing. Suppose there will be measurements to be done on infragravity waves. In that case, measurements should cover at least two locations: an area where infragravity waves are expected to be dominant versus an area where infragravity waves are expected to be unimportant based on present knowledge. Currently, the Multi-year Fieldmeasurements project in the Eems-Dollard is running, where at two locations (Uithuizerwad and the Double Dike) the wave conditions are measured in front of the dike, including infragravity waves, and wave overtopping is measured in the dike.

The participants were more positive about continuing the explicit spatial measurements of wave run-up using flotsam. It was noted that there is no need to measure continuously but that there needs to be a protocol to measure immediately following the rare major storms with large surges.



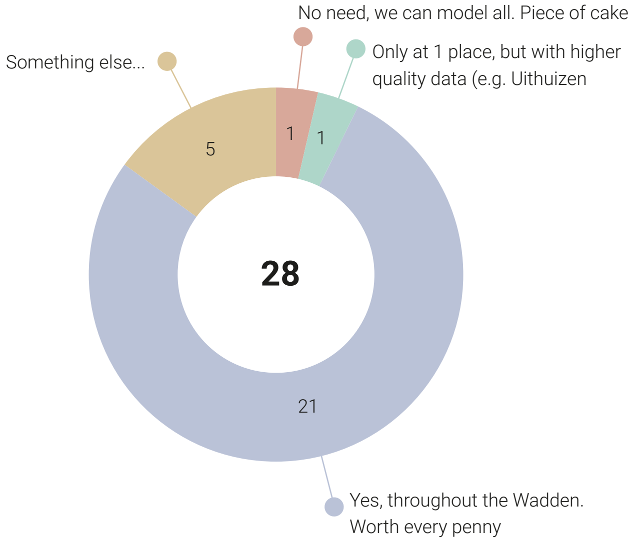
Participant responses to the question who should ultimately decide on foreshore management?

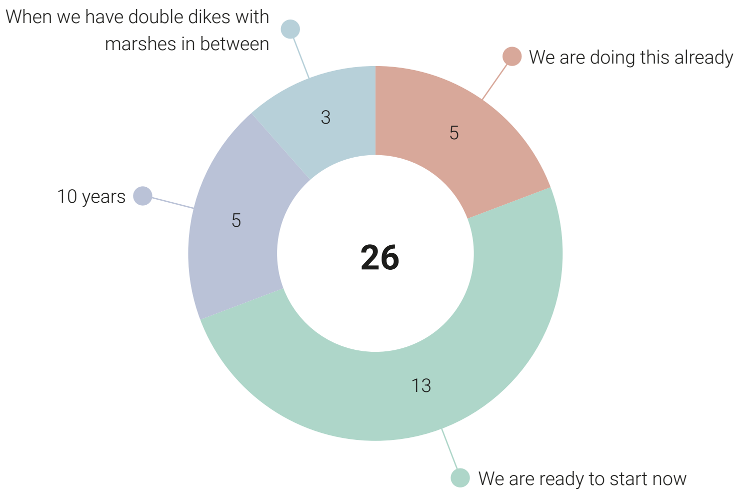
Alternative measuring methods should be explored to enable more frequent monitoring. This alternative resulted in a lively discussion among participants from water authorities. The bottom line seems that we all think there is a need for measurements as a knowledge base. However, protocols need to be standardised as much as possible across all parties involved.

Where are the knowledge gaps?

Finally, we discussed if there are still major knowledge gaps hampering making designs and implementing foreshores in flood defence. It seems that there is sufficient knowledge to apply vegetated foreshores. The participants indicated that they had started or were ready to start. The most important remaining gap seems to be a lack of measurements on the efficiency in wave attenuation during superstorms and the long-term stability of salt marshes.

Nature managers emphasised that they prefer double dike solutions with transitional polders above seaward solutions to preserve the valuable intertidal flats currently fronting the dikes. Given their protected status under EU





Towards a bright future: keep measuring to learn (top) but start application now (bottom). Participant responses to the questions - **Top:** Would it be useful to continue wave and floatsam measurements along the whole Wadden Coast to reduce uncertainties in wave attenuation? **Bottom:** How long will it take before we can actively design foreshores as part of our coastal defence scheme?

law, seaward solutions seem difficult to realise. However, coastal protection is strongly based on Dutch law, so that tailor-made solutions may be necessary. Despite the sometimes opposing visions, there are especially opportunities to explore joined interests towards an applicable solution.

The main overarching outcome was that using vegetated foreshores for flood safety may be challenging. However, they offer promising opportunities for all partners to achieve (partly) both flood defence and nature goals and hence offer a perspective towards nature-based solutions. Implementation requires in-depth knowledge of the system. Thereby, we can get the vegetated foreshores where needed and manage them in a way that benefits both nature and flood safety.

All-Risk recommendations:

- Using vegetated foreshores (marshes) for flood safety offers many opportunities and raises questions about who should be in charge of managing them. It would be worthwhile to initiate pilots to enable learning by doing shared management.
- Invest in spatial-explicit measurements of wave attenuation and wave run-up along the whole Wadden Sea coast. These measurements should include areas with and without vegetated foreshores focusing on the rare large (super)storms.
- Important to keep studying (1) how to construct marshes at wave-exposed areas and (2) which processes drive the long-term lateral dynamics of marshes.
- Seaward solutions are not applicable everywhere. Therefore, it is essential to start gaining a solid knowledge base on landward solutions, such as using transitional polders between double dikes.

Cover layer investigation with Ground Penetrating Radar (GPR) at De Gijster dike in the National Park Biesbosch. Photo by Juan Chavez Olalla.

Chapter 4
Subsurface Heterogeneity

Introduction

By Hans Middelkoop

Several failure mechanisms of dikes are related to the subsoil subsurface. Piping underneath a dike is directly dependent on the lithology and characteristics of the subsurface material, which controls groundwater flow and the potential formation of pipes. Other mechanisms, such as sliding on the dike slope, are primarily related to local groundwater conditions and changing pore pressures in the dike body that arise during flood stages. Furthermore, the formation of deep scours in the river channel may indirectly threaten the channel bank and dike stability, particularly where the channel is directly bordering the dike. Clearly, models used for dike stability assessment require information on the subsurface characteristics, which have great spatial heterogeneity.

Too-simplified estimates of 'average' subsurface properties, may end up in overly-large design standards whereas detailed local investigation of substrate characteristics is expensive.

The project "Subsurface Heterogeneity" aims to support risk assessments through improved assessment of the heterogeneity of the subsurface structure and material, by linking this subsurface heterogeneity with dike body buildup in modelling, and by deploying novel geophysical survey methods.

In project C1, Bas Knaake converted knowledge on the natural development of the Rhine-Meuse delta to 3D models of the subsurface and relevant material properties. He identified critical subsurface conditions for channel scour, and determined where channel banks may be susceptible to flow sliding. By combining these findings with critical subsurface characteristics for piping, he obtained a delta-scale overview of the influence of the subsurface on dike failure potential.

Teun van Woerkom determined in project C2 the relative importance of dike geometry, drainage conditions and material properties in dike failure using a hydro-stability model. He also considered uncertainties in the loading by river floods. He developed a model that reconstructs dike buildup based on dike history, known dike profiles and local core or Cone Penetration Test (CPT) data to obtain more realistic estimates of dike buildup and failure potential.

Juan Chavez explored in project C3 geophysical survey methods to document dike materials and the subsurface beneath dikes. He tested methods based on Electrical Resistivity Tomography (ERT), Frequency Domain Electromagnetics (FDEM), and Ground Penetrating Radar (GPR) data. He used detailed lithological cross-sections determined in the field for testing and validation of statistical methods to convert geophysical signals into physical properties of soils for a given geological setting.

Our results lead to three key recommendations for practice. Firstly, knowledge of the natural development of the Rhine-Meuse delta provides valuable insights into the expected variability of subsurface properties for flood risk assessments. Still, local variability within sediment types remains large, preventing direct prediction of material properties. This information supports efficient coring and CPT surveys to focus on critical dike stretches.

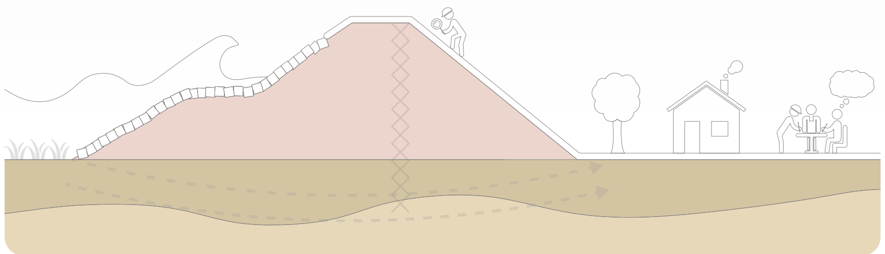
Secondly, improved process understanding of groundwater flow underneath and within river dikes substantially improves estimates of pressure conditions during river flood stages by considering the heterogeneity and layering of river dike material and the changing river water levels during a flood wave. Combining historical information on dike-strengthening with on-site core data can substantially improve local dike buildup schematisation for failure risk assessments.

Thirdly, geological architecture can be captured in geophysical data. The level of detail is smaller than that of CPTs, but the horizontal coverage is larger and continuous. Studying the patterns in geophysical data makes it possible to describe geological architecture more extensively. In particular, it allows localising small lithological anomalies that cannot be detected from the surface or in CPT transects.

Project Summary

C1 - Subsurface-related dike failure mechanisms

Quantitative assessment of subsurface architecture and variability for better estimations of dike failure mechanisms



By Bas Knaake

Utrecht University

Project start: 12/2017
Project end: 11/2021

Promotors

Prof. dr. H. Middelkoop
Utrecht University

Dr. K.M. Cohen
Utrecht University

Prof. dr. E. Stouthamer
Utrecht University

Outcome

The output of this project is better quantitative assessments of regional and local variability within different types of deposits (i.e. architectural elements) via critical subsurface characteristics. Overall, the subsurface architecture and associated sediment deposition conditions in which these elements form play an important role in, for example, scour holes or flow slide locations in the river channel nearby the dikes of the Rhine-Meuse delta. Relevant geotechnical properties show considerable local-scale differences leading to critical subsurface characteristics. These critical characteristics can be implemented within the subsurface schematisation for risk assessments to estimate more realistic parameters and reduce related uncertainties. Furthermore, this

Figure 1: Fieldwork and subsurface data retrieval. Photo by Bas Knaake.

knowledge supports better allocation of resources for data surveys focusing on critical dike sections for failure mechanisms.

Motivation and practical challenge

Several dike failure mechanisms are related to the subsurface buildup, which shows a great spatial variability (**see photos in Figure 1 and 2**). However, current risk assessments rely on oversimplified subsurface properties. Owing to its depositional history, the subsurface shows systematic patterns. Geologic characterisations and reconstructions can provide important contextual information to reduce uncertainties in subsurface parameter estimates.

As earth scientists, we study sedimentology and the genetic history of the subsurface and associated processes. This project offers a great opportunity to integrate this knowledge to understand how the subsurface spatial distribution is related to several river channel and bank failure mechanisms, which may indirectly threaten dike stability, particularly where the dike is directly bordering the river channel. This additional knowledge provides important insights into the geologic boundary conditions and relevant properties that are also relevant when designing flood defences.

Research challenge

This project integrates existing information and knowledge on the subsurface characteristics of the Rhine-Meuse delta in the Netherlands and relates that to failure mechanisms of river dikes or embankments.

Innovative components

Our research focuses on past occurrences of failure mechanisms such as (1) channel scour and (2) channel bank failure (**Figure 2, left**). We

Figure 2: Fieldwork and subsurface data retrieval which is primary input for subsurface characterisations and reconstructions. Photos by Bas Knaake.

particularly focus on the relation with subsurface architecture elements such as the former river channels (**Figure 2, middle**). This project assessed channel scour locations for all the major river branches of the Rhine-Meuse delta (**Figure 2, right**). For bank failures, we made use of an extensive historical database.

We compared locations where channel scours occur to existing geological mappings, such as locations of former river channels. Furthermore, we used 3D subsurface models of the TNO-Geological survey (https://dinoloket.nl) to map the regional and local buildup of the subsurface. These comparisons give important insight into critical subsurface characteristics for a failure mechanism.

Next, we focused on characterising deposits and the geotechnical properties for different architectural elements such as fluvial channel belts. These characterisations help better predict the potential risk areas for a failure mechanism, leading to a more efficient design of flood defences.

Relevant for whom and where?

The history and origin of the subsurface can help advisors and management organisations identify potential risk areas for a failure mechanism when planning or implementing river measures such as dike reinforcements.

Progress and practical application

The results show that scour holes in the Rhine-Meuse delta have a clear link with subsurface architecture and associated depositional history. The downstream area is characterised by high variability in erodible and non-erodible materials. As a result, a sharp increase in scour hole frequency is observed. This relation is especially clear for the Dordtsche Kil branch, near the city of Dordrecht, where subsurface architecture strongly influences the river bathymetry. Due to its depositional history, the northern part of the Dordtsche Kil branch is characterised by an erosion-resistant, stiff clay layer that is locally dissected by former river channels. Instead, the southern part consists of much more homogeneous sand. Resulting from this subsurface architecture, the bathymetry of the northern part of the Dordtsche Kil branch is characterised by local scour holes, and the southern part is much more homogeneous in depth. For details on the results, see the project outputs on the next page.

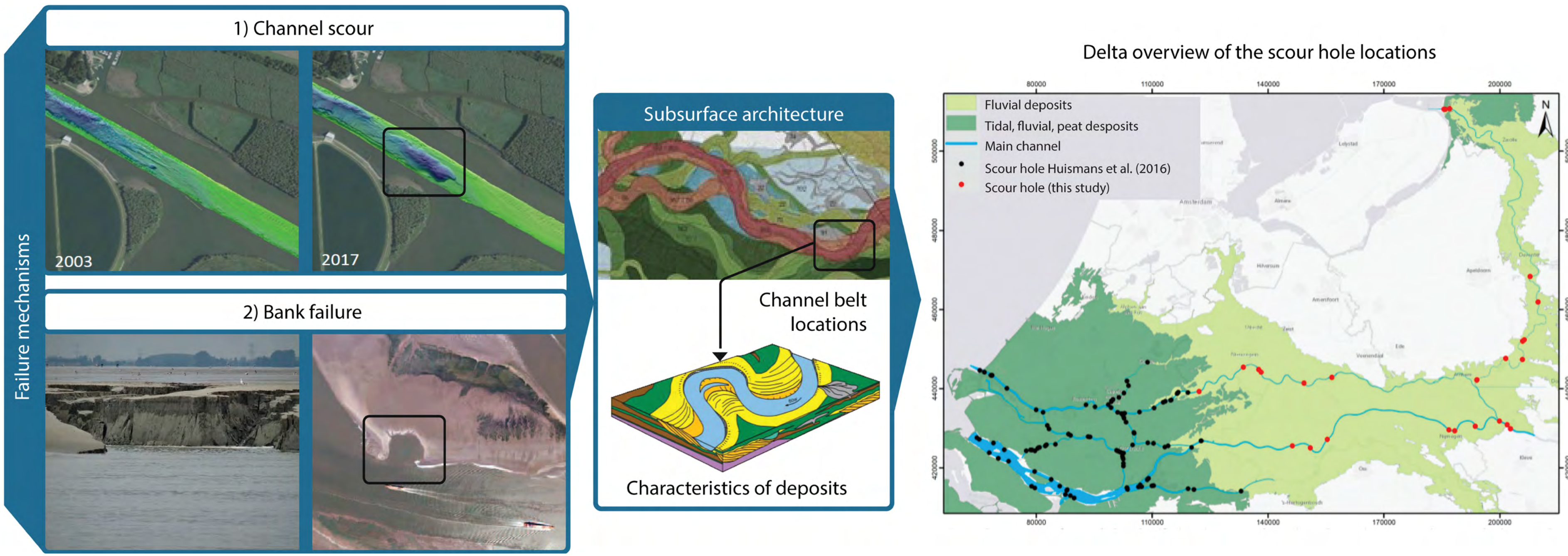


Figure 3: Main components of the research. Photos bank failure by Deltares, middle-figure by Kim Cohen and right figure adapted from Gouw (2017). Overview map from Huismans et al. (2016) and Knaake et al. (2019).

Recommendations for practice

- Incorporate genetic knowledge (i.e. architectural elements) of the subsurface to adopt a more regional approach for more realistic parameter estimates making risk assessments less sensitive to potential outliers within local subsurface data.
- Focus on the good parameterisation (i.e. realistic parameter estimates) of architectural elements for risk assessments.
- Use prior subsurface knowledge for better streamlining data acquisition by focusing field surveys on the more critical areas.

This project assessed the major river branches of the Rhine-Meuse delta until the Western Scheldt. On the map an example from the progress results, the Dordtsche Kil branch (near the city of Dordrecht), is highlighted.

Dordtse Kil 'vluchthaven' looking towards the city of Dordrecht. Photo by Rijkswaterstaat, beeldbank.rws.nl / Joop van Houdt.

Key project outputs

Cox, J.R., Huismans, Y., Knaake, S.M., Leuven, J.R.F.W., Vellinga, N.E., van der Vegt, M., Hoitink, A.J.F. & Kleinhans, M.G. (2021). Anthropogenic Effects on the Contemporary Sediment Budget of the Lower Rhine-Meuse Delta Channel Network. Doi: 10.1029/2020EF001869

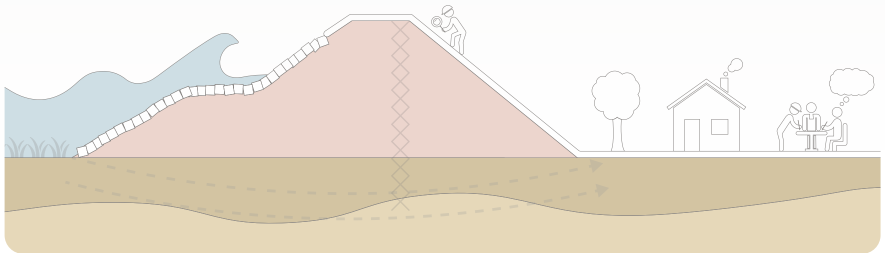
Winkels, T.G., Cohen, K.M., Knaake, S.M., Middelkoop, H. & Stouthamer, E. (2021). Geological framework for assessing variability in subsurface piping parameters underneath dikes in the Rhine-Meuse delta, the Netherlands. Doi: 10.1016/j.enggeo.2021.106362

Knaake, S.M., Straatsma, M.W., Huismans, Y., Cohen, K.M., Stouthamer, E. & Middelkoop, H. (in review). The influence of subsurface architecture on scour hole development in the Rhine-Meuse delta, the Netherlands.

Project Summary

C2 - Groundwater-related dike safety

Assessment of subsurface material, groundwater conditions and dike slope stability considering spatial and temporal variability



By Teun van Woerkom

Utrecht University

Project start: 09/2018

Project end: 09/2022

Promotors

Prof. dr. ir. M.F.P Bierkens

Utrecht University

Dr. L.P.H. van Beek

Utrecht University

Prof. dr. H. Middelkoop

Utrecht University

Outcome

The outputs of this project are a better understanding of groundwater flow through and around river dikes and improved methods for estimating groundwater levels under high river water levels. We developed methods estimating groundwater flow embedded in modelling instead of analytical estimations, using for example a hydro-stability model which can substantially improve groundwater predictions near river dikes. With the improved methods, we give examples on how to include big data in the dike safety assessment, historical dike buildup, and phreatic groundwater because of variable river water levels.

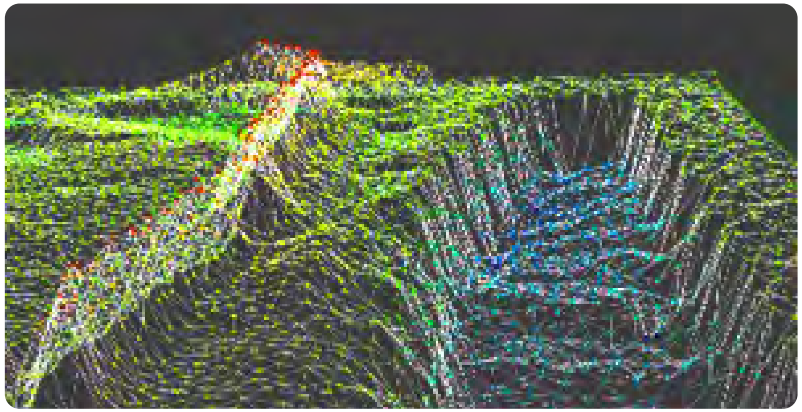


Figure 1: Relative importance of dike geometry, drainage conditions and material properties in dike failure using a hydro-stability model. Image by Teun van Woerkom.

Motivation and practical challenge

In the Netherlands, a country in which history is intertwined with flood safety, we know the large impact high water levels on rivers can have in breaching the dikes. In contrast, the impact of high-water levels on groundwater flow is less understood and recognised by both water authorities and residents, as it is often not a visible thread. Yet, as the river presses more water through the subsoil, ditches are filled up on the landward side of the dikes, and fields on this side may get wet without having a river flood (**Figure 2, top**).

Groundwater flow and high pore pressures are very important for various failure mechanisms of dikes, including piping and slope instability. Of course, the effect of groundwater is strongly linked to the highly variable subsoil material. Due to the limited knowledge and data availability about the subsoil, the groundwater influence is oversimplified for flood safety estimations. Moreover, as the process occurs underground, visualisation is difficult and field data for validation is important yet scarce (**Figure 2, bottom**).

Figure 2: **Top:** Seepage through the dike and the subsoil (Photo by Waterschap Rivierenland). **Bottom:** Tube that is placed in the soil to measure the groundwater (Photo by Waterschap Brabantse Delta) and fieldwork for data collection (Photo by Bas van der Meulen).

Research challenge

To increase the knowledge of the relation between subsoil, river water level and groundwater conditions, and to introduce more realistic groundwater scenarios to dike stability calculations.

Innovative components

Given that the current schematisation of groundwater in dike assessments is simplified, my research focuses on the temporal and spatial components of groundwater-related dike stability. Amongst these are:

1. **Flood wave shape** is highly variable, but dike designs are created using a single characteristic flood event. This investigation shows that the hydrology in the dike and the subsoil strongly differs between flood waves, questioning the current practice of designing flood waves.
2. **Establishing relations** between material characteristics, groundwater hydrology and dike stability. Via many runs of a coupled groundwater and dike stability computer model, the aim is to find the most important factors influencing the dike stability and groundwater

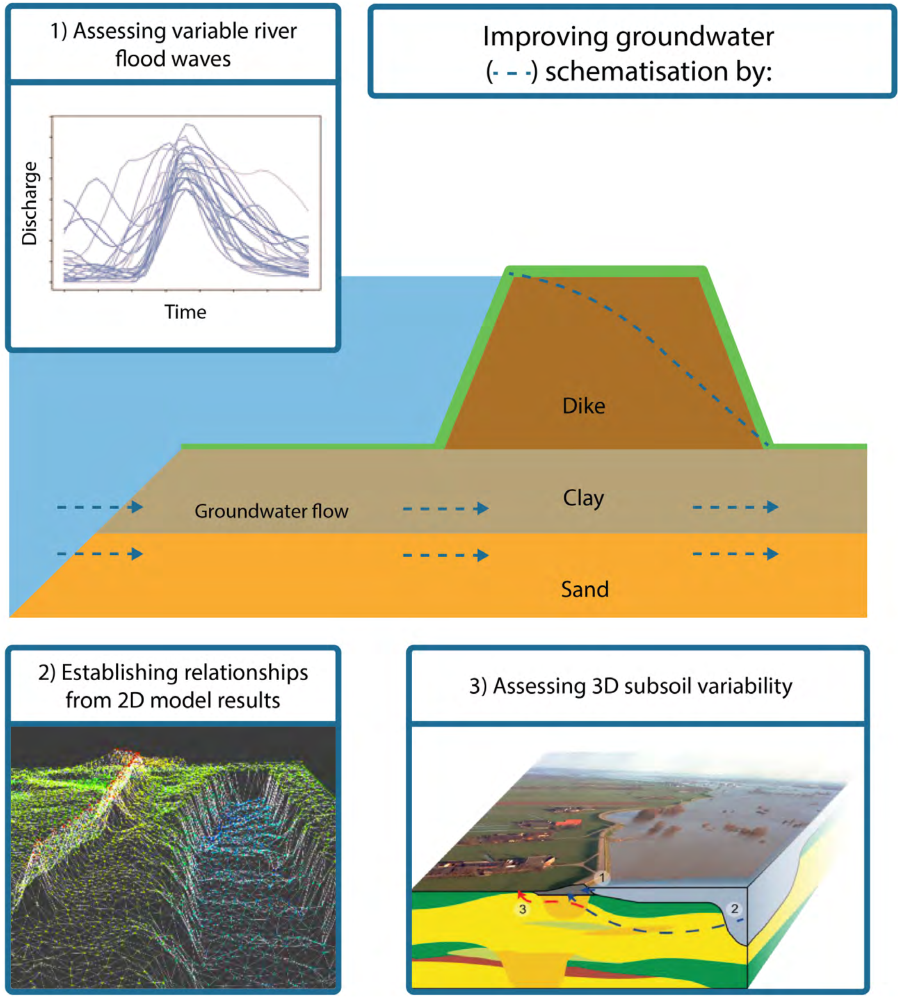


Figure 3: Main components of the research to improve the groundwater schematisation for the dike stability estimations. Based on schemes from Teun van Woerkom.

conditions. The results are compared against stability calculations of a river dike to prove the applicability of these relationships as a first-order screening tool for dike safety.

3. **Assessing subsurface variability in 3D** has been common practice in geological settings, but its use in dike safety assessment (and the related groundwater hydrology) has been limited so far. This section focuses on determining differences between 2D and 3D modelling, suggesting better ways of parameterising 3D effects.

Relevant for whom and where?

Researchers working on the interface of earth sciences and civil engineering. Innovative organisations wanting to use the latest knowledge on underlying processes related to river dike safety.

Progress and practical application

More dynamic groundwater calculations showed that the most influential parameters of dike stability are: (1) variations in pore pressures, (2) the geometry and material of the dike and (3) material properties of the subsoil.

Dike heterogeneity because of historical dike enforcements greatly influences pore pressures in the dike. A method has been developed to create possible dike buildup scenarios, which result in different pore pressures. By assessing multiple scenarios of dike buildup and pore pressures, a probabilistic analysis of groundwater conditions can be performed.

A full probabilistic analysis should also include dynamic pore pressures as a function of dynamic river water levels. The use of time-dependent groundwater conditions causes a substantial lowering in dike failure probability compared to static groundwater levels. For details on the results, see the project outputs below.

Last but not least, the historical dike near Nijmegen-Lent was used as a benchmark on how to estimate dike heterogeneity by simulating its construction history. This case study demonstrates that archaeological observations can increase the data availability of historical dikes and improve simulations of dike interior variability.

Recommendations for practice

- Use model simulations with realistic subsurface and dike buildup scenarios for groundwater level estimation.
- Use time-dependent groundwater conditions that exist because of variable river water levels to provide a more realistic estimation than static groundwater conditions.
- It is important for river dike phreatic level schematisation to incorporate variability in river dike material.

Key project outputs

van Woerkom, T.A.A., van Beek, L.P.H., Middelkoop, H. & Bierkens, M.F.P. (2021). Global Sensitivity Analysis of Groundwater Related Dike Stability under Extreme Loading Conditions. Doi: 10.3390/w13213041

van Woerkom, T.A.A, van Beek, L.P.H., Middelkoop, H., Bierkens, M.F.P. (2020, February 13-14). A coupled hydro-stability model for a sensitivity analysis on dike stability.

van Woerkom, T.A.A, van Beek, L.P.H., Middelkoop, H., Bierkens, M.F.P. (2020, March 12-13). Sensitivity analysis of river dike macro-stability: It's just hydro-logic!

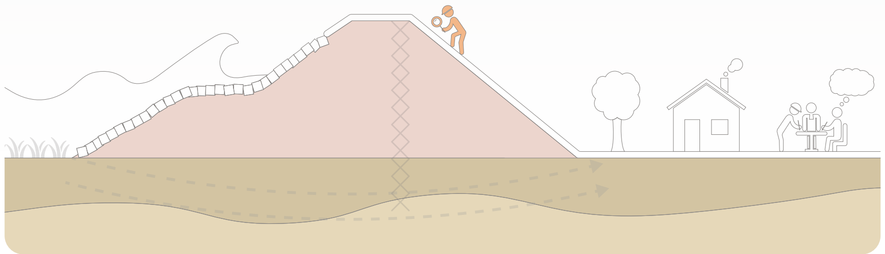
Findings of this research will be applicable to dike reinforcement projects in the Netherlands.

Current impression of the bypass near Nijmegen-Lent, with the old river dike still visible in between the two river branches. Photo by DaMatrix from Wikimedia Commons, CC BY-SA 4.0.

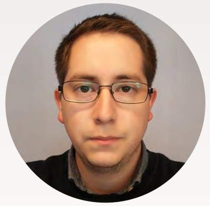
Project Summary

C3 - Geophysical measurements of the subsoil

Guidance for better mapping the horizontal variability of the subsoil



By Juan Chavez Olalla
Delft University of Technology



Project start: 09/2017
Project end: 09/2021

Promotors

Prof. dr. ir. T.J. Heimovaara
Delft University of Technology

Dr. R. Ghose
Delft University of Technology

Dr. D.J.M. Ngan-Tillard
Delft University of Technology

Outcome

The goal of this project was to develop statistical methods to incorporate geophysics into the characterisation of subsoil heterogeneity. The aspects of heterogeneity that have been addressed are the geometry of soil layers and the variability of material properties at small and large scale. The outcome of this project is guidance for better mapping the horizontal variability of the subsoil.

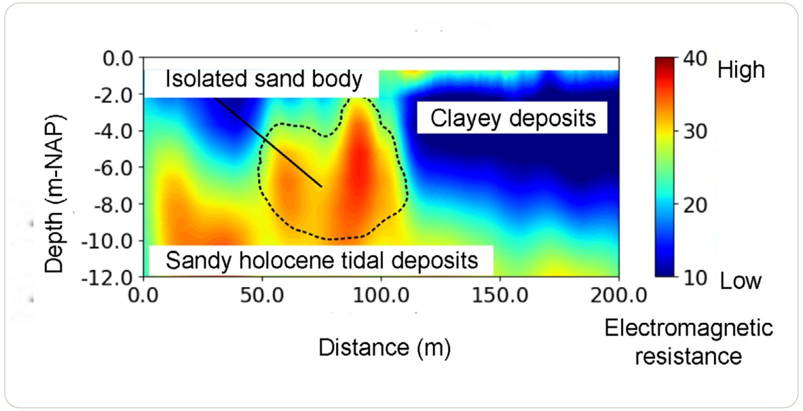


Figure 1: Paleochannel detection with electrical resistivity tomography. Image by Juan Chavez Olalla.

Motivation and practical challenge

Traditional site investigation methods measure the horizontal variability of the subsoil often insufficiently. As a result, geophysical methods are becoming increasingly popular for engineering applications such as dikes and roads because they map the subsoil in a horizontally continuous manner. However, the operational effort required by many geophysical methods does not always pay off. Expectations are, in some cases, beyond the physical limits of the methods. The practical challenge is, therefore, to find the scale of heterogeneity that geophysical methods can resolve which at the same time gives valuable information for geotechnical calculations.

Research challenge

I formulate methods to answer the question: how to incorporate geophysical data for better mapping the subsoil variability? Specifically, I work on uncertainties related to the geometry of soil layers and material properties.

Innovative components

I look at the type of subsoil variability that plays a role in failure mechanisms of dikes (**Figure 3, top-left**). For example, in clay-over-sand dikes, the thickness of the clay layer on the landward side provides resistance against piping (**Figure 3, top-right**). Dikes are longitudinal structures, so it is challenging to map variability with point data, such as cone penetration tests (CPTs). One component of my research is to study the geometrical variability of layers with geophysical methods (**Figure 3, bottom**). I pay special attention to electromagnetic methods that quickly cover large distances such as Electrical Resistivity Tomography (ERT), Frequency Domain Electromagnetics (FDEM), and Ground Penetrating Radar (GPR) data. The innovative aspect is the statistical combination

Figure 2: Geophysical survey in dikes and associated instrumentation. Photos by Juan Chavez Olalla.

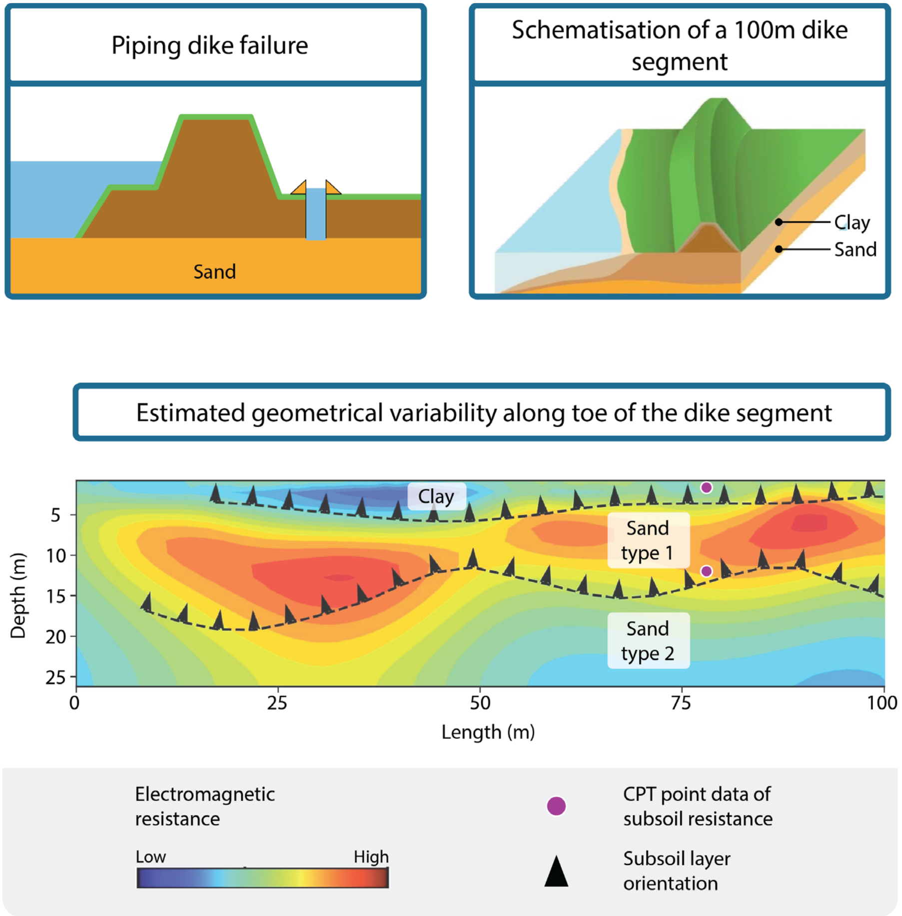


Figure 3: Combination of geophysical data and point data measurements to improve the schematisation of the subsoil below the dikes. Sources: left figure adapted from van Beek (2015), right figure based on scheme from Richard Marijnissen and bottom figure provided by Juan Chavez Olalla.

of geophysical data and point data. Previous approaches use only point data, so they do not explicitly consider the geometrical variability between data points. Another component of this research is related to more elaborate geophysical methods, such as seismic exploration, which require large operational efforts. I study the cases where these methods could bring useful information for geological schematisation.

Relevant for whom and where?

The output of this research is relevant for advisors who assess dike safety where horizontal variability of geological layers is uncertain.

Progress and practical application

Preliminary surveys in test sites show that geological architecture is captured in geophysical data. The level of detail with which it is captured is smaller than that of cone penetration tests. However, the horizontal coverage is larger. By studying the patterns in geophysical data, it is possible to describe more extensively geological architecture. An approach to combine geological knowledge, point data and geophysics is formulated in this research. Part of this approach is aimed at retrieving geometrical variability from tomograms. Another part of this approach is aimed at correlating geophysical and geotechnical properties. For example, electrical resistivity is highly correlated to the cone resistance of a cone penetration test. For details on the results, **see the project outputs on the next page**.

Recommendations for practice

- Use a sequential approach to geophysical investigation from coarse detail (cheap and fast) to fine detail (expensive and slow).
- Interpret geophysical data within a bigger geological context.
- Interpret geophysical data in a consistent and reproducible manner.
- Define the target geological features to be mapped with geophysics before surveying.
- Establish quantitative relationships between geophysical and geotechnical properties.

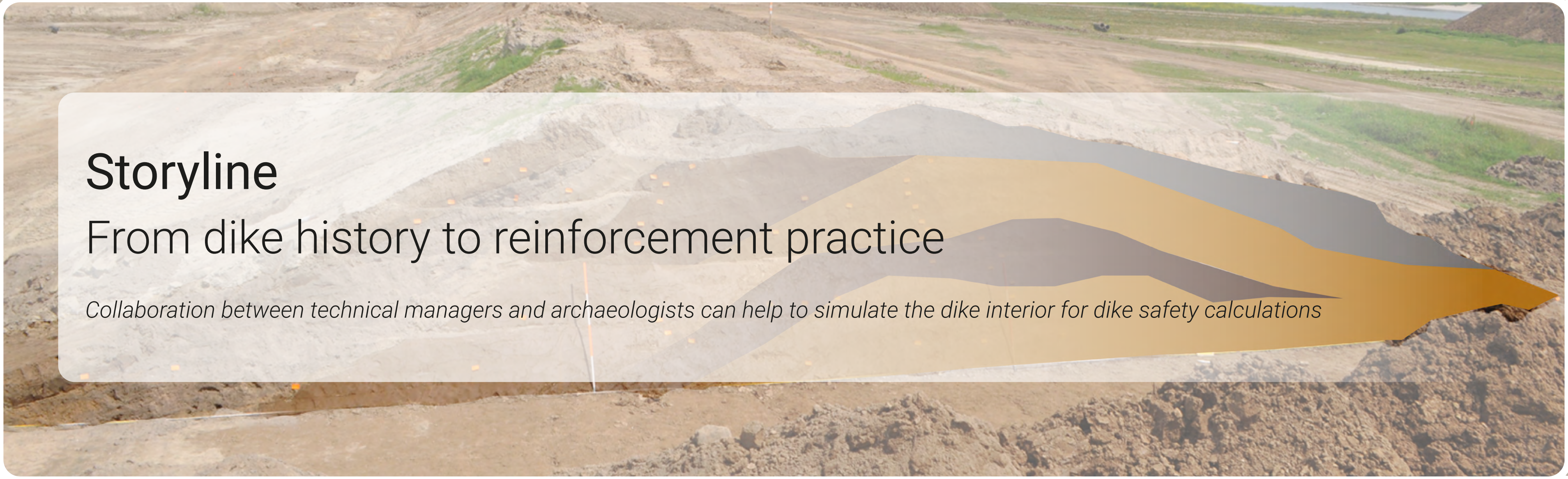
Key project outputs

Chavez Olalla, J., Winkels, T.G., Ngan-Tillard, D.J.M. & Heimovaara, T.J. (2021). Geophysical tomography as a tool to estimate the geometry of soil layers: Relevance for the reliability assessment of dikes. Doi: 10.1080/17499518.2021.1971252

Chavez Olalla, J. (2020) Layer interpolation with tomographic aid. Athens, Third European Regional Conference of IAEG, 20-24 September 2020.

Montfoort: Testing geophysical methods to map a large paleochannel (with Physical Geography group Utrecht University).
Small paleochannel: map paleochannels that are difficult to map with conventional site investigation methods.
Leendert de Boespolder: Calculating the horizontal correlation structure of geotechnical properties with geophysical tomography.

Image by Juan Chavez Olalla.



Storyline

From dike history to reinforcement practice

Collaboration between technical managers and archaeologists can help to simulate the dike interior for dike safety calculations

By Teun van Woerkom
Utrecht University

Throughout the centuries most river dikes in the Netherlands have been reinforced multiple times, which has resulted in highly variable dike interiors. Dike interior material and its variability is an important factor in dike safety calculations. Archeological observations can increase the data availability of historical dikes and improve simulations of dike interior variability.

As an All-Risk researcher at the Utrecht University, most of my work so far has focused on simulating groundwater flow through the natural subsoil that is naturally composed of several layers below the dikes. However, when a colleague showed me an image of his archaeological investigation of a dike related to a reinforcement project, I was just as surprised as he was: Several distinct layers of different material types were visible. The many layers of the dike interior shouldn't have come as a surprise, as I knew many river dikes in the Netherlands have a long history. Throughout their existence, the river dikes were heightened and widened at many occasions. At each enforcement, new soil was added consisting of (slightly) different material, making the current river dike very variable (as can be seen on the images on the next page).

Cover photo: Different material layers of a historical dike. Image adapted from Rondags (2019).

Dike safety assessments ignore historical dike variability

The dike reinforcement practice acknowledges that the dike material is an important aspect for dike stability, but it is mostly oversimplified and assumed to be homogeneous, while the real dike likely consists of many different materials in layers of variable thickness. This assumption may induce errors in dike safety calculations, which may lead to dangerous situations, especially when considering that climate change may increase the river water levels. This problem resulted in the following question:

"Could we simulate dike variability at locations where we do not have an archeological record, to better inform current dike reinforcement practices?"

Levels of flood safety in the Netherlands

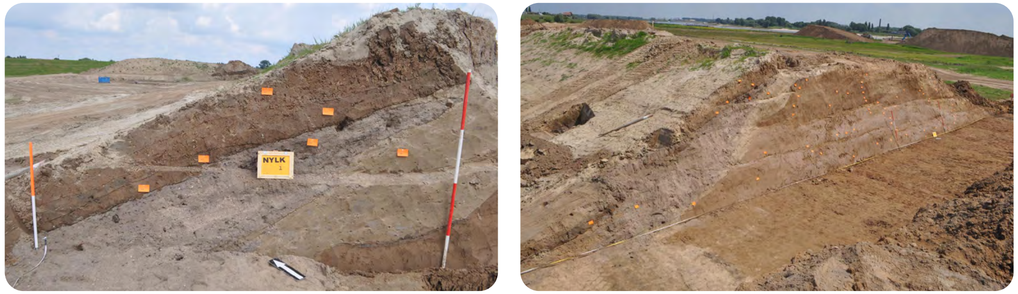
The new dike flood safety standards limit the probability of dike failure to once every 30,000 years, at for example the Grebbedijk. To calculate the safety of a dike with such precision, an accurate determination of dike properties is important. Incorporating historical data of river dike construction in the safety estimation can thus be useful. Yet, this historical data is not available at every location and when available it is not easily accessible.

Historical dike cross-sections in the Netherlands

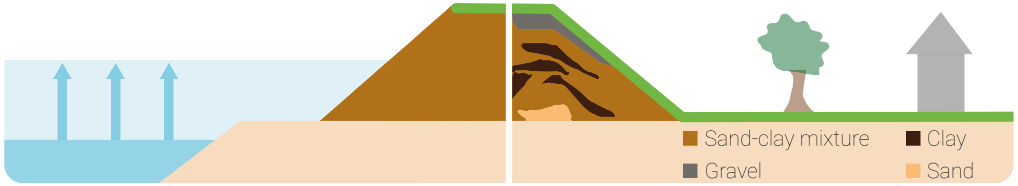
By reviewing multiple sources with dike historical data, I found 106 locations in the Netherlands where archaeological records reported dike construction materials. The map shows this new dataset with all the 106 locations, 47 (greyish points) contained historical dike cross-sections and only 12 (darkest grey points) included a detailed geometry and descriptions of the material that past enforcements were made with.

Age of the river dikes in the Netherlands

However, these locations are not the only places where historical river

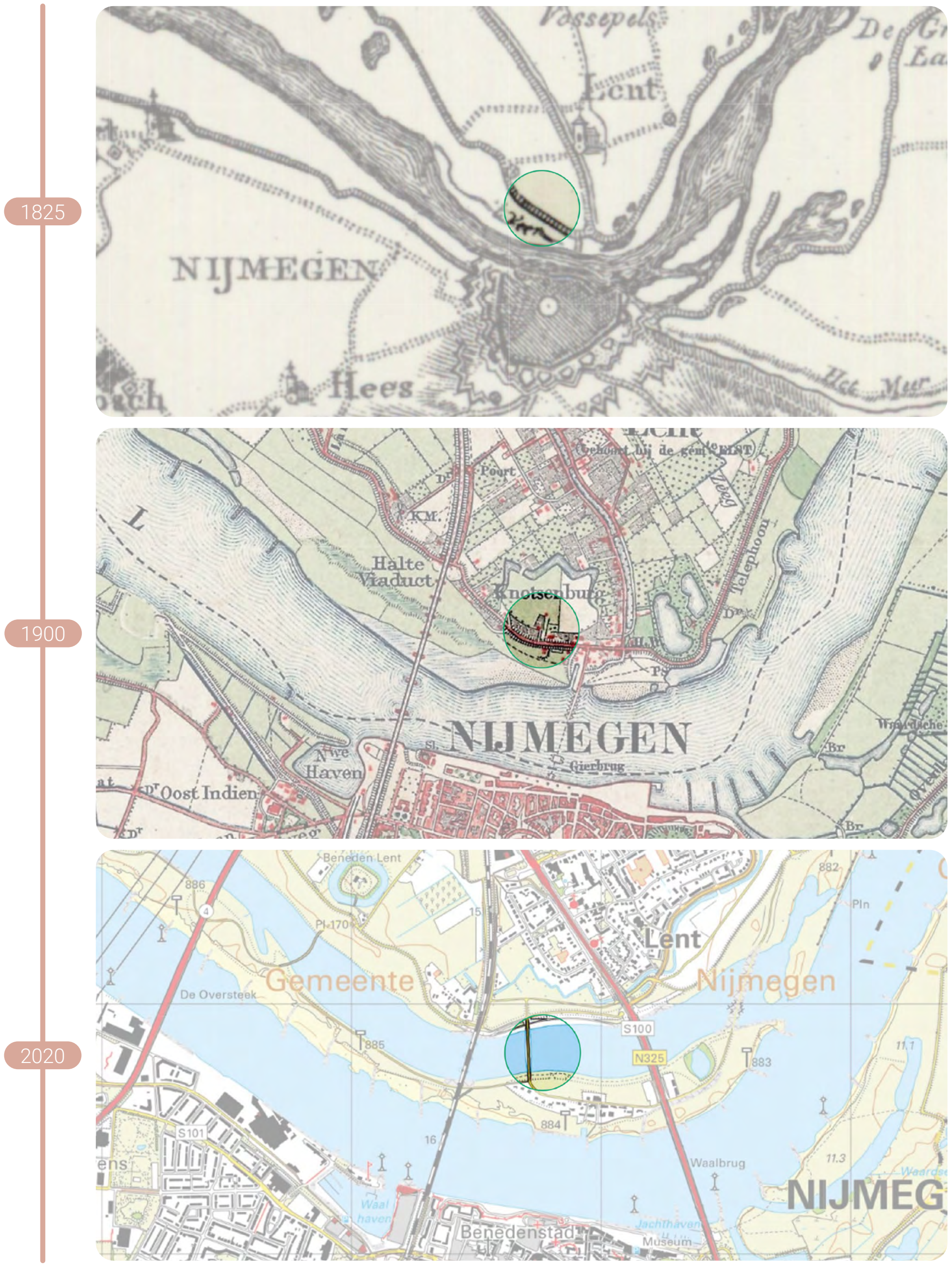


Images of a historical dike, which clearly consists of many different layers of various material types. Photos from Rondags (2019).



A homogeneous vs a variable dike interior providing flood safety under increasing river water levels. Based on schemes from Teun van Woerkom.

Map imagery by Esri, (IHO-IOC) GEBCO, DeLorme, NaturalVue, NGS. Dike ages from Nationaal Georegister.



Historical maps of the Bemmelsedijk. Based on tiled services from topotijdreis.nl (part of Kadaster).

dikes are still present. Many dikes have outlived several dike reinforcement periods. The second map (on the previous page) shows the age of the oldest construction period of the river dikes.

Early Middle Ages
People start to build dikes near communities, which nevertheless flooded regularly.

From around 1200
Dikes were constructed along all major rivers. The material for dike construction was often extracted by the villagers from open-pit mines in the floodplain next to the dike.

From around 1800
Institutionalisation of dike safety and the emergence of steam engines resulted in large-scale dike reinforcement.

After 1958
The new 'Delta Law' puts dike reinforcements high on the nation's agenda, and methods for dike enforcement are further unified.

Example of a historical river dike: Bemmelsedijk, Nijmegen-Lent.
One of the river dikes that has its origin in the early Middle Ages and has a detailed description in the new dataset is the Bemmelsedijk near Nijmegen-Lent, which has recently been excavated to create a bypass that results in more room for the river Waal.

Historical view of dike location
According to historical reports, the Bemmelsedijk was constructed in 1327 and is thus visible in the earliest topographical map of the

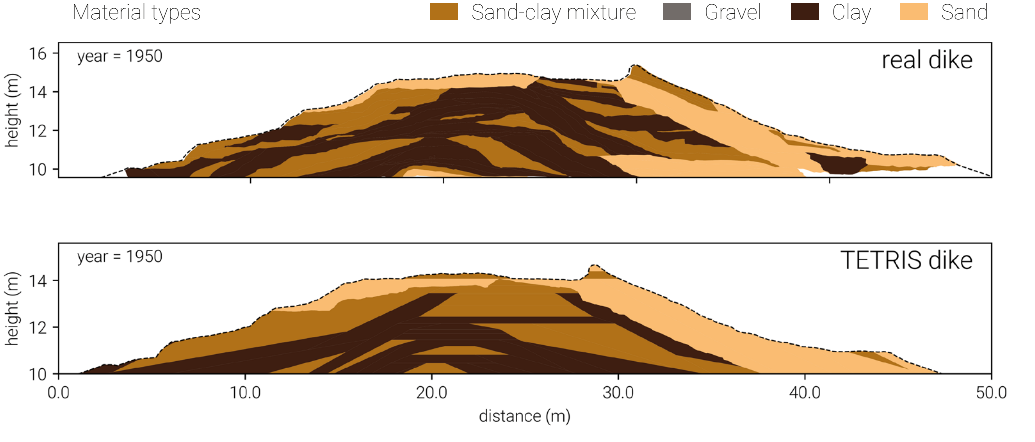
region, dating back to 1815. Travelling forward in time from that year, the dike remains at the same location until its removal in 2015. At many other locations along Dutch rivers, these historical dikes are still standing, which means that the historical dike layers are probably also still present in the current river dike.

Simulating the dike interior variability using the historical dike buildup
To incorporate variable dike interiors in the dike safety assessment, I developed Dike-TETRIS: Typical Embankment Tessellation using Regionally Inherited Statistics. The algorithm uses statistics on historically used material types, reinforcement layer thicknesses and dike surface steepness to construct hypothetical dike cross-sections. Here is a simulation of this TETRIS dike compared with the real construction history of the Bemmelsedijk. The layers in the TETRIS dike pile up following a similar sequence. For nearby river dikes, it might also be possible to simulate the dike interior by looking at the construction history at locations where we do not have an archaeological dike observation.

The opportunities and challenges of dike-TETRIS
The TETRIS algorithm allows to simulate the many layers of the dike interior based on archaeological dike properties. This opens up several opportunities:

- Groundwater simulations can better estimate the evolution of groundwater pressures during high river water levels by considering not only the layers below the dike but also the dike interior.
- Dike slope stability problems can consider non-homogeneous dike interiors and by creating multiple simulations of variable dike interiors, a probabilistic analysis of the dike slope stability can be performed.
- Validating the TETRIS simulations with hydrological, geophysical or geological data can improve the reliability of the simulated

Current impression of the bypass near Nijmegen-Lent, with the old river dike still visible in between the two river branches. Photo by DaMatrix from Wikimedia Commons, CC BY-SA 4.0.



A comparison of the construction history and resulting heterogeneity of an actual river dike (top) and a dike simulated by the TETRIS algorithm. Image by Teun van Woerkom.

TETRIS-dikes.

While the algorithm can accurately recreate the material composition in observed historic dikes, two problems remain:

- The variation in material types and dike history in the Netherlands is high on a small spatial scale, so dikes located 1 km apart may look very different. With the algorithm being very dependent on the observations that it is based on, making predictions of locations where detailed archaeological observations are not close enough lowers the precision of the algorithm.
- Variability in the dike interior is not only a result of different reinforcement periods. Dike breaches, and the rapid filling of the breach with any material available, can also cause interior dike variability.

WHAT IS NEXT?

Technical managers working for the water authorities could already use the TETRIS algorithm to better calculate dike safety. However, the best way to further improve the algorithm is by adding more observations on the river dike interior to the database. These archaeological observations are necessary to make a better estimation of the characteristics at a dike location, which, in turn, improve the TETRIS predictions of nearby dikes. I would encourage any cooperation between specialists in the fields of dike safety and dike history, as they proved to be much more intertwined than previously thought. This cooperation, may in the end lead to much smaller uncertainties in dike safety estimates and thus in safer river dikes all across the Netherlands.

Further reading

Click or scan the QR Code to view the online version of this storyline. Or view:

- A fast geotechnical survey of dike cross-sections (in Dutch). https://www.hwbp.nl/kennisbank/pov-dgg/artikelen/geoscan-en-de-archeologie-van-de-dijk
- Assessing lithological uncertainty in river dikes: Simulating construction history and its implications for flood safety assessment; van Woerkom et al. (in preparation).

Acknowledgements

This work is part of the Perspectief research programme All-Risk with project number P15-21, which is financed by NWO Domain Applied and Engineering Sciences. I thank Maurits van Dijk (technical manager dike reinforcement projects at Regional Water Authority Drents Overijsselse Delta) and Jan-Willem Oudhoff (specialist of dike history at Buro de Brug), colleagues at the Utrecht University, Pien Buter (visual design) and Juliette Cortes (editorial support) from the All-Risk team for their input on this storyline.

Searching for paleochannels with Electrical Resistivity Tomography. Photo by Juan Chavez Olalla.

The theme:
Better use of subsurface information to improve the parameter estimates of models that determine the occurrence of piping, slide flow of channel banks or other failure mechanisms of river dikes.

Would you like to see the presentations of the researchers? You can view them **by clicking or scanning the QR Code.**

Reflection

Better mapping of the subsurface structure

Webinar team

Moderator

Hans Middelkoop

Utrecht University

Introduction

Ane Wiersma

Deltares

Speakers

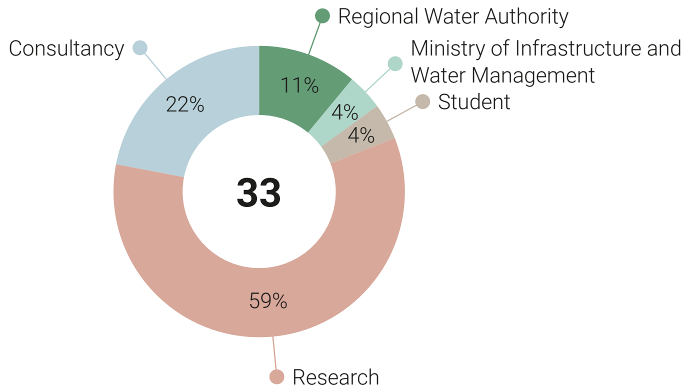
Juan Chavez Olalla

Delft University of Technology

Bas Knaake

Utrecht University

Participants



This reflection emerged from the discussion between researchers and participants during the All-Risk webinar organised on June 2, 2021.

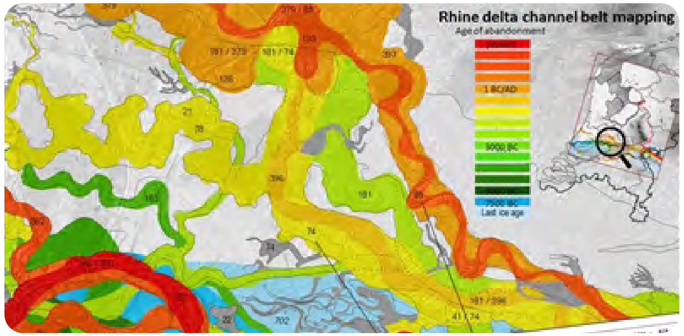
Structure of the subsurface

The structure of the subsurface, the occurrence of sand and clay layers, and the characteristics of permeable sand layers are important preconditions for failure mechanisms of dikes, particularly for piping. The heterogeneity in the subsurface structure of the Rhine-Meuse delta results from the delta's palaeo-geographical development and associated deposition of sediments. We can map this heterogeneity on different spatial scales using various source data. On the coarsest scale, the heterogeneity concerns the location of old rivers' sand bodies across the delta. This information is contained in the GeoTOP data and is well known. On a more detailed scale, the heterogeneity includes local occurrences of sand lenses or other forms of local lithological differences that are difficult to detect. Cone penetration test (CPT) data and corings are now widely applied on this scale. However, these data remain 'point' observations; geophysical methods could provide an important addition here because they provide a full 2D profile of the subsurface structure and material properties. The condition is, of course, that geophysical data can be linked to subsurface properties, for example, by combining CPTs with a few boreholes. Therefore, the key question is, how can we better use subsurface information to improve the parameter estimates of models that determine the occurrence of piping, slide flow of channel banks, or other failure mechanisms of river dikes?

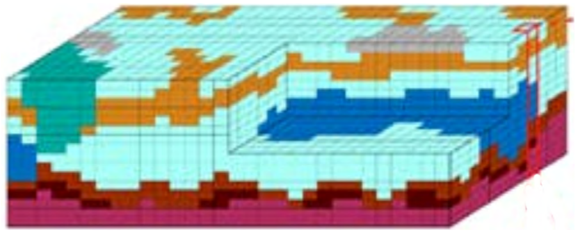
Discussion

What sources of information do we have?

Participants need subsurface information on a spatial scale of several metres in a horizontal direction. In the vertical direction, a much higher (decimetres, dm) resolution is required. As incorporated in GeoTOP, subsurface maps give a good picture of the lateral heterogeneity of the subsurface but give less detail in the vertical direction. Of the currently



Subsurface map



GeoTOP or three dimensional view of the subsurface

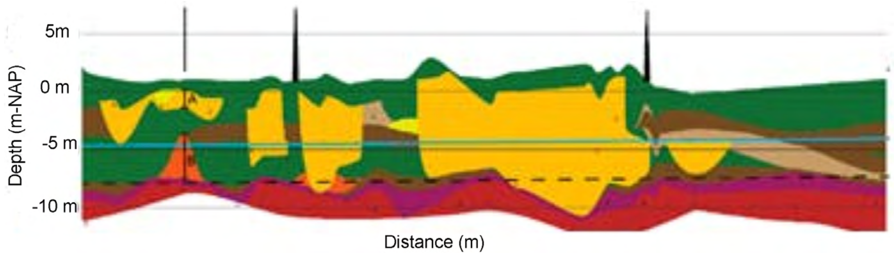
Snapshots of some of the available information to map the subsurface. Images by Geological Survey of the Netherlands | TNO.

available data sources, there is a clear preference for corings and CPTs, with the detailed information from the CPTs being the most important. The cost of coring is significantly higher, core logs sometimes have less vertical detail, and only provide the necessary parameter values for the models after further laboratory analyses.

Combining CPTs with boreholes, supplemented with geophysical profiles, can provide the most spatial detail. Data from the boreholes serve to translate CPT results and geophysical profiles into lithology and parameters for the models. This translation could be done with direct 1-to-1 comparison at the core locations, via simple empirical relationships using data from multiple cores, or more refined (using local neural network techniques). The subsurface maps and GeoTOP can then be used on a larger (> 100 m) scale to determine where the subsurface and its properties must be determined in more detail with local corings, CPTs and geophysical measurements.

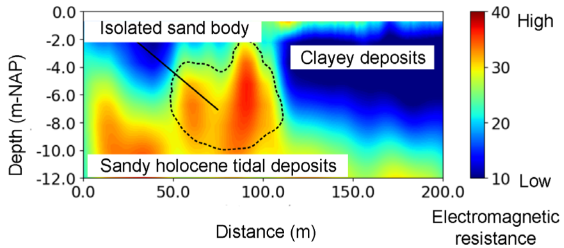
Barriers to implementation?

Participants mentioned several 'technical' barriers to applying this integration of sources in practice. In particular, standardisation of procedures,



Subsoil profiles from borehole data

Cone Penetration Test (CPT) data



Geophysical measurements

Snapshots of some of the available information to map the subsurface. Image left by Juan Chavez Olalla. Image CPT by Geological Survey of the Netherlands | TNO.

with uniform standards and guidelines, and ultimately including them in the Dutch national key registry of the subsurface (BRO)[1], still require several steps to go. In addition, there are also non-technical barriers, including budget considerations, feasibility, experience and education, and acceptance of new methods.

Overall, the biggest challenge is seen in the mismatch between the data requirements and level of detail of current models applied to determine the occurrence of failure mechanisms on the one hand and the availability, resolution and quality of in-situ data from the field.

Conclusions and perspective

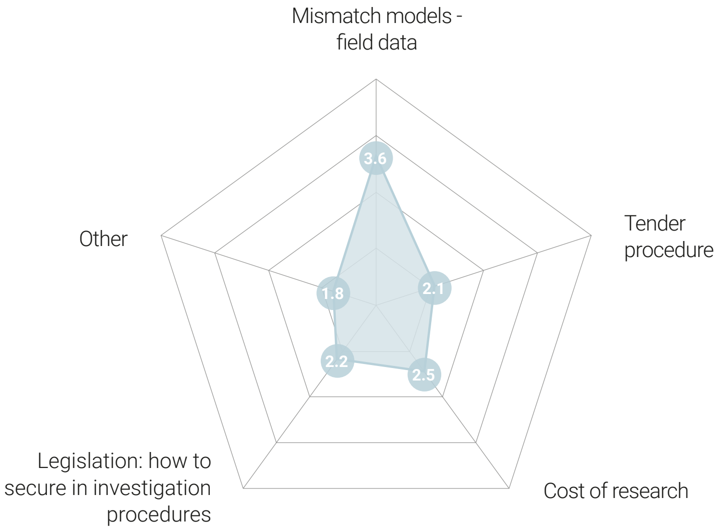
Considerable progress can be made by using a good representation of the subsurface, its structure and properties, as input for models that determine dike failure mechanisms. The gains will lie in detecting critical spots within the subsurface that require further detailed research and reducing the uncertainty of model parameters. 'Large-scale' information such as subsurface maps and GeoTOP can provide a good context for further local investigation. There are good opportunities in combining (cheap) CPTs, boreholes, and geophysical methods for the latter. The challenge is to translate CPT and geophysical data into information for models. Knowledge about the subsurface and how different types of sediment are formed can reduce uncertainty in model parameters at locations where such information is absent, for example, by a priori known differences in grain sizes between genetically different types of subsurface material. Geophysical methods are also ideally suited to detect very local and 'unpredictable' heterogeneities in the subsurface.

[1] https://basisregistratieondergrond.nl/english/

Technical barriers

Non-technical barriers

Participant responses to the question: What technical or non-technical barriers are there to using this information?



Participant responses to the question: Where are the biggest challenges?

A major scientific challenge remains the mismatch between available information about the heterogeneous subsurface and the current models, their schematisation and required model parameters. It is important that we achieve improvement in surface information and application in the models, but that this can also be converted into a manageable method for application in practice for the managers, in which one can work with 'standardised' procedures.

Testing current and new methods is difficult. We can explore how this can best be done by focusing on specific cases or dike trajectories where researchers work with the regional water authorities. In addition to subsurface data, we prefer to have data at our disposal that provides information about groundwater levels, groundwater flow, piping, etc., under extreme hydraulic conditions. This data allows us to learn how the dike system reacts under such conditions and where critical situations (can) arise. Extreme high-water peaks (such as this summer along the Meuse) are important events to collect such data, but these are rare. Nevertheless, collecting field data from past and future flood events remain important.

All-Risk recommendations:

- Incorporate genetic knowledge (the 'architectural elements' building up the delta) of the subsurface to adopt a regional approach for more realistic and robust parameter estimates.
- Focus on a good parameterisation of architectural elements in risk assessments.
- Use prior subsurface knowledge for better streamlining of data acquisition by focusing these on critical areas.
- Combine point data measurements from cores and CPTs with geophysical data for improved and full-2D schematisation of the subsoil below dikes.

Reflection

Data-driven dike reinforcements – Constructive feedback from new and historical sources

Webinar team

Moderator
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Introduction
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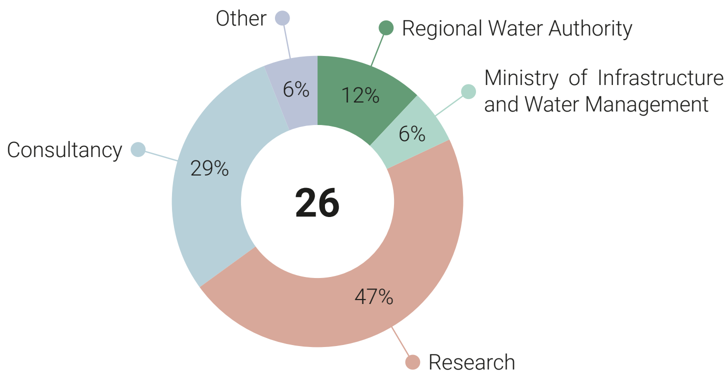
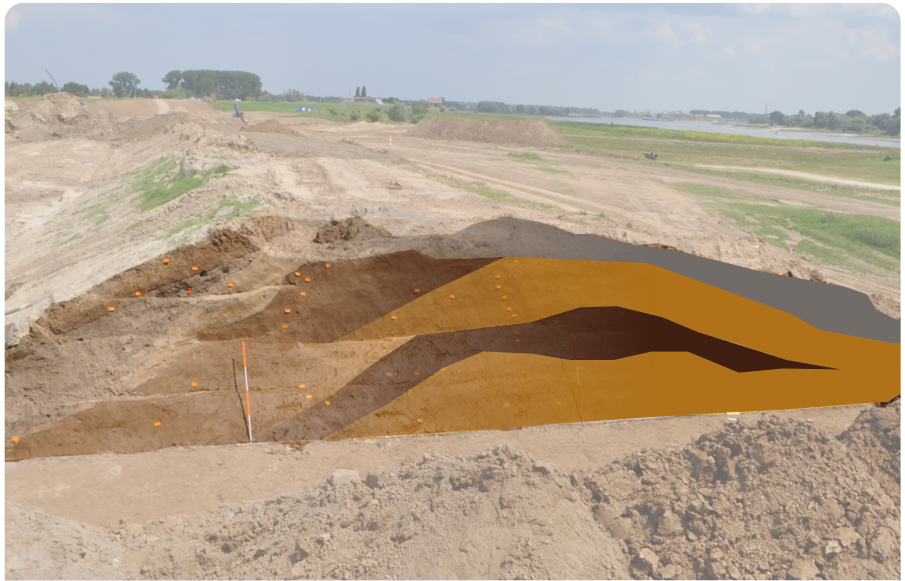
Participants





Different material layers of a historical dike. Image adapted from Rondags (2019).

The theme:
The technical assessment of dike reinforcement projects in the Netherlands is flooded with data. Before, during and after dike reinforcements, a lot of data is collected and stored. This webinar attempted to bridge the gap between conventional and new data sources by presenting new methods for improving dike safety through data and discussing the general use of different data sources.

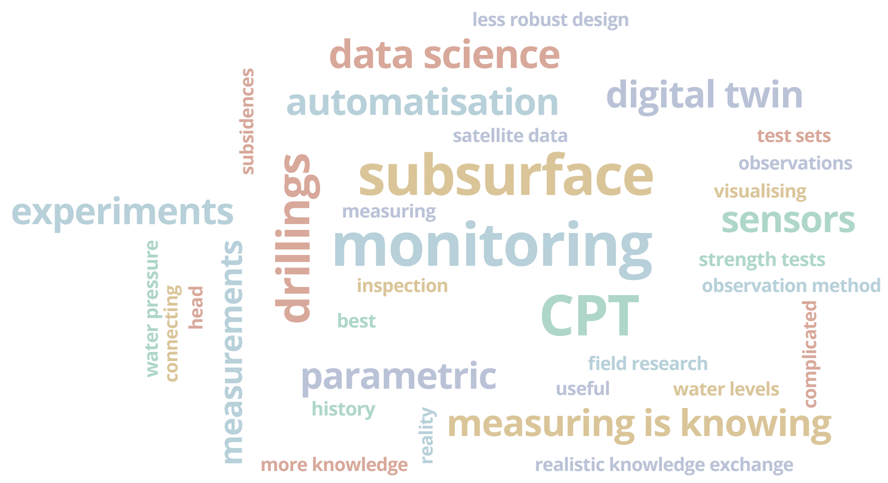
Would you like to see the presentations of the researchers? You can view them **by clicking or scanning the QR Code.**

This reflection emerged from the discussion between researchers and participants during the All-Risk webinar organised on July 5, 2021.

Data-driven dike reinforcements

In addition to traditionally used data sources such as drillings, cone penetration tests, and statistics of extreme water levels, recently interest has increased for long-term monitoring of groundwater levels, historical data, performance information, and combining data from different data sources. One of the data sources that have not been used so far is archaeological data of the dike buildup. By using the properties of historical dikes, an estimate can be made of the dike buildup of current dikes. This information can subsequently also be used for groundwater and dike stability schematisation, which is crucial to assess dike safety in more detail. Another component is the use of information on the observed performance of dikes to improve failure probability estimates. Examples of performance information are survived loads such as high water or test loads and measurements during such load situations.

Furthermore, there is already a large toolbox of existing techniques to interpret different data sources. A combination of all types of data would probably give a complete picture, but this is an impossible task in practice. Thus, priority must be given to the most effective data types.

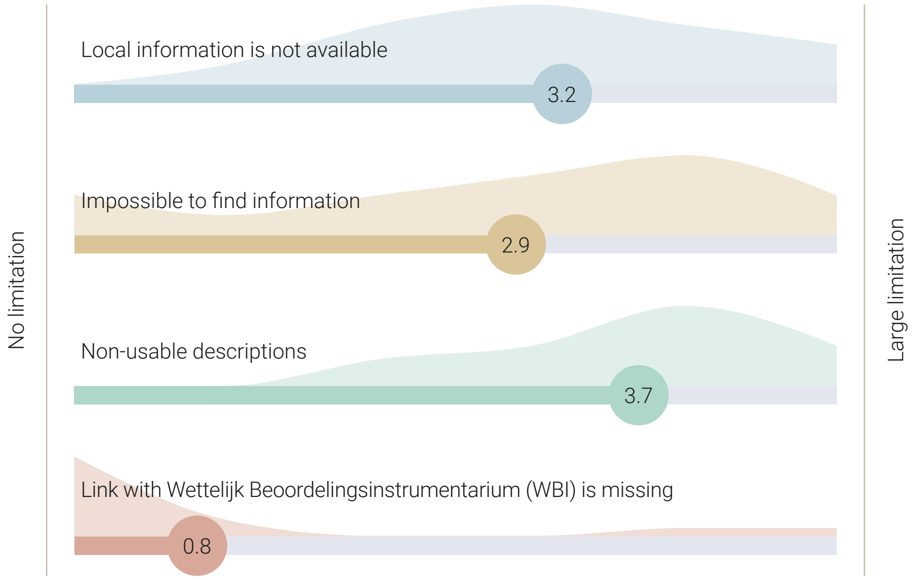


Participant responses to the question: What terms come to mind when you think of "data-driven dike reinforcement"?

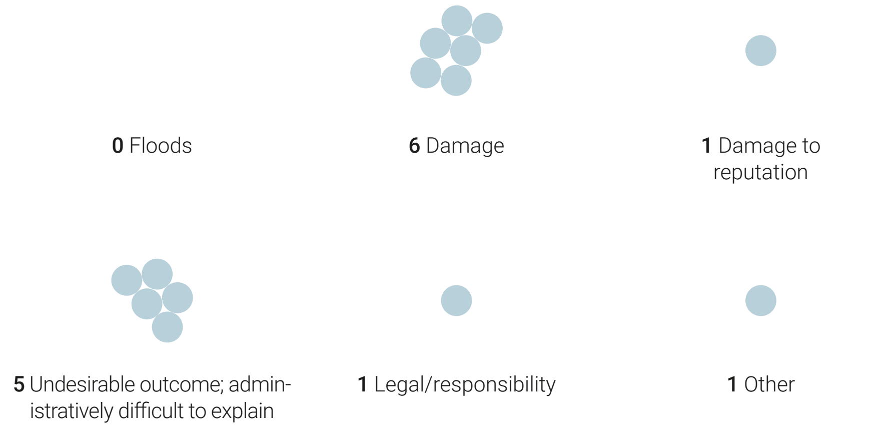
Reflections on the use of two new data sources: archaeological dike cross-sections and test loads

Two new data sources are discussed: archaeological dike cross-sections, to understand the dike structure better, and proven strength by test loading of dikes to reduce uncertainty in strength.

According to the participants, the use of archaeological dike cross-sections can be implemented in the *Wettelijk BeoordelingsInstrumentariu*m [WBI, for assessment] (Rijkswaterstaat, 2017). The WBI is mainly seen as a basis for safety assessment, a kind of recipe. People already look much further than the WBI rules in many situations, and historical data also fits in. In addition, it would be nice if standard classification tests were done more often when soil research is done. If these tests are used in



Participant responses to the question: To what extent do you find the following aspects a limitation to the use of archaeological data in dike assessment?



Participant responses to the question: What do you think is the biggest risk of using test loads?

a wide range of types of research, such as geotechnical and historical research, different types of research can be combined more easily, and better conclusions can be drawn about the behaviour of soil. Such a classification standard of Dutch soils based on basic tests has already been developed and would be a good addition to the historical data.

Many participants feel that test loads are a promising method to determine dike safety better but are concerned about possible risks such as the 'damage' that a test load may cause. This concern is remarkable because a test load's cost-benefit analysis may explicitly include this risk. A risk-neutral decision-maker would always decide to carry out a test load if the benefits of reinforcement cost reduction are larger than the costs and risk-related concerns to the test load.

The fact that participants label test loads 'undesirable' and identify 'damage' as the greatest risk may indicate that decision-makers are slightly risk-averse. Many participants also find it difficult (administratively) to explain when a test load results in some damage. In addition, they find it difficult to have to explain that the dike is weaker than previously assumed. This concern is also remarkable because finding a weak spot is very valuable, especially if that spot would otherwise have gone unnoticed.

Optimisation of data use in dike reinforcements

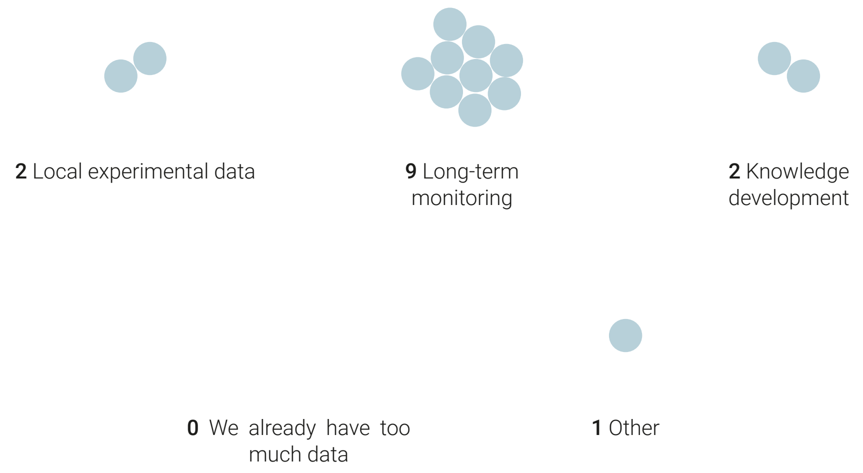
The new data sources, historical dike data and test loads are just two of the many possibilities for gathering more information about our dikes. When we present these various possibilities to the participants, long-term monitoring is seen as the best option for optimising dike reinforcements. However, we often see that all the information after a dike reinforcement disappears into storage and is not used to adjust the safety image continuously.

Long-term pore water pressures are in particular seen as data that is almost always lacking at present, making good uncertainty estimates very difficult. However, the influence of the uncertainty of pore pressures is not necessarily the greatest uncertainty in calculations.

The participants clearly prioritise how to improve flood risk management (see figure on the right). (Long-term) monitoring is very important, as well as full probabilistic safety assessments. Full-scale experiments are also important. The use of historical data is less attractive than risk-driven research because it is hampered by its availability and difficulties regarding adequate data descriptions for further reuse.

Conclusion and outlook

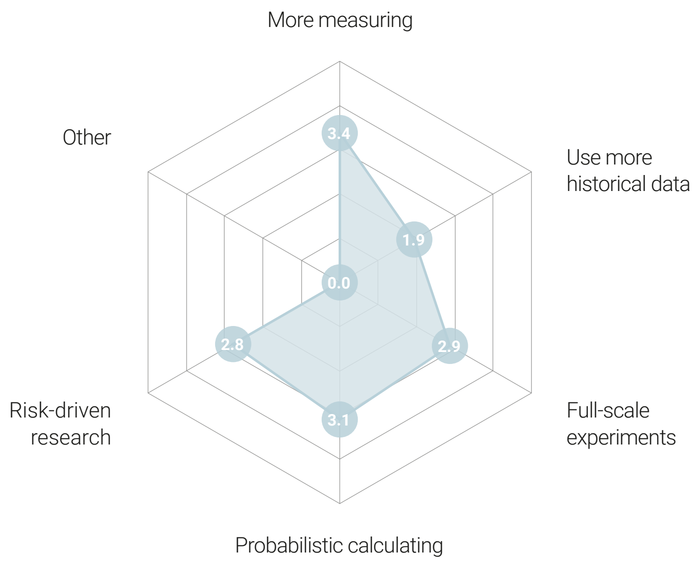
Whatever data sources have been used, there is a unanimous view that data should be (re)used as much as possible in the broadest possible application of projects. The ideal picture of the future is that current



Participant responses to the question: What data can we use to best optimise dike reinforcements?

and historical data is used to continuously adjust the probability of failure and a residual lifetime of flood defences, and thus to be 'in control' regarding flood safety. To this end, it is desirable to have all data on current and historical dike reinforcements publicly available. An important point of attention here is proper access to the data to be present and easily accessible. The improved data management requires good agreements between the client (Water Authorities) and the contractor (consortium/contractor) about which data are relevant or can become relevant in the future.

Since it is expected that we can benefit a lot from long-term monitoring of dikes, this aspect deserves extra attention. Relevant knowledge questions are:



Participant responses to the question: What do you think are the most important steps to improve flood risk management?

- How long do we have to monitor to derive reliable characteristics? and
- How can we specify in advance how new data and insights will affect the dike reinforcements, so that this vision remains constant over the longer term, independent of changing project managers?

A misconception is that the behaviour can be captured generically in simple calculation rules with this long-term data. Although monitoring will clarify the behaviour, it remains more important to understand and interpret the situation in geotechnical engineering.

To continuously update our estimates of the remaining lifetime of dikes, we also need a good understanding of how soil and soil behaviour change over time and the effect on the probability of failure. For example, an increasing probability of failure due to cracking and a decreasing probability of failure due to ageing of soil and proven strength. The impact of future climate change also plays an important role. Together with the existing monitoring methods and new developments, the dike safety specialist's toolbox will contain more and more possibilities to use data to estimate the reliability of dikes better.

All-Risk recommendations:

- Use innovative data to assess dike safety. This can provide many new insights and improve the assessment.
- Commit to long-term monitoring of dikes.
- Make dike data available for wider (re)use.

Researchers, students and dike specialists at a large-scale piping experiment in the Flood Proof Holland testing facility in Delft." Photo by Joost Pol.

Chapter 5
Reliability and Strength of Flood Defences

Introduction
By Bas Jonkman

The Netherlands cannot exist without water management and water infrastructure. Flood defences protect 60% of the country from flooding, and their reliability is thus essential. To meet future demands, 1,500 kilometres of defences (40% of the total length of defences) have to be reinforced in the coming decades along rivers and coasts.

This is the central challenge and task for the national dike reinforcement programme (Hoogwaterbeschermingsprogramma in Dutch – HWBP). There are high requirements for the quality and reliability of reinforced defences. Also, interventions need to be implemented in the surroundings with respect for population, landscape and ecology. This all requires a continuous improvement of the knowledge of the reliability and performance of defences and the quality of solutions.

As the dike reinforcements span over decades, knowledge developed in research programmes such as All-Risk can be implemented in the HWBP programme after several years. Ideally, a continuous cycle of knowledge development and implementation would be linked to HWBP for the coming decades.

All-Risk project D "Reliability and Strength of Flood Defences" has focused on a better understanding of failure mechanisms, models and reinforcement techniques. The research by Joost Pol (D3) has shown how the growth of pipes under a dike can be better understood and modelled. Another important mechanism is wave overtopping. Vera van Bergeijk (D5) has given insight into when and how wave overtopping leads to erosion of the inner slope. Weiqiu Chen (D6) has investigated the role of oblique ("diagonal") wave attack on dikes, and the effects of transitions.

A difficult and "uncertain" failure mechanism concerns the stability of dikes. Mark van der Krogt (D4) showed how the performance and settlement of dikes during construction could give important information about the strength during the entire lifetime. Guido Remmerswaal (D1) has developed the next generation of stability models – the Material Points Method (MPM). With these models, it can be evaluated if there is a risk of a series of cascading slides after initial failure.

Important insights in our field of expertise are often developed in large-scale projects or experiments. Arny Lengkeek (D2) has evaluated the failure test of the "Eemdijk" – a dike reinforced with sheet piles. He has developed the knowledge to understand the performance of these combined solutions. The findings from All-Risk researchers will contribute to a more precise assessment of the reliability and more efficient reinforcements. The insights have been developed in collaboration with end-users from the government, research institutes and the private sector. In addition to the research, an important component is the development of "human capital". Most All-Risk researchers and graduates will continue their careers within this challenging field of work.

This project has resulted in three main recommendations that can contribute to a better assessment and more efficient reinforcement of flood defences. Firstly, the new knowledge and advanced models can help to come to a better assessment of the reliability for instability and piping. Secondly, it appears to be very valuable to collect more information on the performance of defences during high water situations, in the construction phase and through large-scale field tests. Thirdly, new knowledge and models for overtopping resistance can be used for the assessment and design of dikes.

Last but not least, it is noted that extreme events can also give new insights into safety, reliability and the need to reduce flood risks. The unexpected floods in Limburg in the summer of 2021 will lead to an adjustment of our estimates of the frequencies of floods in the area. During the same event, many defences along the river Meuse have safely withstood the extreme high loads – a form of "proven strength". The floods in Limburg, Germany and Belgium have shown that our efforts to reduce flood risks are never finished; many uncertainties need to be anticipated – particularly in a changing climate.

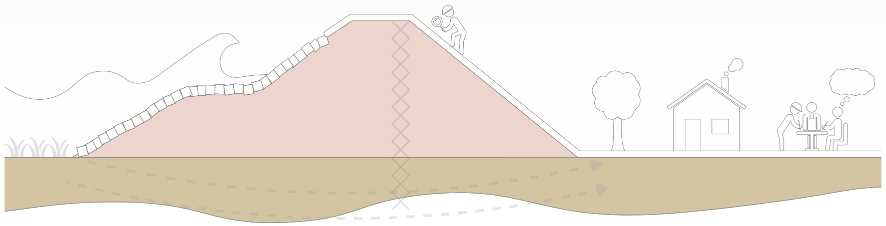
Project Summary

D1 - Residual dike resistance

Insights in the process after a slope instability

By Guido Remmerswaal
Delft University of Technology

Project start: 09/2017
Project end: 09/2021



Promotors

Dr. P.J. Vardon
Delft University of Technology

Prof. dr. M.A. Hicks
Delft University of Technology

Outcome

The current assessment of dike slope instability is limited to predicting the likelihood of the initial instability, as conventional methods can not predict the failure process beyond. This project has further developed the Material Point Method (MPM), which can evaluate the processes after an initial instability. Analyses of simple dike geometries with MPM have shown that a significant reduction in the calculated probability of flooding can be achieved by assessing the complete failure process. Moreover, the results show that secondary failures are more likely when the first failure occurs in a weak layer than a more homogeneous material.

Figure 1: Macro-instability in Saxony-Anhalt (Germany) without flooding. Photo from Jüpner et al. (2015).

Motivation and practical challenge

The challenge of this project is to predict for which dikes slope instability can(not) be allowed, i.e. depending on whether it causes flooding. The failure process of slope instability starts with a crack in the crest or inner slope (**Figure 2, photo 1**). After the crack has developed, deformations start as the slope slides (**Figure 2, photo 2**). For dikes with residual resistance, these deformations may stop before flooding occurs, while for others, large deformations occur (**Figure 2, photo 3**) potentially leading to secondary slides. Flooding is unlikely to occur for some dikes even after very large deformations. For others, the deformation will lead to flooding due to a dike breach (**Figure 1, photo 4**). Allowing an initial slope instability for dikes with residual dike resistance may be possible when flooding is unlikely to occur, i.e. a dike breach is unlikely. Considering this residual resistance can lead to more efficient designs, especially for dikes with a large width. Dike reinforcement can then take place where it is most necessary. Modelling and understanding the failure process helps predict in which cases the failure process stops before flooding due to a dike breach. Thereby, we can help engineering expertise evaluate and expand the existing guidelines for dike slope instabilities.

Research challenge

Implementing the new safety standards requires more realistic estimates of the probability of flooding. However, these realistic estimates are difficult as current assessment methods only predict failure initiation, not the failure process until flooding. Therefore, the challenge of this research was to design a method to predict the failure process and to use the method to determine the effect of residual dike resistance on the probability of flooding.

Innovative components

To predict if a dike may breach after the initial slope instability, I developed and used the (Random) Material Point Method (R)MPM. MPM

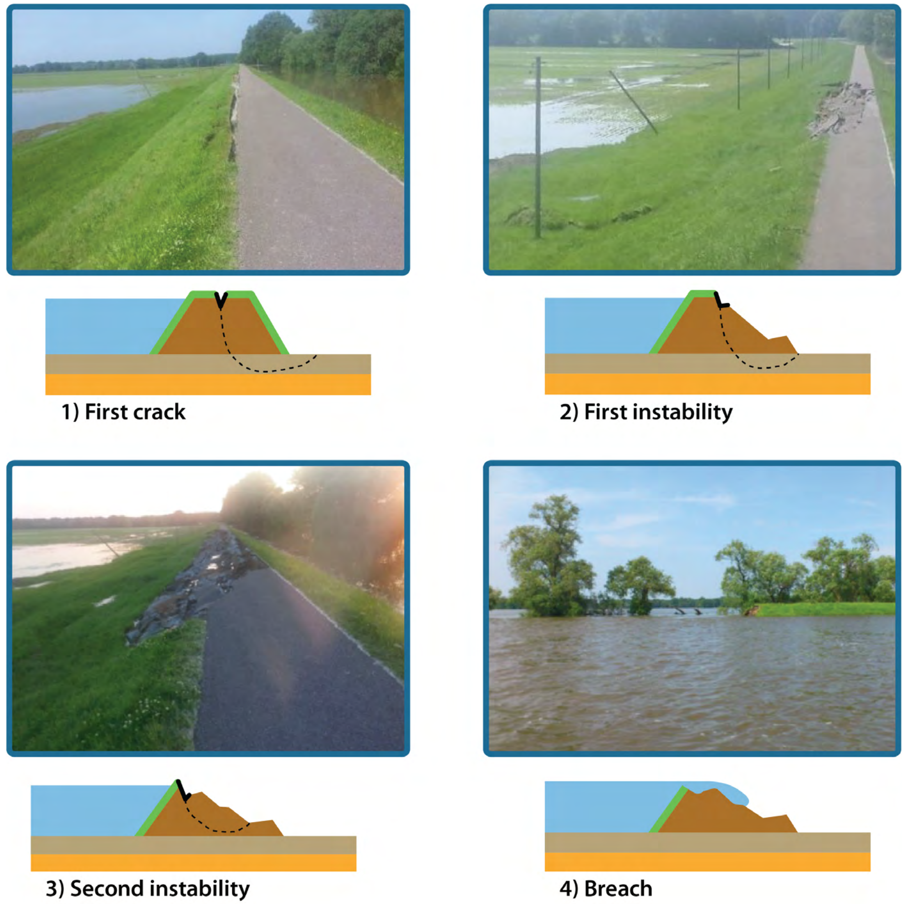


Figure 2: Sequence of slope instabilities that lead to flooding. Photos by Grubert (2013) and schemes adapted from Calle & Knoeff (2002).

is a new modelling approach similar to the widely used Finite Element Method that allows us to model the start of the initial failure and the dike deformations that may follow. Thereby, I determine the residual dike resistance, which is the difference between the probability of slope instability and a dike breach (**Figure 3**).

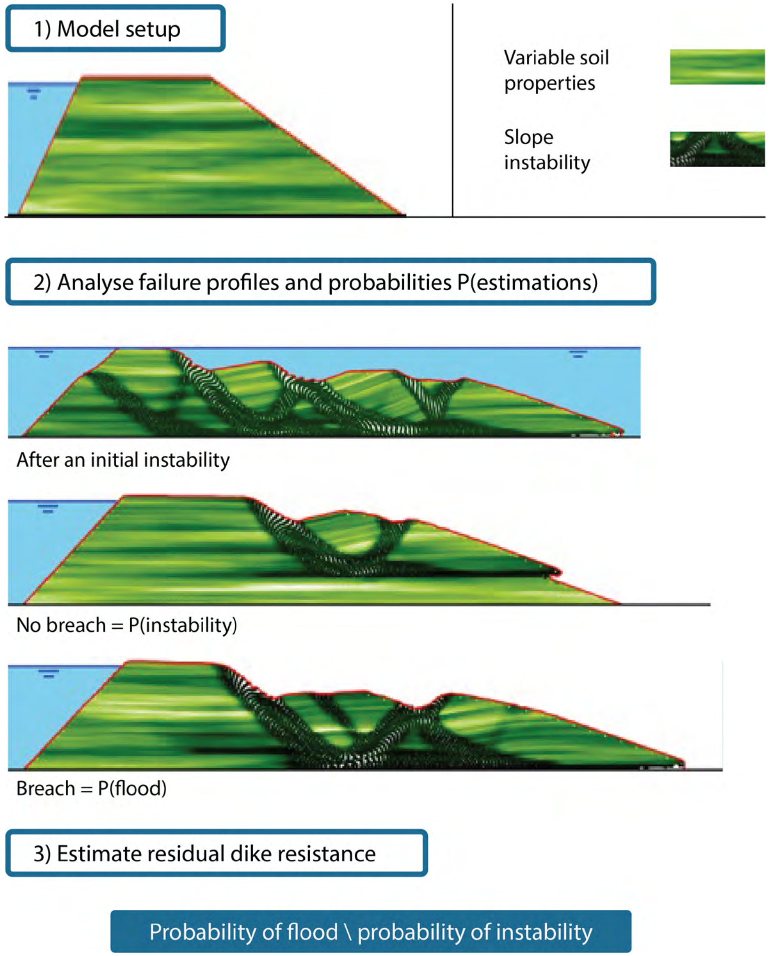


Figure 3: Main components of the modelling approach to estimate residual dike resistance. Based on Schemes from Guido Remmerswaal.

The model is set up for a given dike section and accounts for the variability in the dike and subsoil properties by generating several possible realisations of the material properties, each equally likely to occur yet different. Due to the variability, the failure process may also be highly variable, and MPM is therefore expanded into a fully probabilistic tool (Random MPM). Thereby, I extend the current probabilistic framework for dike design to include residual dike resistance. RMPM computes for each realisation if initial instability and flooding occur. The probability of initial instability and flooding can be estimated from all these failure processes. Thereby, the residual dike resistance is estimated. Finally, the results are compared to the existing guidelines to provide insight into their applicability.

Relevant for whom and where?

The research is relevant for anyone designing or assessing dikes who considers taking residual dike strength into account for dikes with a large width or dikes with a height above the water level.

Progress and practical application

Significant residual dike resistance was present in the examples tested, especially for wide dikes or lower water levels (compared to the dike height). In other words, MPM can reduce the calculated probability of flooding significantly compared to initial failure, reducing overconservative calculations.

The dikes tested in the examples were relatively weak compared to realistic dikes. This condition ensured a relatively high probability of initial failure and saved on computation costs. Consequently, these examples had a relatively 'low' residual dike resistance compared to realistic examples. The benefit of using MPM can therefore be expected to be higher for more realistic examples.

The analysis showed that the reduction is highly dependent on the geometry, material properties, soil variability and river/sea water level.

Current guidelines for residual dike resistance assume a 'safe' remaining dike geometry after the initial failure, which will never result in flooding. However, due to the large variation in outcomes after an initial failure, such a 'safe' geometry has not been found in the examples tested. In other words, the probability of flooding can be significantly reduced by residual dike resistance but will not become zero. For details about findings, **see the project outputs below**.

Recommendations for practice

- Evaluate failure processes up to flooding to reduce overconservatism.
- Be careful with quick estimations of the failure process.
- Provide detailed descriptions of dike slope failures for the development of MPM.
- Use MPM to model the failure process without replacing conventional methods for estimation of initial failure.
- Account for the effect of soil variability on slope instabilities as it leads to more efficient designs (with or without modelling the failure process).

Key project outputs

Remmerswaal, G., Vardon, P.J. & Hicks, M.A. (2021). Evaluating residual dyke resistance using the Random Material Point Method. Doi: 10.1016/j.compgeo.2021.104034

González Acosta, J.L., Remmerswaal, G., Vardon, P.J. & Hicks, M.A. (2019). An investigation of stress inaccuracies and proposed solution in the material point method. Doi: 10.1007/s00466-019-01783-3

So far the research components are developed for typical dike sections in the Netherlands without a specific case study or location in the map.

Project Summary

D2 - Modelling of sheet pile reinforced dikes in organic soils

Insights from the full-scale Eemdijk test

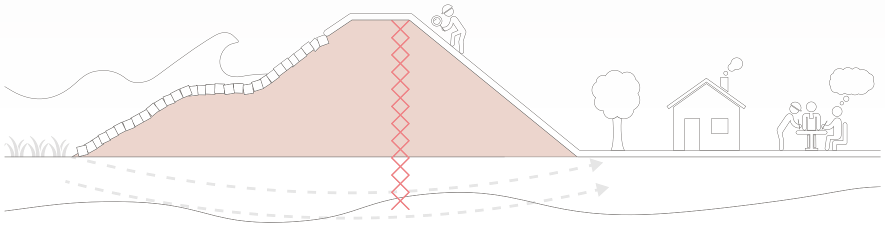
By Arny Lengkeek
Delft University of Technology

Project start: 09/2017
Project end: 09/2021

Promotors

Dr. ir. R.B.J. Brinkgreve
Delft University of Technology

Prof. dr. ir. S.N. Jonkman
Delft University of Technology



Outcome

This project developed an adjustment of the cone penetration test (CPT)-based classification chart to account for organic clays and peat. Furthermore, new CPT-based correlations are developed for geotechnical parameters of organic soils. Moreover, we developed a new model based on critical state soil mechanics, linking the effective strength parameters to undrained strength parameters, following existing approaches for slope instability analysis. Finally, we carried out a back analysis study of the Eemdijk full-scale dike failure test, consisting of three tests: (1) a ground dike, (2) a sheet pile reinforced dike and (3) pull-over tests on sheet pile panels. The interpretation of the test measurements provided valuable insights into the sheet pile performance to extreme loading conditions and beyond failure.

Figure 1: Eemdijk full-scale test; dike with sheet pile reinforcement prior to failure. Photo by Arny Lengkeek.

Motivation and practical challenge

As a geotechnical engineer with over 20 years of practical experience on hydraulic and geotechnical projects in the Netherlands and abroad, my motivation is related to better combining the theory with engineering and practice for dikes. Therefore, this project builds upon the current slope stability assessment approaches of dikes with sheet pile reinforcement and my experience in soil parameter determination, constitutive models and soil-structure interaction. This knowledge comes together in interpreting the soil investigation tests and related parameters, which are input for the advanced finite element method (FEM) models used for the stability, the strength of the sheet pile and the deformation assessment. Moreover, the Eemdijk full-scale test was a unique experiment that allowed me to validate analytical models' performance in the dike engineering practice.

Figure 2: Eemdijk full-scale test; dike with sheet pile reinforcement after failure. Photo by Arny Lengkeek.

Research challenge

This project answers the following research question: How does a dike reinforced by a sheet pile stability wall perform under high water conditions, and how can this be modelled? Subquestions are divided into two categories. The first category applies to parameter determination for dikes in general, and the second category to the Eemdijk experiment ("Eemdijk damwandproef") that focuses on dikes reinforced by sheet piles.

Innovative components

In the Netherlands and other deltas globally, very soft and highly organic soils are omnipresent. With the adjustment of the CPT-based classification these organic soils are better classified. Furthermore, new CPT-based correlations are developed, for example the soil unit weight for soils, ranging from sands to peat. A new theoretical model (CSR model) was developed, implementing the Limit Equilibrium Method (LEM) on slope stability analysis. The new relationship obtains the undrained shear strength based on effective strength and stiffness parameters. Finally, regarding the "Eemdijk damwandproef", two parallel 60 m long full-scale test dikes of which one was reinforced with a sheet pile were loaded until failure:

1. Sheet pile pullover tests consisting of 4 sheet pile configurations in length and width.
2. Ground dike stability test where the water level in the sand core of the dike is step-wise increased by infiltration.
3. Sheet pile dike stability test to create a realistic load scenario and failure mechanism.

Relevant for whom and where?

Engineers who design dikes with structural inclusions, such as sheet piles, with finite element method (FEM) models. Engineers who use CPTs for parameter determination of soft organic soils for civil engineering projects in general.

Progress and practical application

This project developed improved CPT-based classification and correlations for the organic soils, directly applicable for Dutch dike engineering projects. The correlations are based on statistical methods and include the confidence interval.

The new developed CSR model to obtain the undrained shear strength strikes a balance between the current practice using the empirical Stress History and Normalised Soil Engineering Properties (SHANSEP) equation and the theoretical elaboration of undrained shear strength based on critical state soil mechanics. The CSR model allows for a variable spacing ratio that can be fitted to laboratory test data. The CSR model can be implemented in LEM, where it can be used for stability analysis.

The Eemdijk full-scale test gave insight into the soil-structure interaction of the structurally reinforced dike on soft soil, loaded by high water and uplift conditions. The capacity of sheet piles complies with the Eurocode and even shows robustness after failure for a less

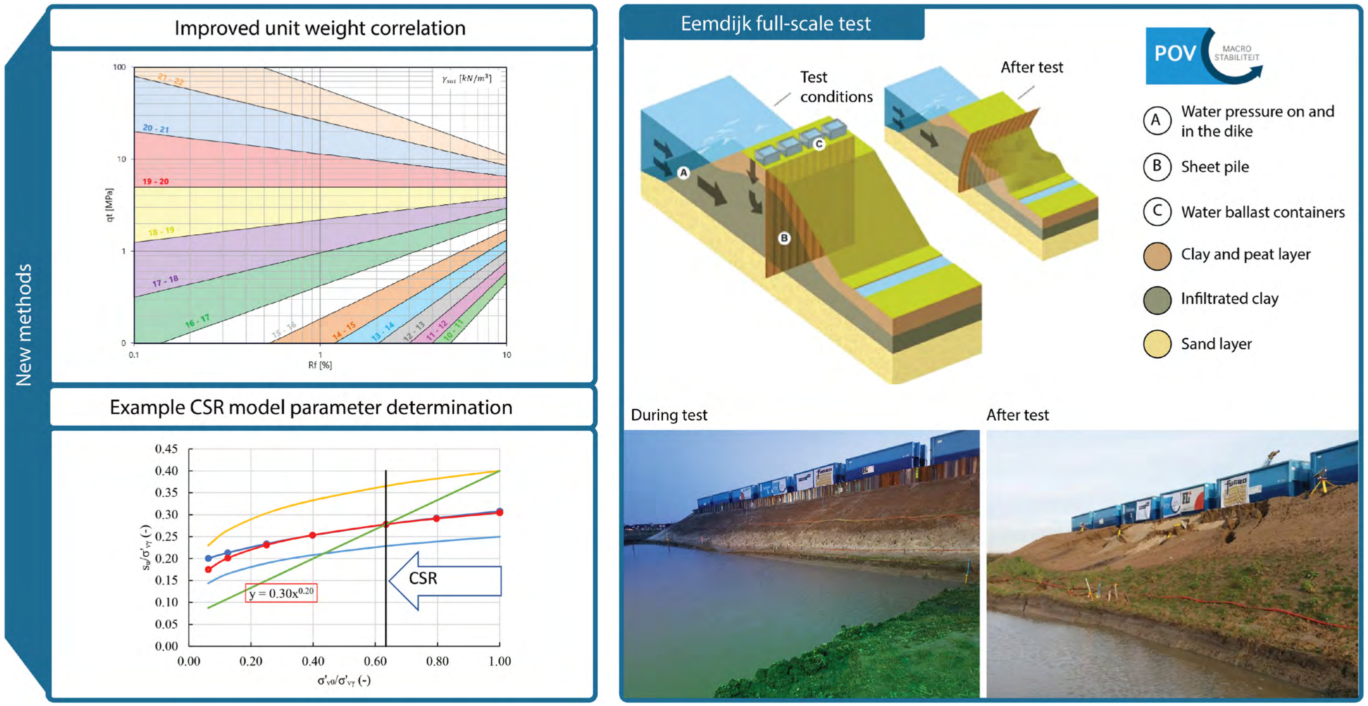


Figure 3: Components of the research relating the new methods and the Eemdijk full-scale test including an illustration and photo impressions during and after the test. Sources: Illustration and after test photo by POV macrostabiliteit. During test photo taken by Arny Lengkeek.

conservative approach than in the current guidelines. The sheet piles contribute to the dike's water-retaining capacity after structural failure and prevent breaching. For a detailed description of each finding, **please check the project outputs below**.

Recommendations for practice

- Consider using the updated CPT based classification given its improvements compared to previous methods for the sedimentary deposits found in the Netherlands.
- Consider using the new CSR model to compare effective strength and undrained strength parameters and reduce uncertainties in parameter determination and stability analysis.
- The back-analysis of the Eemdijk confirms that despite the complex soil-structure interaction, the FEM models perform well. The strength and deformations are underestimated due to anisotropy and 3D effects. The reduction of stiffness parameters is not required for advanced models as the reduction in strength parameters already covers this.

Key project outputs

Lengkeek, H.J., Jonkman, S.N., & Kanning, W. (2021). Application of geo-statistics and pairwise established CPT-based correlations for line infrastructure. http://isc6.org/images/Cikkek/Sessions/ISC2020-487.pdf

Lengkeek, A., Naves, T., Post, M., & Breedeveld, J. (2019). Eemdijk full-scale field test programme: sheet pile pullover tests. Doi: 10.32075/17ECSMGE-2019-0456

Breedeveld, J., Zwanenburg, C., Van, M., & Lengkeek, A. (2019). Impact of the Eemdijk full-scale test programme. Doi: 10.32075/17ECSMGE-2019-0398

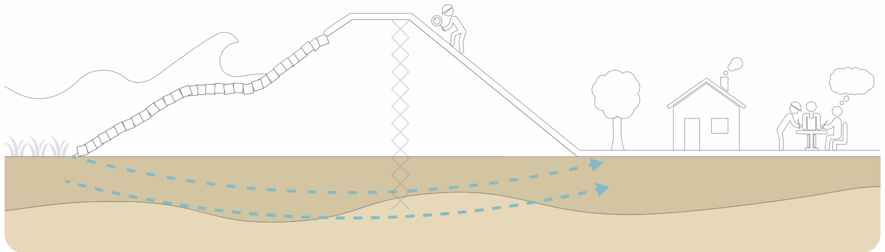
The components of this research are developed for a range of typical dike sections for the Dutch riverine area, and for a case study of a full-scale test embankment in Eemdijk.

Photo © NOS / Eric Feijten.

Project Summary

D3 - Time-dependent piping and interactions

A framework for safety assessment with time-dependent failure processes



By Joost Pol

Delft University of Technology

Project start: 09/2017

Project end: 03/2022

Promotors

Ir. W. Kanning

Delft University of Technology

Prof. dr. ir. S.N. Jonkman

Delft University of Technology

Prof. dr. ir. M. Kok

Delft University of Technology

Outcome

The project focuses on two aspects of the new definition of safety standards as flooding probability. The first aspect is related to piping and accounts for most of the results, which show how time-dependent pipe development affects dike reliability. To this extent, we performed lab experiments, developed a pipe progression model, and integrated this knowledge into a time-dependent piping reliability analysis. Our analysis shows that dike reliability increases significantly in relatively short high-water durations or effective flood fighting. The second aspect explored the potential impact of interactions between failure mechanisms.

Figure 1: The Waal river dike at Beuningen during the 1993 flood. Photo by Rijkswaterstaat, beeldbank.rws.nl / Bart van Eyck.

Motivation and practical challenge

It is of great societal importance to improve safety estimates to optimise investments. Current safety assessments result in unexpected high failure probabilities for some failure mechanisms, such as piping. These conservative estimates for the probability of failure may result in high costs for dike reinforcement projects in the Netherlands. In the case of high water levels (**Figure 1**), including the flood duration in the analyses is one of the aspects that can contribute to lower assessed failure probabilities and more efficient reinforcements.

Related to piping, the dike failure starts when water flowing through a sandy dike foundation erodes so much sand that it forms a small (mm size) channel or 'pipe' (**Figure 3**). Therefore, an important challenge is the interpretation of field observations during floods. For example, sand boils are the only visual manifestation of piping, but most do not result in a dike breach. A better understanding of the erosion process in the laboratory and the field (**Figure 2**) is important to estimate the likelihood of a dike breach during a flood to plan emergency responses.

Research challenge

The research aims to show how to quantify failure probabilities, including (uncertain) flood durations and time-dependent failure processes. The assessment framework is elaborated for piping, for which a model shows the development over time.

Innovative components

Including time-dependent information in dike safety assessments requires understanding the development of failure mechanisms such as piping at different levels over several flood events. To do so, I use the following innovative components:

Figure 2: Piping in the laboratory. Photo left by Toan Nguyen and photo right by Joost Pol.

1. A better understanding of the development of the piping erosion process over time, using small-scale and large-scale experiments.
2. Modelling of the piping erosion process for deriving a simplified model that complements the current practice (Sellmeijer model).
3. Exploring when interactions (causal dependencies) between failure mechanisms are relevant.

Based on this improved understanding, I am developing a probabilistic framework to integrate uncertainties and time aspects in hydraulic loads, dike properties and failure processes, both over single and several flood events. The framework quantifies the effect of time dependence in several types of water systems such as rivers, coasts, and lakes. The project focuses on piping failure, but similar probabilistic methods can be used for other failure mechanisms.

Relevant for whom and where?

Technical managers of flood defences, especially in areas with short flood durations. They can use the research to improve reliability estimates in assessment, design and operational phases. The research can also help in the planning of emergency measures.

Progress and practical application

At the moment of writing (December 2021), the analysis of the experiments is finished. In the following months, the pipe erosion modelling and reliability analysis will be fine-tuned and applied to field-scale examples. The results so far indicate that a time-dependent analysis can considerably reduce calculated piping failure probabilities. The time-dependent analysis can decrease the probability of piping failure with several orders of magnitude in areas with short, storm-dominated floods. This effect is smaller in prolonged river floods but still significant if combined with timely flood-fighting interventions. Results also show that a breach often occurs after the flood peak. Reaching this peak can take several days in riverine areas, which is a significant delay for allowing operational flood management. The results can be applied in tailored dike reliability analysis and used to derive simplified rules for assessing time-dependent pipe development.

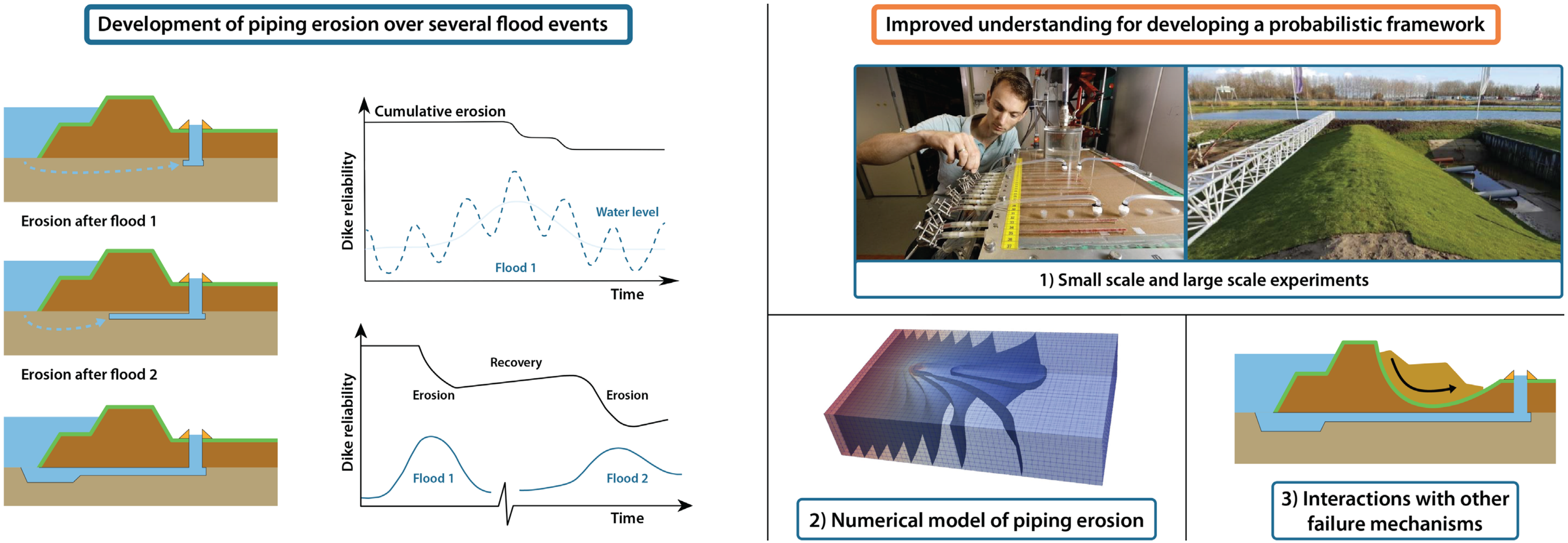


Figure 3: **Left:** Piping schemes adapted from van Beek (2015) and dike reliability graphs sketched by Joost Pol.
Right: Main components of the research. Left photo © Sam Rentmeester and right photo and schemes by Joost Pol.

Recommendations for practice

- Safety assessments and reinforcement projects should consider where they can benefit from the time required for piping development.
- Discuss including flood-fighting interventions in reliability analyses; this yields lower failure probabilities and more efficient designs combined with slow pipe development.
- Derive simplified rules for the assessment of time-dependent pipe development.
- Keep investing in experimental research to study the piping process.
- When using a failure path analysis to quantify residual strength, check for potential interactions between failure mechanisms, decreasing the reliability.

Findings of this research are developed in the laboratory and a field test site and will be applicable to dike reinforcement projects in the Netherlands.

Photo by Joost Pol.

Key project outputs

Pol, J.C., Kanning, W. & Jonkman, S.N. (2021). Temporal Development of Backward Erosion Piping in a Large-Scale Experiment. Doi: 10.1061/(ASCE)GT.1943-5606.0002415

Pol, J.C., van Klaveren, W., Kanning, W., van Beek, V.M., Robbins, B.A. & Jonkman, S.N. (2020). Progression Rate of Backward Erosion Piping: Small Scale Experiments. 10th International Conference on Scour and Erosion (ICSE-10) : Arlington, Virginia, USA. 18-21 October, 2021 (pp. 93-102).

Pol, J.C., van Beek, V.M., Kanning, W. & Jonkman, S.N. (2019). Progression rate of backward erosion piping in laboratory experiments and reliability analysis. Doi: 10.3850/978-981-11-2725-0_IS4-3-cd

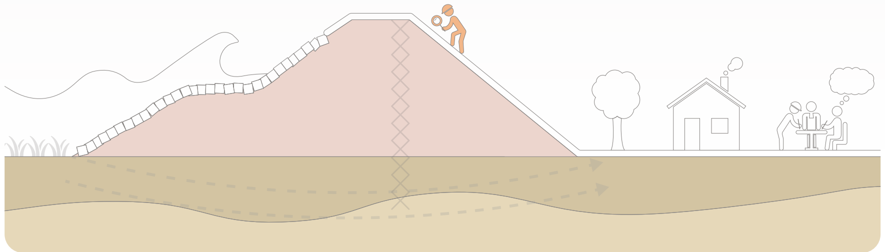
Project Summary

D4 - Incorporating past performance

Improved methods for estimating dike failure probability

By Mark van der Krogt
Delft University of Technology

Project start: 09/2017
Project end: 09/2021



Promotors

Dr. ir. T. Schweckendiek
Delft University of Technology

Prof. dr. ir. M. Kok
Delft University of Technology

Outcome

This project developed methods to improve the reliability estimates for dike slope stability by considering performance information. By incorporating the information of survived (proof) loads and monitoring during the construction of dikes, reliability estimates become more credible, safety assessments improve, and the design of dike reinforcements can be made more efficient. Even when it takes money or risk to obtain the performance information, a strategy with obtaining performance information can be cost-effective, improving the efficiency of flood risk management.

Figure 1: Construction of a dike. Source: HWBP (2018, p.103), photo taken by Pascal Ogink.

Motivation and practical challenge

Flood safety in the Netherlands is expressed in terms of the probability of typical failure mechanisms as of 2017. Dikes are assessed for safety by (semi-)probabilistic analyses methods. However, these failure probability estimates are dominated (among other factors) by the knowledge about the soil properties, which is often limited and uncertain. This limited knowledge is particularly the case for slope instability failures at the landward side, which may or may not lead to flooding due to a dike breach (**Figure 2**).

Measuring, monitoring and adding information about the past performance of dikes can reduce uncertainty and thus lead to better failure probability estimates. Some of this performance information is available when measuring the soil properties or monitoring existing dikes. Performance information is also gathered during dike reinforcement projects (**Figure 1**), such as pore water pressure monitoring and measurement of settlement during the dike construction. Unfortunately, not all information is used to assess the dikes' safety or improve estimates of the expected lifetime.

Research challenge

This research aims to develop updated methods to efficiently combine different performance information sources into safety assessments. I focus on dikes in the Netherlands with high reliability requirements, which are designed with a low probability of failure, due to the high potential flood damage a failure of these flood defences can cause.

Innovative components

I explore several ways to improve failure probability estimates by incorporating different types of past performance information:

Figure 2: Examples of slope instability on the landward side with and without flooding due to dike breach. Sources: Landesbetrieb für Hochwasserschutz und Wasserwirtschaft Sachsen-Anhalt (LHW) and Jüpner et al. (2015).

- Identification of how error sources combine into the total uncertainty in the spatial average of soil properties measured using cone penetration tests (CPTs in **Figure 3.1**).
- The value of information for proof loading (**Figure 3.2**) and pore pressure monitoring (**Figure 3.3**) by using a decision tree (joint component with related project A1).
- How loads during the construction stage (**Figure 3.4**), such as the weight of the soil used to reinforce dikes, can improve reliability estimates for a dike in flood conditions.
- Further reducing uncertainty by combining observations during the construction (**Figure 3.4**) such as survival, settlement measurement, and pore water pressure monitoring.
- Development of event trees to estimate the probability of flooding based on several (**Figure 3.5**) successive conditional instabilities.

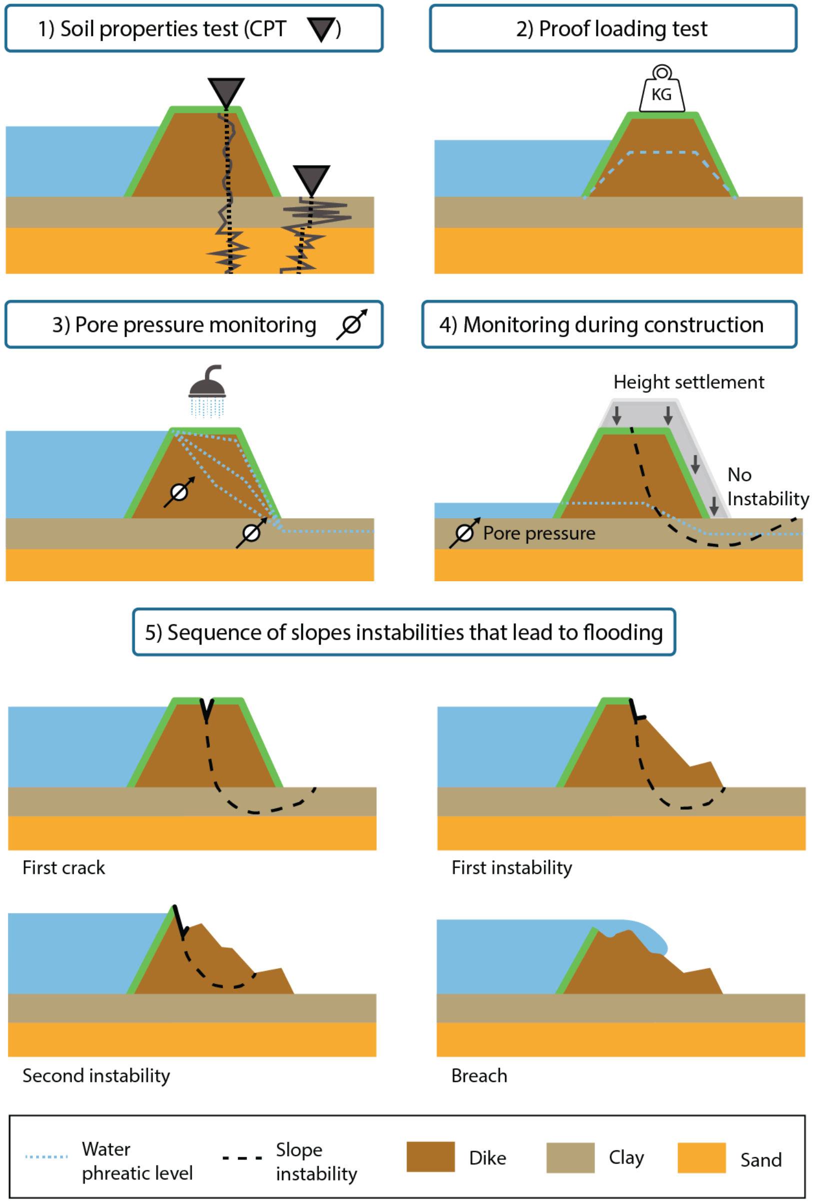


Figure 3: Schemes 1 to 5 with the type of performance information considered in this project. Based on schemes from Mark van der Krogt. 3.5 adapted from Calle & Knoeff (2002, Figure 4.1).

Relevant for whom and where?

Researchers interested in probabilistic analysis and organisations wanting more targeted and cost-effective flood protection.

Progress and practical application

The research demonstrated that characteristic values of soil properties determined with CPTs could be considerably higher if averaging of random errors is considered. Additionally, we can reduce uncertainty in site-specific transformation models by minimising the distance between boreholes and soil investigation tests (CPTs) and reducing bias in the measurements.

The construction of dikes is a large load on the soft subsoil. Using Bayesian updating, the information of construction survival can be incorporated in the dike reliability assessment. This reduces uncertainty and improves the estimates of the probability of failure. Depending on the situation, the probability of failure can reduce by more than a factor of 10. This reduction is especially significant when the load effects during construction are very similar to the future flood situation that is being assessed, such as for dikes on soft subsoils.

Uncertainty reduction measures such as proof loading and pore water pressure monitoring applied to typical dike sections in the Netherlands have a positive Value of Information, thus are often worth investing in. For a detailed description of each finding, **see the project outputs on the next page**.

Recommendations for practice

- Preferably use multiple boreholes sufficiently distanced rather than multiple measurements within one borehole to reduce uncertainty in site-specific transformation models for statistically homogeneous geological deposits (on a regional scale).
- Collect performance information during the construction of dike reinforcements (such as the survival of the construction phase and measurements of settlement after raising dikes) to reduce uncertainties, and use this information for optimising designs during the dike reinforcement.
- Consider performance information in future dike safety assessments, as it may extend the dike reinforcement lifetime, which is particularly interesting in light of accelerated climate change.
- Consider deliberately taking a small risk, for example, by adopting a more critical, staged loading scheme or proof loading, to potentially obtain a larger reliability update and thus a less costly design. This reliability update is especially important at locations where otherwise expensive (structural) solutions would be required.

Key project outputs

van der Krogt, M.G., Schweckendiek, T. & Kok, M. (2018). Uncertainty in spatial average undrained shear strength with a site-specific transformation model. Doi: 10.1080/17499518.2018.1554820

van der Krogt, M.G., Schweckendiek, T. & Kok, M. (2021). Improving dike reliability estimates by incorporating construction survival. Doi: 10.1016/j.enggeo.2020.105937

van der Krogt, M.G., Klerk, W.J., Kanning, W., Schweckendiek, T. & Kok, M. (2020). Value of information of combinations of proof loading and pore pressure monitoring for flood defences. Doi: 10.1080/15732479.2020.1857794

The components of this research are developed for a range of typical dike sections for the Dutch riverine area, and for a case study of a full-scale test embankment in Eemdijk and are applicable to dike reinforcement projects in the Netherlands.

Photo © NOS / Eric Feijten.

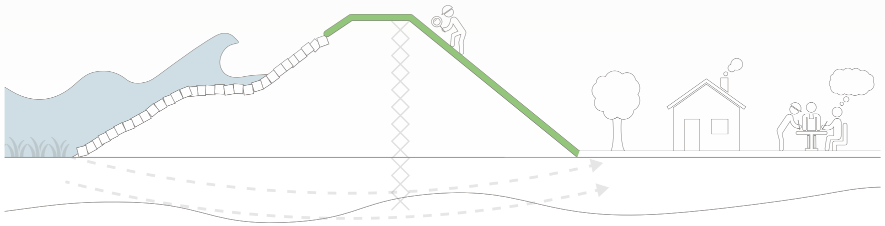
Project Summary

D5 - Overtopping flow and cover erosion

By Vera van Bergeijk
University of Twente

Project start: 10/2017
Project end: 10/2021

Better models to account for the effect of transitions on the dike design



Promotors

Prof. dr. S.J.M.H. Hulscher
University of Twente

Dr. J.J. Warmink
University of Twente

Outcome

We developed several tools for quantifying the hydraulic load on the dike cover by overtopping waves, so the load can now be calculated along the dike crest and the landward slope, including the effects of transitions. Transitions in geometry, such as slope changes and height differences, have a major impact on the overtopping load, contrary to transitions in cover type such as roughness, which have a limited effect on the load. The developed tools can be used to account for the effects of transitions in existing calculation methods for the design and the safety assessments of dikes to determine the best location and design of transitions.

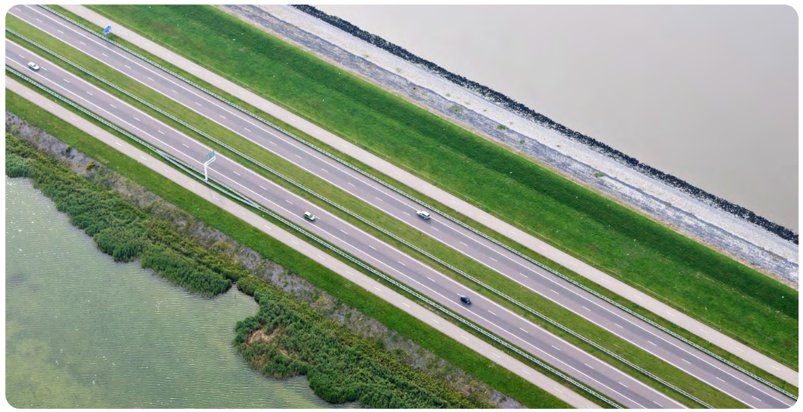


Figure 1: Transitions in cover type and geometry on the Afsluitdijk. Photo by Rijkswaterstaat, beeldbank.rws.nl / Joop van Houdt.

Motivation and practical challenge

In the Netherlands, the introduction of multi-functional flood defences has led to an increase in the number of transitions on flood defences. Examples of these transitions are roads on grass-covered dikes (**Figure 2, top**) and geometrical changes such as berms and objects, including stairs and trees. During storms, high waves can overtop the dikes and run down the landward slope. The large forces of these overtopping waves lead to erosion of the grass cover (**Figure 2, bottom-left**). Once the cover is eroded, the core material of the dike starts to erode, weakening the dike and potentially resulting in a dike breach in the end. Wave overtopping was indeed one of the main failure mechanisms that led to dike failure during the flood of 1953. Recent experiments and numerical studies have shown that transitions are weak spots in the dike profile (**Figure 2, bottom-right**). At these locations, the erosion by overtopping waves starts. However, we do not know how these transitions affect the overtopping flow and dike cover erosion. Thus, it is hard to include transitions in current calculation methods for dike failure.

Research challenge

The challenge is to quantify the hydraulic load of overtopping waves on the crest and the landward slope of grass-covered flood defences, including transitions. We use models to study the important processes at transitions and quantify the load so the effects of transitions can be included in existing calculation methods to improve the designs of transitions on dikes.

Innovative components

To address the above challenge, we developed two types of models. The first model is simple and fast, while the second numerical model calculates the forces pulling on the dike cover in more detail (**Figure 3, top-left**). In the models, locations are identified where the hydraulic forces

Figure 2: **Top:** Road on a grass-covered sea dike. Photo by Vera van Bergeijk. **Bottom-left:** Wave overtopping on a grass-covered dike with a road on top. Source: https://coastalpartners.org.uk/. **Bottom-right:** Erosion of the grass cover at the inner toe during field tests. Source: Hoffmans (2014).

are high, resulting in erosion of the grass cover and failure of the dike. See the **top-right scheme in Figure 3** for a zoom into the slope at a location with a high load that pulls hard on the grass cover leading to erosion.

Moreover, existing calculation methods can only be applied to one location of the dike profile. These new models calculate the forces along in the entire dike profile and therefore calculate the upstream and downstream effect of transitions on the flow. Lessons learned from the detailed model

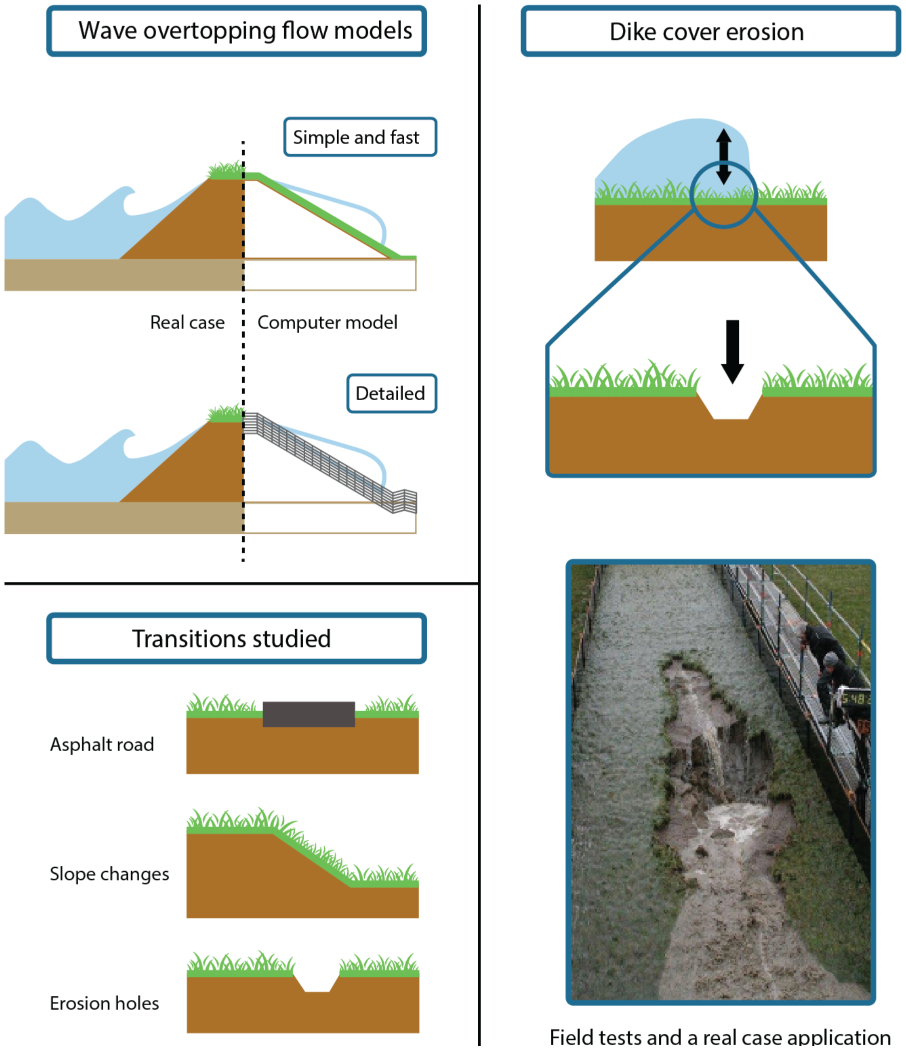


Figure 3: Innovative components of the research approach. Based on schemes from Vera van Bergeijk. Photo by Juan Pablo Aguilar Lopez.

are simplified and implemented in the fast model. Thereby, we studied three types of transitions (**Figure 3, bottom-left**):

- cover type: an asphalt road on a grass-covered dike.
- geometry: slope changes such as a horizontal berm.
- height differences: existing erosion holes or irregularities in the profile.

To determine the effect of transitions, we use the data of field tests on a grass-covered dike with a road on top near Millingen a/d Rijn. We further use the new green design of the Afsluitdijk to find vulnerable locations for grass-cover erosion (**see map on the next page**).

Relevant for whom and where?

Professionals or organisations involved in the design, assessment and maintenance of transitions on flood defences. The modelling approach developed in this study can be used to determine the failure probability of wave overtopping for complex flood defences with several transitions.

Progress and practical application

In this project, different modelling tools are developed that are freely available and widely applicable. These models are more accurate than existing calculation methods and can be applied to flood defences with several transitions. A model study of the new design of the Afsluitdijk showed that transitions result in a lower critical overtopping discharge that is ten times smaller than flood defences without transitions. Furthermore, the inner toe was the weakest cross-dike location because of the high flow velocities.

Another transition in geometry is the inner crest line. The wave can separate at the crest line in the case of a steep inner slope resulting in high impact forces at the reattachment location. A similar process was observed at transitions in height that occur at damages leading to an additional load. Additionally, simulations with the fast model show that the failure probability increases significantly for damaged dikes due to cover erosion or slope instability. For a detailed description of the findings, **check the project outputs below**. The models use a dataset of experiments on a grass-covered dike near Millingen and are further applied at the Afsluitdijk.

Recommendations for practice

- Calculate the hydraulic load of overtopping waves and the erosion along the dike profile to find vulnerable locations for cover failure.
- Account for transitions and other anomalies in the calculation methods for the design and the assessment of grass-covered dikes.
- Height transitions have a major impact on the hydraulic load and have the most erosive power. Therefore, reducing the number of height transitions can make flood defences more resistant to overtopping.
- Determine the strength of the cover layer and the core materials of flood defences to develop more realistic failure definitions.

Key project outputs

van Bergeijk, V.M., Warmink, J.J. & Hulscher, S.J.M.H. (2022). The wave overtopping load on landward slopes of grass-covered flood defences: Deriving practical formulations using a numerical model. Doi: 10.1016/j.coastaleng.2021.104047

van Bergeijk, V.M., Verdonk, V.A., Warmink, J.J. & Hulscher, S. J.M.H. (2021). The Cross-Dike Failure Probability by Wave Overtopping over Grass-Covered and Damaged Dikes. Doi: 10.3390/w13050690

van Bergeijk, V.M., Warmink, J.J., van Gent, M.R.A. & Hulscher, S.J.M.H. (2019). An analytical model of wave overtopping flow velocities on dike crests and landward slopes. Doi: 10.1016/j.coastaleng.2019.03.001

The models use datasets of experiments on a grass-covered dike near Millingen and are further applied at the Afsluitdijk.

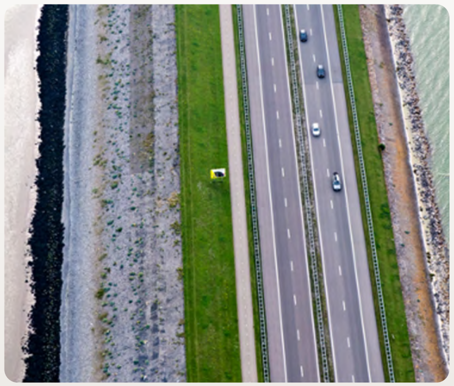


Photo by Rijkswaterstaat, beeldbank.rws.nl / Joop van Houdt.

Project Summary

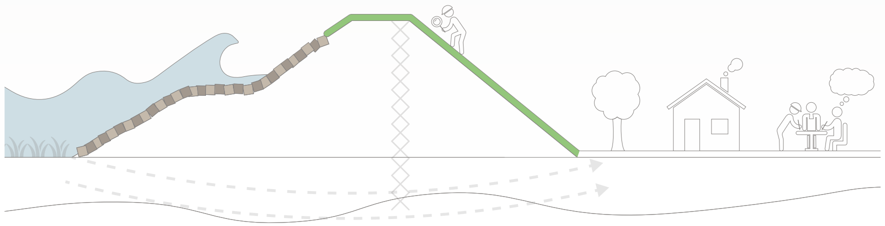
D6 - Berms and roughness elements

Better methods for estimating their influence on the wave overtopping discharge

By Weiqiu Chen

University of Twente

Project start: 09/2017
Project end: 09/2021



Promotors

Prof. dr. S.J.M.H. Hulscher
University of Twente

Dr. J.J. Warmink
University of Twente

Prof. dr. M.R.A. van Gent
Deltares, Delft University of Technology

Outcome

In this project, we developed new empirical equations and numerical models for predicting the effects of berms, roughness and oblique waves on wave overtopping at dikes. Better estimates of these effects can lead to more accurate predictions of wave overtopping, which are important for dike design and reinforcement. Physical model results demonstrated that roughness elements applied on the upper part of the waterside slope are more effective in reducing the overtopping discharges. The newly developed numerical models can predict the overtopping discharges and overtopping flow parameters with a good accuracy, which shows a potential to become a complementary tool with empirical equations for predicting wave overtopping at dikes.

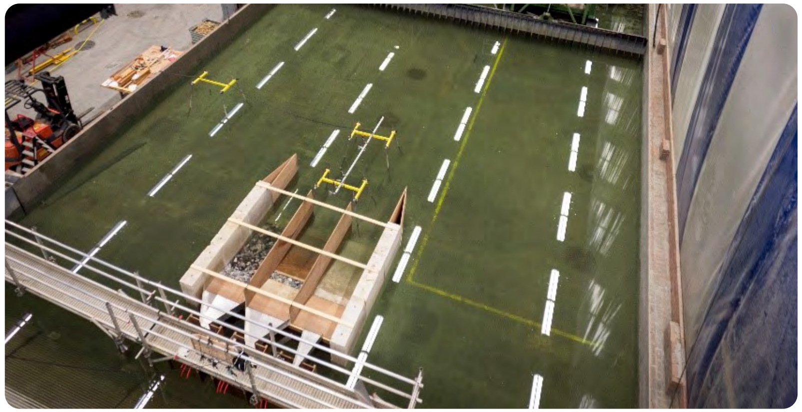


Figure 1: Physical model tests in the Pacific Basin at Deltares. Photo by Deltares.

Motivation and practical challenge

Due to climate change, sea-level rise and land subsidence, there is an increasing risk of coastal flood disasters worldwide, especially in low-lying countries like the Netherlands and densely populated countries such as my homeland China. Against this background, some existing flood defences such as coastal and riverine dikes may not satisfy the safety standard and therefore require reinforcement. To reduce the average overtopping discharge at dikes, reinforcement measures are typically built over the slope of the waterside. These measures include transitions with almost horizontal slopes, also called berms, and roughness elements such as block revetment (**Figure 2, top**). Thereby, permeable and impermeable blocks over the slope transitions of dikes can dissipate the energy of the overtopping discharge (**Figure 2, bottom**). The presence, absence, or combination of these elements naturally leads to the question: To what extent can these reinforcement measures reduce overtopping rates? Improved prediction methods are necessary for more efficient dike design and reinforcement.

Research challenge

As shown in the pictures in **Figure 2**, almost horizontal berms and various types of roughness elements are combined along the waterside slope, but what are the effects of these elements on the average overtopping discharge at dikes?

Innovative components

This project gives better insights into the influence of berms and roughness elements on wave overtopping with the aim to define more accurate guidelines for the design and safety assessment of dikes. The main components of my research are:

Figure 2: **Top:** Various types of roughness elements and a berm applied at a dike. Source: EurOtop (2018, p. 103). **Bottom:** Wave run-up and overtopping at dikes in the Netherlands (left) and embankments in Italy. Source: EurOtop (2018, p.103 and p. 51).

1. **New empirical equations for estimating the berm and roughness influence.** These new equations are derived based on experiments for a combination of permeable, impermeable and smooth revetments over slopes on the waterside with a berm. The equations were further validated against the numerical model to estimate the average overtopping discharge at dikes.

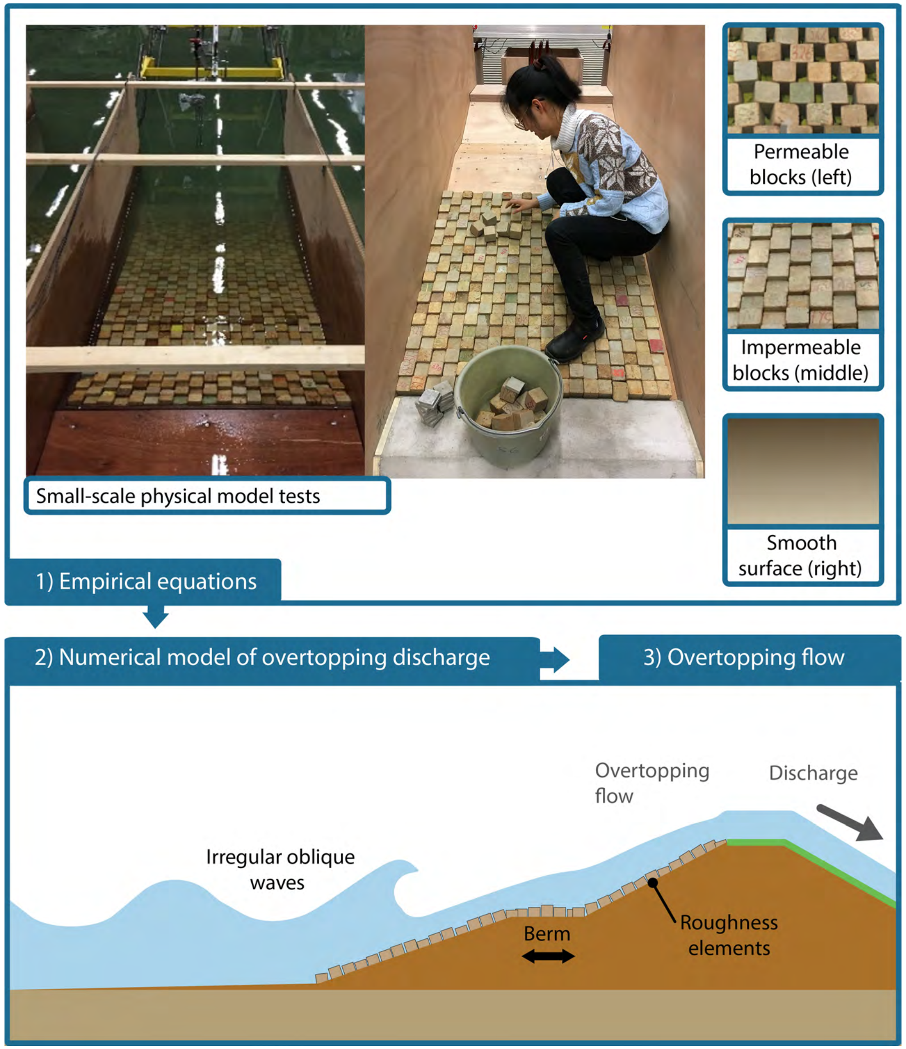


Figure 3: Main components of the research. Photos provided by Weiqiu Chen and scheme adapted from EurOtop (2018).

2. **Numerical model of overtopping discharge.** We used OpenFOAM software to model the overtopping at dikes to accurately predict the average overtopping at dikes with a berm and roughness elements. This model is also extended to 3D to include the effects of the oblique waves.
3. **Numerical model of overtopping flow characteristics.** We extended the 2D OpenFOAM model to study the influence of berms and roughness on the overtopping flow velocity and layer thickness at the waterside edge of the dike crest. These flow parameters can be used as the inputs for erosion models.

Relevant for whom and where?

Designers and advisors concerned with reducing flood risks by applying berms and/or roughness elements at dikes.

Progress and practical application

We conducted physical model tests with four configurations of permeable, impermeable and smooth surfaces in the experimental facilities of Deltares in the Netherlands. We derived new empirical equations for estimating the influence of berms and roughness on average overtopping discharges based on the analysis of the experimental data. The new roughness equation can deal with varying roughness along the slopes with a berm. We found that the roughness elements located on the upper slope contribute the most to reducing overtopping discharge. The results show that the new equations significantly improved the predictive accuracy of overtopping discharge compared to existing prediction methods from available technical guidelines (TAW, 2002; EurOtop, 2018). We also developed an OpenFOAM numerical model within which it is easy to change the dike configurations and estimate the average overtopping discharge and flow parameters.

Recommendations for practice

- For estimates of overtopping discharges, take into account that the roughness factor in existing overtopping equations is not constant but varies with wave properties and crest freeboard.
- Consider applying roughness elements at the higher part of the water-side slopes to effectively reduce overtopping.
- Further investigate the dependency of oblique wave influence on the berm width for a more accurate prediction of overtopping discharges when oblique waves and a berm are present at the same time.

Key project outputs

Chen, W., van Gent, M.R.A., Warmink, J.J. & Hulscher, S.J.M.H. (2019). The influence of a berm and roughness on the wave overtopping at dikes. Doi: 10.1016/j.coastaleng.2019.103613

Chen, W., Marconi, A., van Gent, M.R.A., Warmink, J.J. & Hulscher, S.J.M.H. (2020). Experimental Study on the Influence of Berms and Roughness on Wave Overtopping at Rock-Armoured Dikes. Doi: 10.3390/jmse8060446

Chen, W., Warmink, J.J., van Gent, M.R.A. & Hulscher, S.J.M.H. (2021). Numerical investigation of the effects of roughness, a berm and oblique waves on wave overtopping processes at dikes. Doi: 10.1016/j.apor.2021.102971

Findings from this project are developed in an experimental lab but are applicable to dike locations where the berms and combined roughness elements are applied.

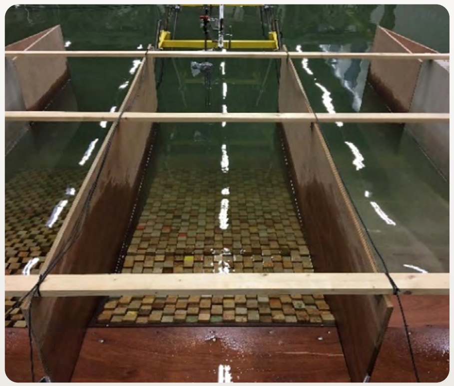


Photo by Weiqiu Chen.

Storyline

Increased flood safety due to time-dependent pipe growth

Dike safety assessments can be optimised when considering the time that the water flowing underneath the dike takes to erode its foundation.

By Joost Pol
Delft University of Technology

Piping or the erosion process in the dike foundation takes time and may not evolve into a dike breach and flooding during a high-water event. Quantifying the time-dependent aspects of piping helps the responsible authorities and technical advisors to reduce the scope of reinforcement efforts and that way meet safety standards faster and cheaper.

Piping is a gradual erosion process. It starts when water flowing through a sandy dike foundation erodes so much sand that it forms a small (mm size) channel or 'pipe' that may (or may not) grow into a shortcut towards the river. Dike safety assessments and designs neglect the time piping takes to develop. Without considering the time development of piping, the dike failure calculations may be too conservative, particularly if:

- high-waters are relatively short, or
- the piping erosion can be stopped with timely flood fighting interventions.

Piping accounts for a large part of the reinforcement costs of the Dutch dikes

Large parts of the Dutch dikes may need to be reinforced with

Cover photo: Large-scale experiment at the Flood Proof Holland test facility to study piping resistance after multiple flood events. Photo by Joost Pol.

respect to piping for meeting the safety standards (target probability of dike failure shown in the map).

Historically, sand boils (*blue dots on the map*) mainly occur in the river area (*see the storm surge - river flood area division on the map*), raising the question of whether piping is a risk along coasts. Although the number of sand boil observations may be lower in the coastal area, one of the two dike breaches (*red stars on map*) in the Netherlands attributed to piping is located along the coast (Strijenham breach near Tholen).

River vs coastal flood duration
One factor that influences piping is the flood duration. Riverine floods are typically caused by long-lasting high water levels (weeks). Instead, storm surges at the lakes and coast are typically short-lasting (days). In coastal areas, the development of piping is limited by the short events. In river areas, there is more time available for pipe erosion, which in turn may also give extra time for flood fighting by, for example placing sandbags.

If we can predict how fast piping develops, we can optimise reinforcements and inform flood fighting operations. However, considering or (not) the time factor into dike assessments and design practice may depend on the case. Therefore, I made the following research question part of my PhD research (see project D3) at the TU Delft and the All-Risk programme:

"How much does dike safety improve for river and coastal dikes, when considering the time piping takes to develop?"

Studying piping under short-lasting high water levels and with timely flood-fighting interventions
By using three complementary methods, I investigated the time-dependent aspects of piping:

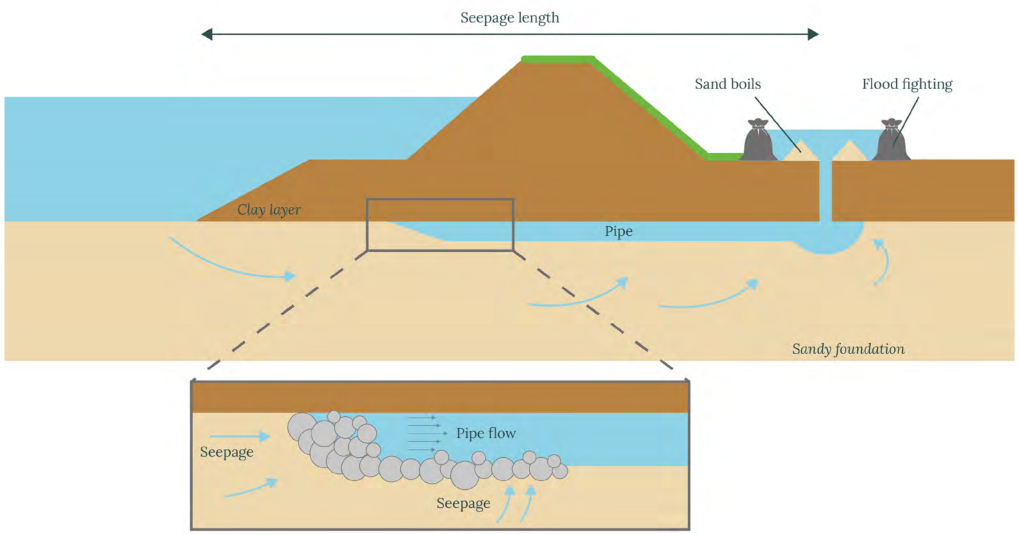
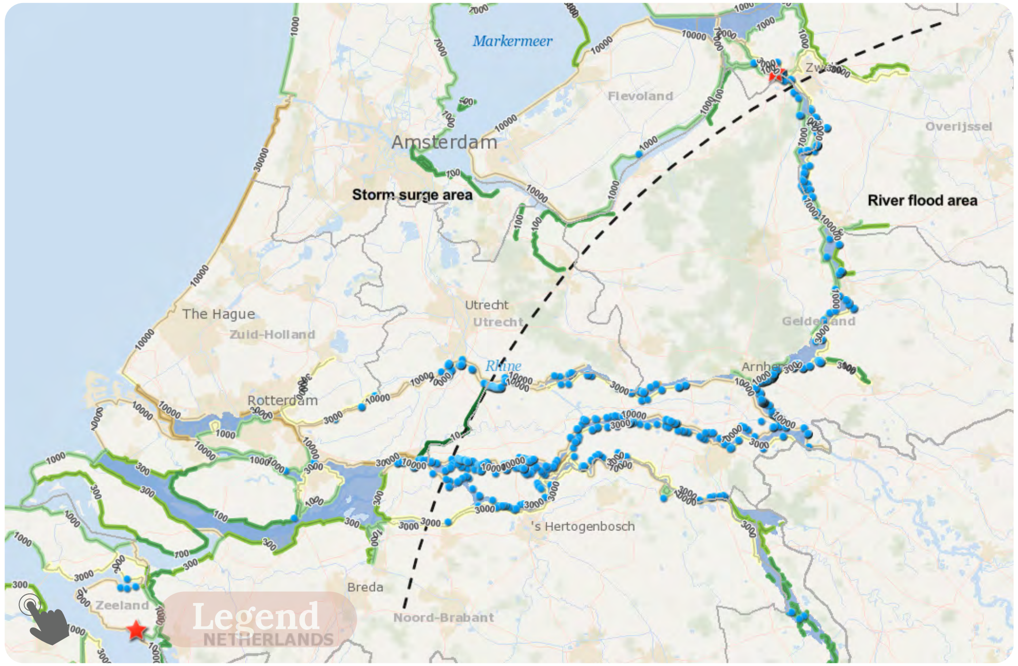
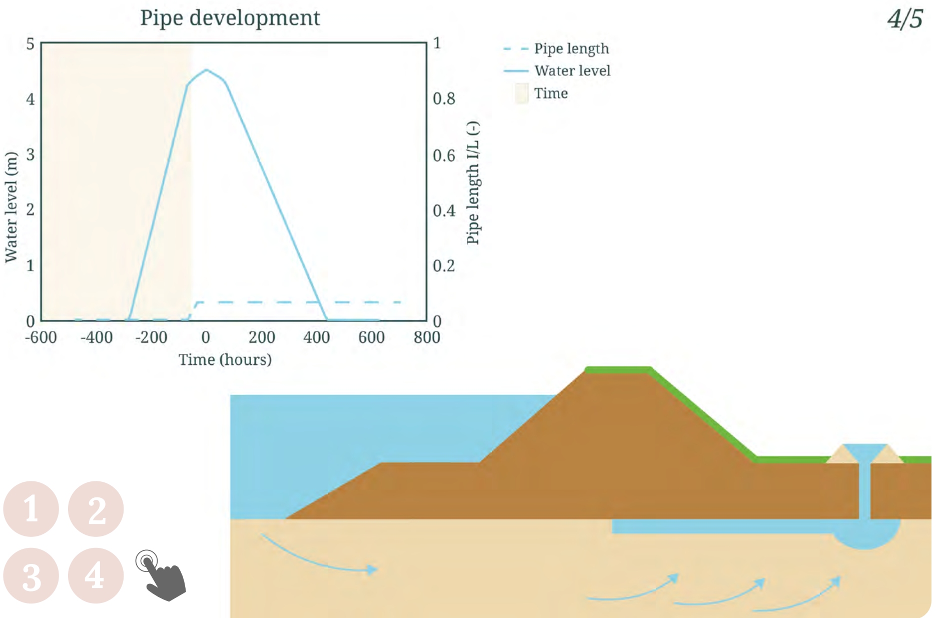


Illustration of the piping erosion processes. Adapted from Robbins & Sharp (2016, Figure 1).



Map data by Esri, (IHO-IOC) GEBCO, DeLorme, NaturalVue, NGS. Primary dikes from Nationaal Georegister, sand boil observations via https://wellocaties.app.

Experiments on pipe development. **Top left:** large-scale test in the Flood Proof Holland facility at the TU Delft. **Top right:** measurements during the large-scale test. **Bottom right:** sand boil in the large-scale test. **Bottom left:** small-scale experiments. Photo © Sam Rentmeester.



The development of the pipe length during a high water event. Based on schemes by Joost Pol.

- Lab experiments at small (50 cm) and large (10 m) scales increase our understanding of the piping processes in the pipe (mm size), reveal which factors influence the time scale of erosion, and help validate the below pipe development models.
- A simplified pipe development model helps predict piping for dike properties and water levels beyond the conditions of the lab experiments.
- Probabilistic methods allow to include uncertainties of, for example, the high-water duration, the soil properties and the seepage length to determine whether a particular dike meets the safety standards.

The factor time in the piping failure process

The figure on the left illustrates the development of the pipe length during a high water event. Important factors that determine whether a pipe develops into a breach during a high-water event are:

- The pipe length which is already present before a high-water event occurs.
- How early in the event pipe growth starts. This is related to the timing of clay layer cracking (uplift) and sand boil formation (heave).
- The rate of pipe progression, which increases with increasing grain sizes and higher water levels.
- High water level duration (short storm surge vs. long river floods) determines the time available for erosion.
- The effectiveness of flood-fighting interventions by considering their detection error and required time for the sandbags placement.

Six hypothetical cases

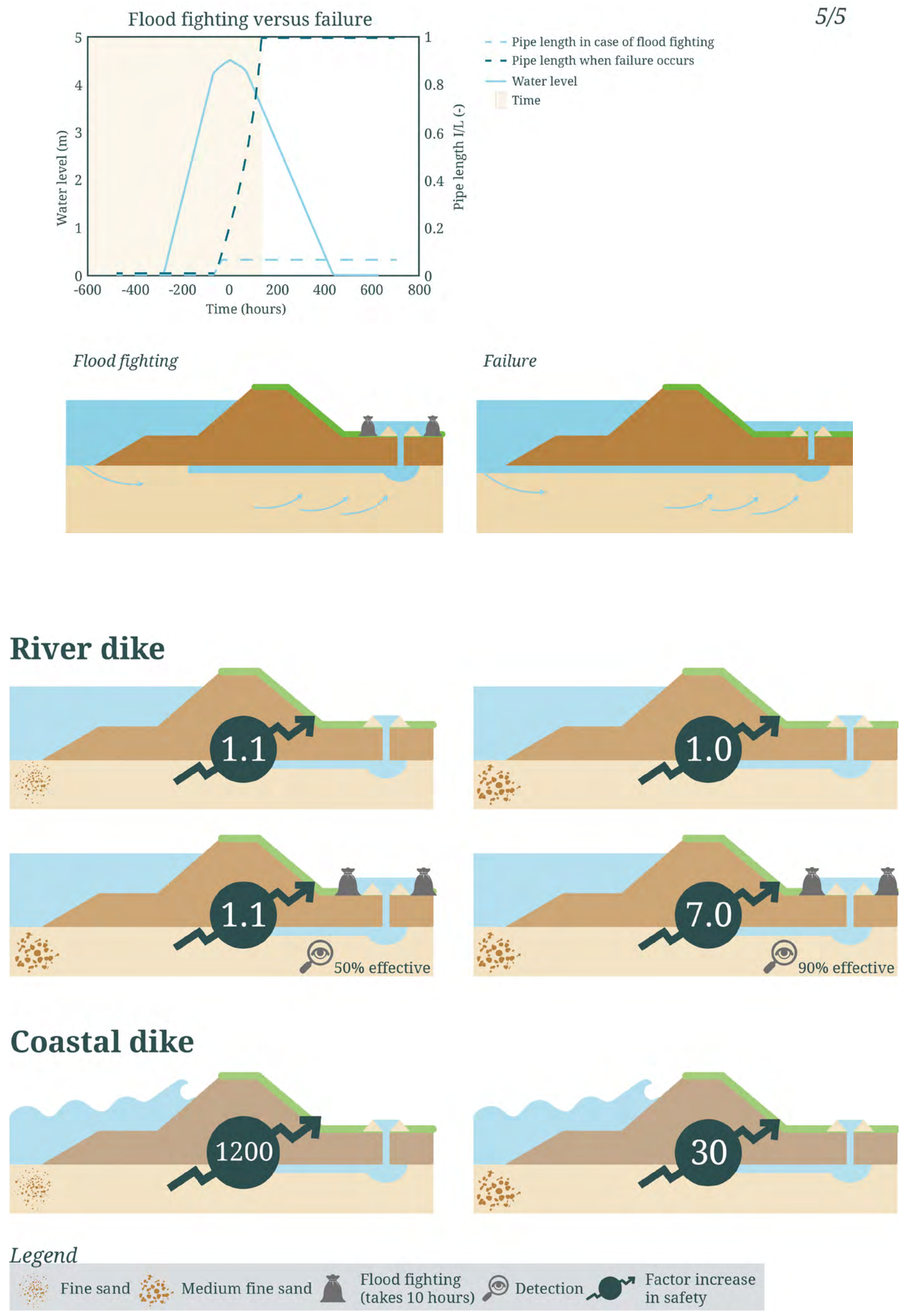
To find out whether the time development of piping makes a difference in the river and coastal dikes, I formulated six cases in which I varied the parameters which one might expect to have a significant influence on the calculated safety level and thus on the required dike reinforcement.

The six cases are hypothetical dikes, four for a river dike and two for a coastal dike. In all cases, the seepage length is 50 m, with the conservative assumption that a pipe is already present up to 1/2 the seepage length.

- For both coastal and river cases, I varied the grain size from fine sand (0.180 mm) to medium-fine sand (0.350 mm).
- The high-water duration varies between the extreme cases of storm surge (days) and Rhine river discharge (weeks).
- For the river case, I consider two scenarios for flood fighting effectiveness with sandbags (detection 50% or 90% successful). In coastal cases, flood fighting interventions are not considered as these are hardly possible during a storm.

When does it make a difference?
For each case, I calculated the probability of failure with and without considering the timing of pipe development. The ratio between these probabilities indicates the difference between considering or not considering the timing of piping development into the dike safety assessment calculations. The higher this factor, the larger the increase in dike safety.

These results indicate that the high water duration has the largest impact. In the river cases, there is hardly a change in failure probability because the high water lasts much longer than the time required for pipe erosion, but in the coastal cases it is highly unlikely that piping leads to a breach during a single storm. The coastal cases show that the slower erosion in fine sand compared to medium fine sand can make a large difference. Regarding the river cases, the results show that a significant safety increase can be achieved in case of effective flood fighting (90% successful detection, 10 hours placement time).



Results of the experiment with the six hypothetical dikes. Based on schemes by Joost Pol.

Lessons learned

Considering the time needed for piping development can significantly reduce the failure probability. Not only in coastal areas with short storms but under certain conditions, such as effective flood fighting, also in river areas.

The comparison between the six hypothetical cases with still some conservative assumptions already provide great insights under which conditions the time of piping development is a relevant factor, and by which order of magnitude it affects the failure probability.

Finally, including the factor time for piping requires a shift in thinking: there is not just a critical water level, but combinations of peak water level and high-water duration that gradually lead to failure.

Next steps

As this research is still ongoing at the time of writing, I currently use the experimental data to improve the physical basis of the simple pipe development model. Furthermore, I am studying the effects of pipe development under multiple high-water events. Those findings may justify loosening the conservative assumption that there is a pipe present already up to 1/2 the seepage length.

A useful step for practice would be to use the research findings to derive simplified rules to include the effects of time in dike safety assessments. For instance, a reduction factor on the computed failure probability, depending on the governing high water duration, seepage length and foundation soil.

Since flood fighting appears to be an important factor in the river area, a discussion is needed when we want to use that information in dike design. If we want to include it, the effectiveness (detection accuracy and required time) of interventions needs to be quantified further and improved.

Interested to know more?

Click or scan the QR Code to view the online version of this storyline. Or view:

- Progression rate of backward erosion piping in laboratory experiments and reliability analysis (Publication on earlier version of the reliability analysis)
- Temporal Development of Backward Erosion Piping in a Large-Scale Experiment (Publication on large-scale test)

Acknowledgements

This work is part of the Perspectief research programme All-Risk with project number P15-21, which is financed by NWO Domain Applied and Engineering Sciences. I thank Ludolph Wentholt from STOWA and Anouk te Nijenhuis from the Flood Protection Programme HWBP, Lieke Lokin from HKV, visual designer Pien Buter, and Juliette Cortes from the All-Risk editorial team for their input on this storyline.

Wave overtopping on a grass-covered dike with a road on top. Photo via https://coastalpartners.org.uk/.

Dike cover failure during experiment on a dike near Millingen. Photo by Juan Pablo Aguilar Lopez.

The theme:

Wave overtopping results in a high hydraulic load on the dike cover and can lead to erosion of the grass cover. The overtopping research in the All-Risk programme was focused on two aspects: methods for the outer slope and methods for the inner slope.

Would you like to see the presentations of the researchers? You can view them **by clicking or scanning the QR Code.**

Reflection

Towards a realistic approach of resistance against wave overtopping

Webinar team

Moderator

Jord Warmink

Twente University

Speakers

Weiqiu Chen

Twente University

Vera van Bergeijk

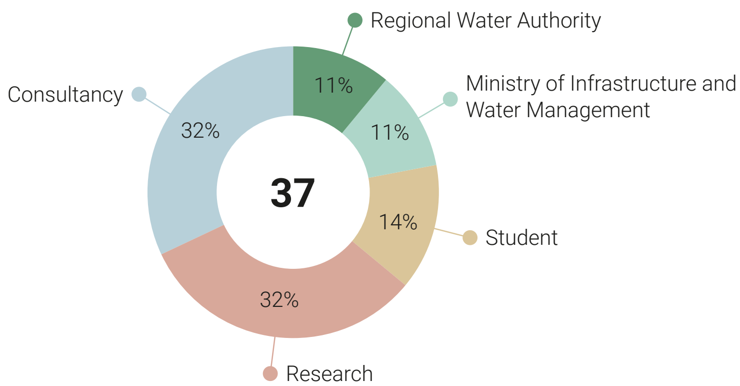
Twente University

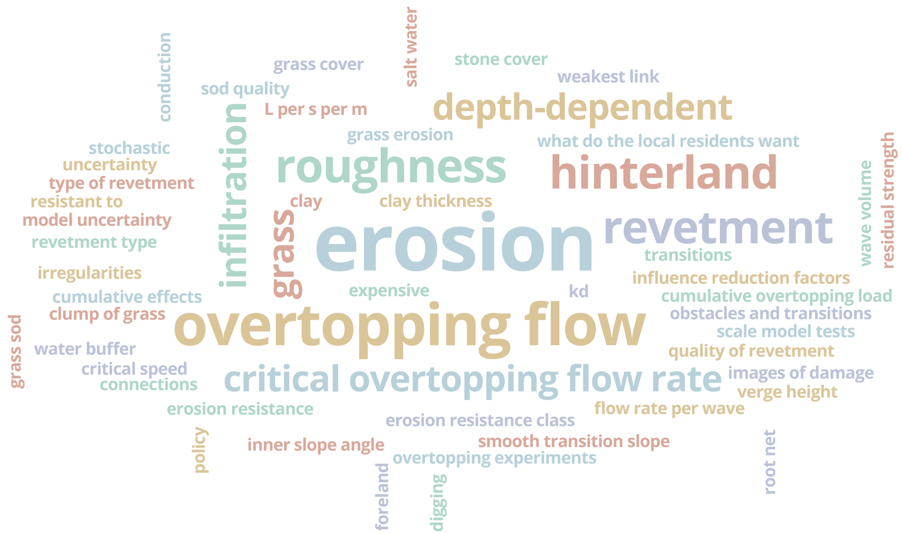
Introduction

Aroen Mughal

Hillblock

Participants





What terms do you think of when realistically estimating resistance to wave overtopping?

This reflection emerged from the discussion between researchers and participants during the All-Risk webinar organised on June 10, 2021.

The amount of wave overtopping – and thereby the load on the cover – can be reduced using a berm on the outer slope in combination with roughness elements. Weiqiu Chen performed physical experiments and numerical simulations to improve the existing empirical formulations for wave overtopping including the effect of these two components. Additionally, the effects of transitions on the wave overtopping flow and resulting cover erosion on the inner slope are studied in the All-Risk programme. Vera van Bergeijk developed multiple models to gain more insights into the load and erosion of overtopping waves near transitions. These two aspects are combined in a case of Hillblock where a numerical model is developed to calculate the load on the dike cover along the entire dike profile. The gained insights into the load are used to develop block revetments to reduce the load and to increase the strength of the cover on both the outer and the inner slope.

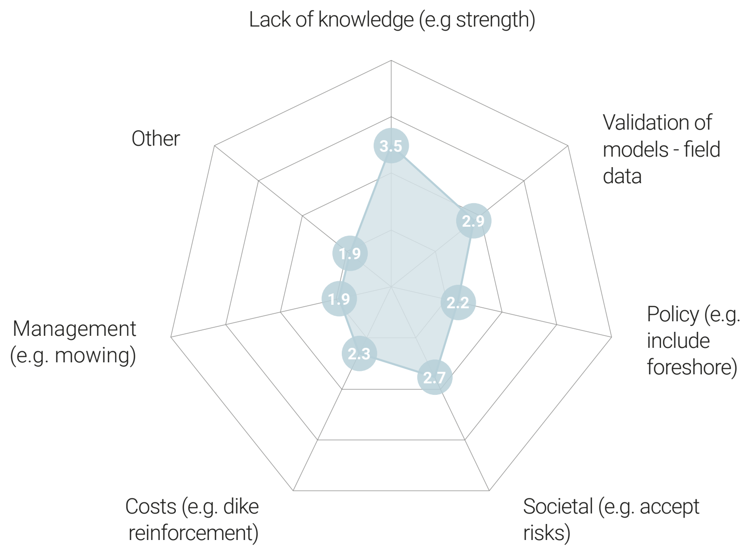
The discussion

The maximum allowable amount of overtopping is expressed as the critical overtopping discharge, a measure for the volume of water that is allowed to flow over the dike per second without causing failure of the dike cover. Failure of the dike cover is defined as the exceedance of 20 cm erosion depth related to the depth of the topsoil where the roots of the grass cover lead to additional cover strength. At the moment, 10 l/s/m is the maximum allowable overtopping discharge used in dike designs although overtopping tests have shown that the grass cover is able to resist larger amounts of wave overtopping. The participants respond positively to allowing more wave overtopping provided that the grass cover is able to resist these amounts. It is not possible to perform inspections and emergency measures during these large amounts of wave overtopping. This should not be a problem since inspections are never performed during design conditions and it will probably be too late for emergency measures during these extreme overtopping conditions.

There are multiple methods to strengthen a dike for wave overtopping such as improving the grass quality, reducing the wave load, strengthening of the weak spots such as transitions or heightening of the dike. The best method depends on the situation, for example, the effect of a rougher outer slope only has a limited effect for river dikes where the waves are small. Strengthening weak spots and improving the grass quality are interesting options for dikes with limited available space. The effect of these options remains uncertain while the heightening of the dike will always work, however, against which costs?

Increasing knowledge and inspection/monitoring are mentioned as options to reduce risks and existing knowledge gaps. Few observations of overtopping on the inner slope are available next to the experiments with the wave overtopping simulations, but insights into the grass cover strength can also be gained from studying wave run-up. The quality and damages to the grass cover are easier to inspect during conditions without wave overtopping. The wave overtopping simulator is a useful tool to gain knowledge during design conditions.

The main uncertainties are related to transitions and water levels and therefore these two components have a major impact on the future risk. Draught seems to have a smaller impact: observations during last summer (2020) showed that the grass cover coloured brown but the root structure that provides the main resistance was not damaged. Other challenges are related to knowledge gaps in the erosion process such as residual strength, head-cut erosion and the maintenance of transitions and the grass cover. Additionally, social challenges exist related to the multi-functionality of dikes such as the use of space and working with opposing interests.



Participant responses to the question: What are the main challenges?

Towards a realistic approach of resistance against wave overtopping

The dike cover has failed according to the current failure definition when the upper 20 cm are eroded, while the dike is still able to fulfil its water-retaining function. The failure definition would become more realistic and less conservative when the strength of the underlying clay layers is included. However, the follow-up erosion processes remain uncertain and the resistance of the remaining soil layer for overtopping is unknown. More research into these two topics is required before the failure definition can be extended. This also became clear during the webinar where the participants indicated that it is essential to increase the knowledge on the entire dike cover (grass cover and underlying clay layer) to make the dikes future proof. Additionally, information on the strength of the dike core is desired since it is currently unknown what will happen with the dike core during overtopping and if the dike core can contribute to the residual dike strength. This holds specifically for river dikes where the strength of the dike core will be essential to reduce the number of reinforcements, especially when the strength of the core can be incorporated in the assessment.

About experiments and numerical models

Wave overtopping experiments provide many insights into the load that the dike cover can resist. However, these experiments are expensive and it is often not possible to adapt the dike geometry. This means that the results are only applicable for the conditions that were tested. Moreover, the overtopping experiments showed that the dike cover often fails near anomalies such as animal burrowings or transitions. In these cases, it is difficult to determine the dike cover strength. Numerical models can help to extend the results, such as formulas and calculation methods, to other conditions and dike geometries. Additionally, models can be used to increase our understanding of the failure process of the dike cover. For example, the formulas for the overtopping discharge are extended so the effects of a berm and roughness elements can be calculated more accurately. Numerical models are also useful to study the processes and gain insights into the load on the dike cover which is difficult to measure during experiments. Each process can be studied separately in a model to determine the dominant process at transitions. For example, it is challenging to measure the effect of turbulence during wave overtopping conditions. Simulation of wave overtopping experiments with a numerical model makes it possible to determine the amount of turbulence and thereby increase our knowledge of the hydraulic load and strength of the dike cover.

It became clear during this webinar that we are open to allowing more wave overtopping and wish to incorporate the residual strength in the current assessment. However, we need to increase our knowledge on the erosion processes before this could be implemented, for example, the strength of the soil layers under the grass cover and the processes near transitions and damages in the dike profile.

All-Risk recommendations:

- Use numerical models to extend calculation methods outside of the tested range and to gain insights into the important processes.
- Consider a combination of a berm and roughness elements on the outer slope as this may reduce the amount of overtopping. This reduction is calculated more accurately using the new formulas.
- Calculate the load and erosion along the crest and landward slope, because it is not known upfront what the weakest point along the dike profile is, and transitions also have an effect on the flow downstream.
- Perform more research into the strength of the grass cover, underlying clay layers and dike core; this can help to adapt the failure definition, making the assessment of grass erosion by overtopping waves more realistic and less conservative.
- Expand knowledge about the erosion process by overtopping waves, such as the effect of erosion near transitions and the erosion mechanisms at larger erosion depths.

Dike breach caused by inner slope instability. Photo by Weichel (2013).

The theme:
Macro instability of the inner slope is an important failure mechanism that has a large influence on the costs of dike reinforcements and their impacts on the landscape. There are various uncertainties considering the strength parameters and models. There seem to be various options when a dike does not meet the standards: better parameter estimation, better models, or realising a conservative and expansive reinforcement. Which options could we explore to deal with macro instability in an efficient manner?

Would you like to see the presentations of the researchers? You can view them **by clicking or scanning the QR Code.**

Reflection

Macro stability – better parameters or models, or do we need to reinforce the dikes?

Webinar team

Moderator

Bas Jonkman
Delft University of Technology

Speakers

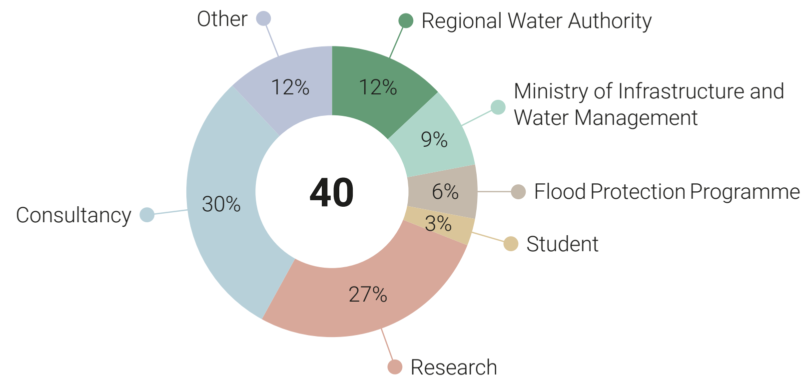
Arny Lengkeek
Delft University of Technology, Witteveen +Bos

Introduction

Martin Schepers
Aveco de Bondt

Guido Remmerswaal
Delft University of Technology

Participants



This reflection emerged from the discussion between researchers and participants during the All-Risk webinar organised on June 14, 2021.

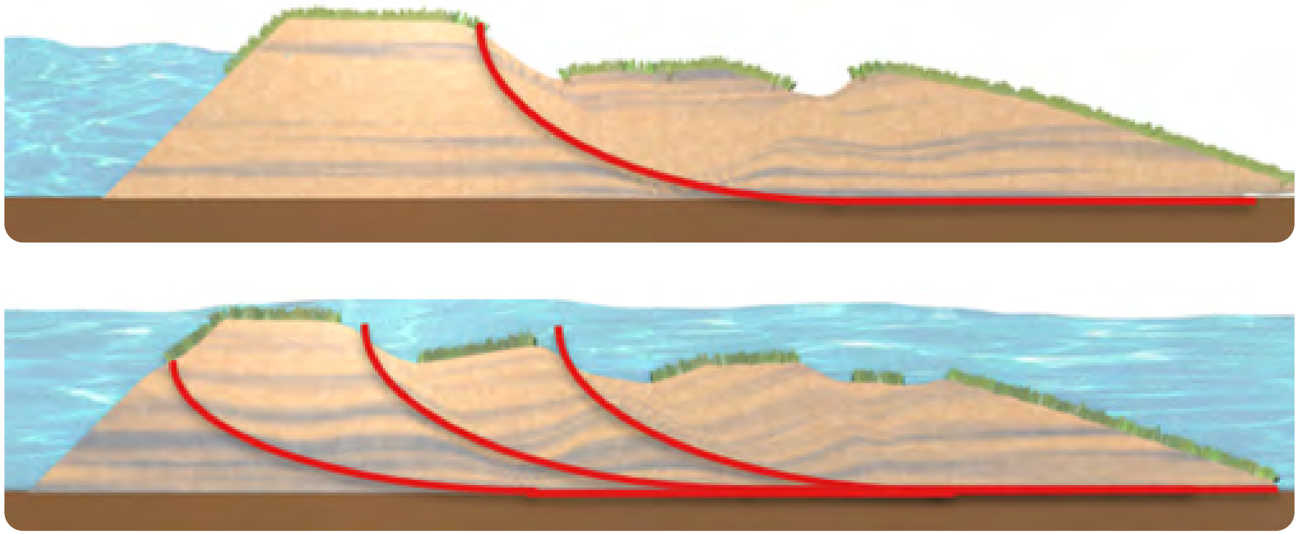
Contributions, discussion and reflection

During the introduction presentation, Martin Schepers discussed the challenges in the field. He signalled that there are many uncertainties in the knowledge and information, and that expertise is not equally distributed amongst organisations. He also emphasised that there is a gap between theory and practice. Arny Lengkeek summarised his research (D2) as part of All-Risk, which also focused on the Eemdijk full-scale field test. He presented new insights in soil classification and parameter estimation, particularly for weak deltaic soils that are present in the Netherlands. The new methods can contribute to a better estimation of the safety of a dike and more efficient reinforcements.

Guido Remmerswaal presented his research (D1) in the field of MPM (Material Point Method). The method – which is still under development – enables the user to analyse multiple subsequent slides and therefore gives insight into residual strength. The residual strength is much dependent on the heterogeneity of the soil strength. Follow-up slides are possible due to correlations between weak soil layers.

The discussion focused on multiple topics

Participants seemed to agree that the main challenge is the lack of knowledge. This concerns multiple types of knowledge, and their combination, e.g. project experience, and expertise in various fields such as geotechnics, models and probability. The participants acknowledged that there is a need to share and transfer knowledge. There is no one recipe for success, but multiple key success factors. This need is about

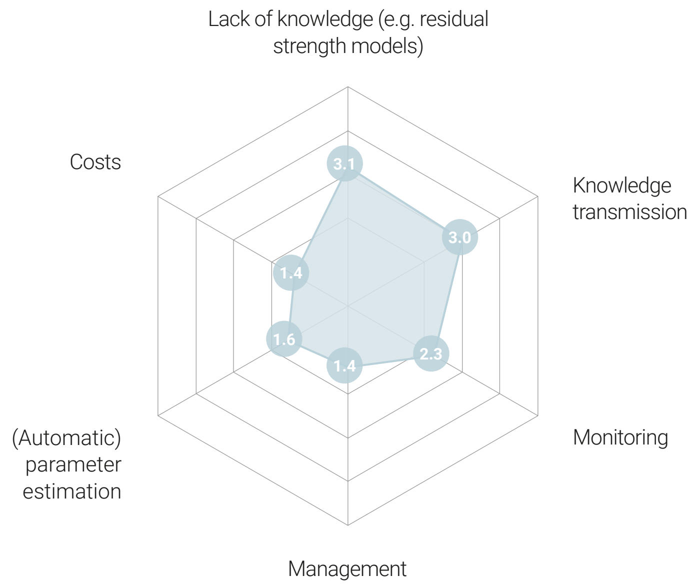


A single slide, **or** subsequent slides that can lead to flooding. Illustration by Coco Man and Guido Remmerswaal based on Remmerswaal et al. (2021) and Man (2021).

sharing knowledge (also between engineering firms) and establishing an open environment to share experiences concerning topics that can be sensitive, such as slides, deformations, and incidents during projects. Webinars seem a suitable format. Knowledge from experts in other fields, such as archaeology or soil science, should not be forgotten either. Knowledge from other domains such as archaeology and physical geography should also be involved.

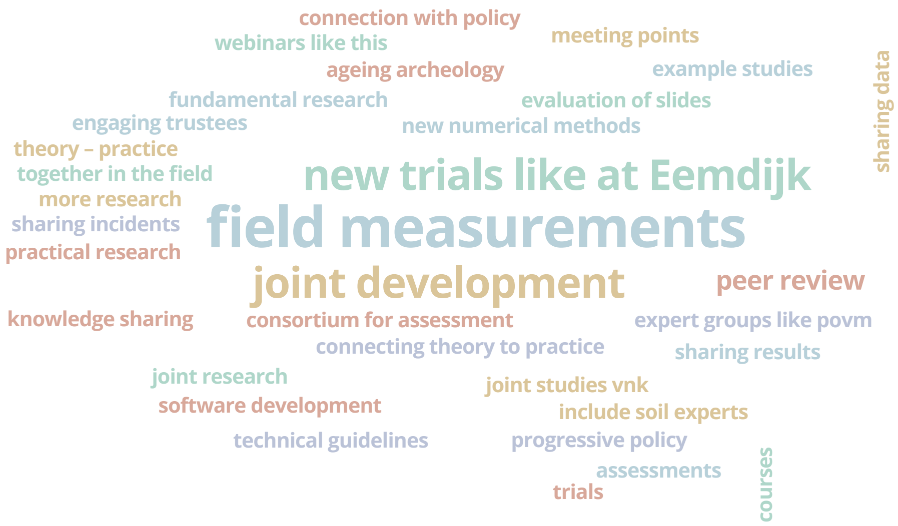
Other factors and initiatives were also considered important: *More soil investigations and better soil classification methods.* Not all participants agreed that including residual strength was a good idea. This also became clear in the case study that was discussed. While some participants would accept large slides and deformations as long as flooding did not occur, others did not consider slides acceptable. It was mentioned that for dike managers, other functions (e.g. road function) and perception of safety would make it undesired to experience regular instabilities.

The participants emphasise that the positive effects of residual strength can only be included in a design if all negative effects are also included (e.g. residual loads and/or ignored causes of failure). When modelling residual strength, it is therefore important to calculate the entire failure path. In addition, side functions (e.g. road function) must also be taken



Participant responses to the question: What is the most important challenge for macro-stability?

into account, for which again different acceptable probabilities apply. The discussion also focused on approaches that could contribute to a better soil characterisation. The majority seemed to support an approach in which expert knowledge would be combined with smart methods for automatic parameter estimation. Also, novel techniques such as artificial intelligence (AI) could offer opportunities and could be useful to utilise large data collections. When applying new techniques, experts should still be involved to avoid black boxes. Automated approaches may shift the balance towards automation and quantity of calculations, at the expense of quality.



Responses to the question: How do we get the required knowledge at the next level?

All-Risk recommendations:

- Share experience and expertise through webinars and expert communities. This could concern academic knowledge, but also practical experiences, slide incidents and experiences with reinforcements.
- Utilise newly developed classification methods for soft soils.
- Reinforcing dikes with sheet piles can contribute to more robust failure behaviour (more residual strength and fewer deformations and dike breaches), and it reduces the sensitivity for the presence of local weak soil layers.
- Develop MPM toward broader applicability (stable calculations for multiple soil types and dike geometries).
- Knowledge concerning parameters and soil behaviour during large deformations is essential in this respect.
- Explore possibilities to combine existing methods for instability assessment with MPM to gain more insight into the possibility and likelihood of follow-up slides and failure processes.
- Define criteria for acceptable deformation of dikes (also linked to the Eurocode), considering the extent and acceptable frequency of deformations.

Professionals and interested people receive information about a reinforcement project at the Lauwersmeerdijk during 'Dijkwerkers on Tour'. Photo by HWBP.

Chapter 6
Law, Governance and Implementation

Introduction

By Willemijn van Doorn-Hoekveld and Marleen van Rijswick

Although the lion's share of research within All-Risk is technical in nature, what is innovative about this programme is that it also focuses on the non-technical legal-administrative questions. This broader approach is relevant to actually put the technical innovations and research into practice. Technically, anything can be made, but flood protection does not take place in an isolated laboratory, but in the physical living environment, where people, property and other interests, such as nature conservation, spatial planning or recreation, also have to be taken into account.

Within the governance part of the All-Risk programme, the research team in project E1 made room for legal questions from practice. Some example results of this project include the advice of the researchers on the conversion of the safety standards from the Dutch Water Act to the upcoming Environment and Planning Act, the exceptions for achieving the obligations of result to meet the new safety standards under the Environment and Planning Act, the division of responsibilities in the Double Dike project, and how to legally deal with foreshores.

Moreover, the research of Emma Avoyan (project E2) also had a central role. Emma showed that despite the legal complexity, attempts at organising cross-sector collaboration within dike reinforcement projects are largely successful. In the exploration phase, two factors appear to be crucial: project managers with skills to connect and the willingness of collaborating parties to contribute financially. Other factors that contributed to productive collaboration were the engagement and shared motivation of the collaborating parties and the presence of relevant expertise or knowledge. A policy-relevant question is how these conditions for successful collaboration can be further developed or promoted.

Last but not least, Martijn van Staveren (project E3) investigated why and how various forms of knowledge can be brought together to design effective and broadly supported flood interventions. In his work, Martijn acknowledges the challenges of reaching out to and appreciating for their contribution to flood risk management different forms of knowledge, which are not yet operationalised or standardised.

Overall, central to the governance projects were the workshops organised with, by and for the users. The workshops showed a great need for clarity about responsibilities, tasks and the clashing sectoral interests of various policy fields. It also turned out that the law is not always well-equipped to be applied to innovations, but many successful projects have overcome these challenges through improved collaboration. Since the biggest challenge, climate change, will only increase the need for innovations, the need to fit these innovations well into the legal system and turn successful collaboration into an established practice will also continue. **To this end, we highlight the following recommendations.**

Firstly, to involve lawyers early on in dike reinforcement projects so that opportunities and preconditions offered by the law can be considered at an early stage. Although ambiguities and bottlenecks can arise from the legislation, in practice, these obstacles can often be resolved so that innovations can proceed.

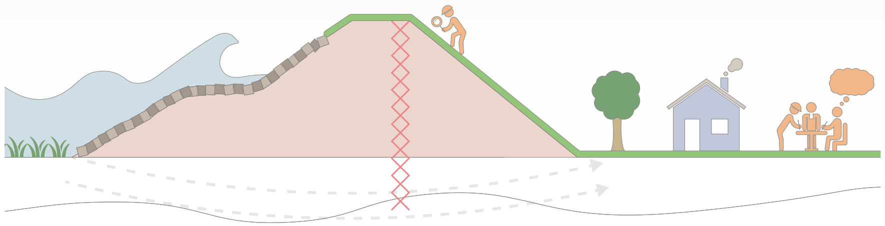
Secondly, to increase the chances of successful collaboration, water authorities should recruit project managers with skills to connect, encourage parties to contribute with resources, and facilitate a collaborative process that motivates parties to cooperate and generate the necessary knowledge and expertise.

Thirdly, there are often various – sometimes relatively unknown – forms of knowledge present that can make a valuable contribution to dike reinforcement projects. Be inspired and go in search of this knowledge with an open attitude and see which knowledge is useful, and be creative in the search for new cooperation opportunities.

Project Summary

E1 - Legal aspects of implementation

Guiding framework and legal advice regarding the new flood protection standards



By Monica Lanz
Utrecht University

and Willemijn van Doorn-Hoekveld
Utrecht University

Project start: 11/2017 Project end: 03/2023

Contributors

Dr. mr. H.K. Gilissen
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Prof. mr. H.F.M.W. van Rijswick
Utrecht University

Dr. mr. F.A.G. Groothuijse
Utrecht University

Outcome

The legal implications of the new risk approach vary according to circumstances in individual cases, but the balance between a lawful, efficient, effective, and acceptable approach must be ensured. This project provided advice regarding the transition of the safety standards in the upcoming Environment and Planning Act (Omgevingswet) and its legal framework to assess lawful, efficient, effective, and acceptable water management. Several academic and professional papers on the legal implementation of the new flood risk standards show the contribution to the overall All-Risk project, such as the book on Foreshores (Roode et al., 2019) focusing on legal implementation. Finally, all this knowledge was shared via workshops and webinars with the end-users, focusing amongst others on flood risk management related to other policy fields, such as nature conservation.

Figure 1: Lady Justice. Photo by Openbaar Ministerie.

Motivation and practical challenge

As a team, we are tackling questions that arise regarding the 'Water Act' (*Waterwet*) and the future 'Environment and Planning Act' (*Omgevingswet*). This legislation regulates the general use and management of water for the whole of the Netherlands and particularly the implementation of the new flood protection standards. Our interest lies in the way the government gives shape to its related public tasks, and the way laws and regulations protect the various interests of stakeholders. The legal challenges for the implementation often derive from the conflicting responsibilities between stakeholders. In addition to this, there is a need for more integrated flood protection balancing between lawfulness, effectiveness, efficiency and acceptability. Therefore, the research for All-Risk has a special meaning for us since it involves the safety of all the people in the Netherlands that live behind dikes. We feel honoured to contribute to this purpose!

Research challenge

With this interest in mind, our research focuses on investigating which kind of legal obligation the new flood protection standards imply for the Dutch water authorities. Moreover, which legal strategies can they apply to contribute to its implementation?

Innovative components

We provide a decision tool that outlines the legal strategies for water authorities to allow areas adjacent to the dikes to contribute to flood risk protection (**Figure 3, top**). The choice between an active, passive or no regulation strategy hugely depends on: (1) The effect of the foreshore on the water safety, and (2) the developments of these areas that may increase flood risk-like natural physical processes and human activities.

Figure 2: Members of the team (left to right): Herman Kasper Gilissen, Frank Groothuijse, Willemijn van Doorn-Hoekveld and Marleen van Rijswick, Monica Lanz (not in picture).

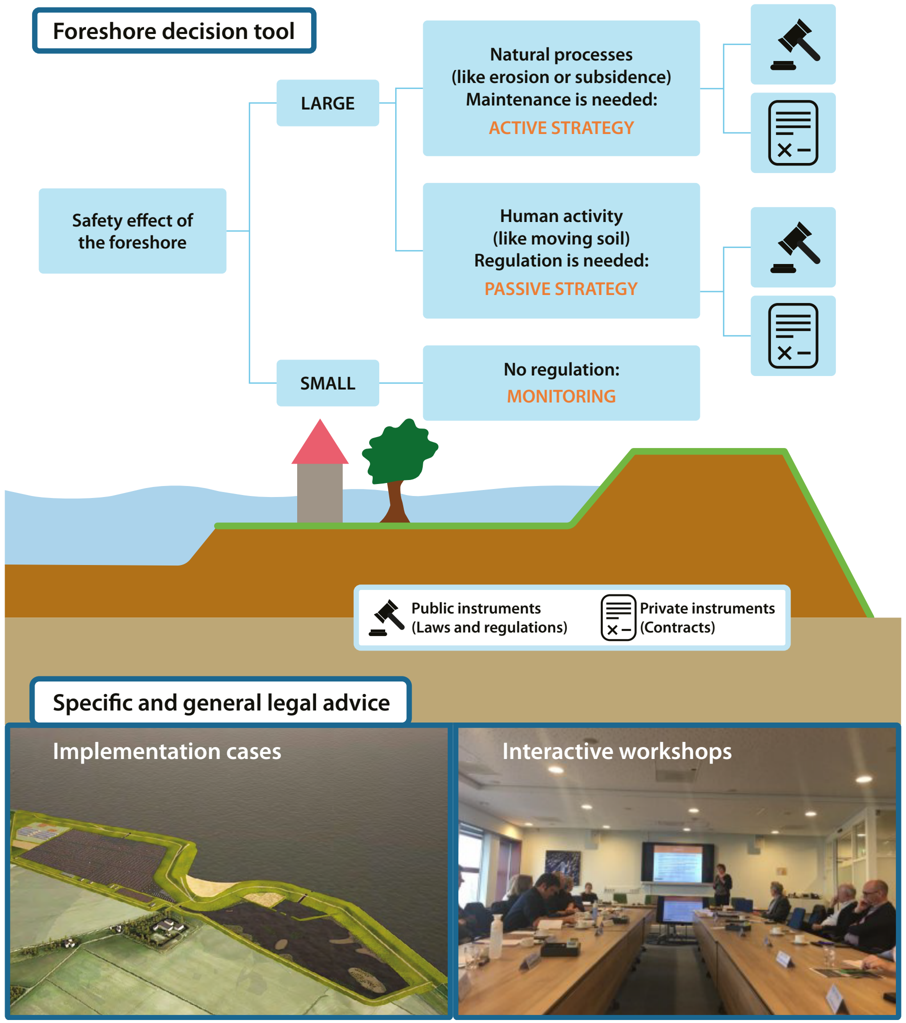


Figure 3: Components of our research approach. The top scheme was adapted from the Handreiking Voorlanden (Roode et al., 2019, p. 89). Image left by https://eemsdollard2050.nl/ and photo right by Marleen van Rijswick.

Depending on the circumstances, the choice can be implemented through public law (regulations) or civil law (contracts).

In the '*Double Dike*' case (**Figure 3, bottom-left**) we advised the Regional Water Authority Noorderzijlvest on the distribution of legal responsibilities. This is an innovative case that will be part of a reinforcement on the north Dutch coast and is not only suitable for flood safety but also for nature, agriculture and recreation. Via interactive workshops (**Figure 3, bottom-right**), we further provide general advice along with other legal specialists of our programme (Soppe Gundelach Advocaten and Element Advocaten) to implementation cases derived from the All-Risk projects (A to D).

Relevant for whom and where?

Our research is relevant for all users with legal responsibilities in flood protection (such as regional and national water authorities, provinces and the Ministry of Infrastructure and Water Management). They can use our findings to handle their duties lawfully.

Progress and practical application

There is a difference between the obligation to *make an effort* to reach the flood protection standards, and the *obligation to achieve* the flood protection standards. Our study of the (new) legislation found that the Dutch water authorities must meet the flood protection standards. Only a few exceptions are provided by law. This obligation ensures legal certainty (including clarity about the government's liability).
Our guiding framework builds upon existing assessment methods and design principles for resilient, resource-efficient and legitimate flood risk governance. So far, the advice for the project-transcending explorations (*POV Voorlanden*) resulted in a legal document (*Juridisch*

Achtergronddocument Voorlanden) and a contribution to the Foreshores guide (Handreiking Voorlanden, 2019). If you are interested in more legal aspects of the implementation of the new risk-based approach, **we invite you to view the project outputs below!**

Recommendations for practice

- Find a good balance between (legal) certainty and flexibility to stimulate innovations in flood risk management.
- Identify the aim (how to comply with the standards) for concrete projects, make the legal responsibilities of authorities clear and provide insight to authorities about the available policy instruments and how to use them.
- Don't fear the law: it provides enough room to manoeuvre to realise a diversity of innovative projects.

Key project outputs

Gilissen H.K., Groothuijse F.A.G., van Doorn-Hoekveld, W.J. &. van Rijswick, H.F.M.W. (2017). 'De nieuwe systematiek van veiligheidsnormering voor primaire waterkeringen: niet eenvoudiger, wel beter'. Tijdschrift voor Bouwrecht 2017(9), pp. 946-657.

van Doorn-Hoekveld, W.J., Gilissen, H.K., Groothuijse, F.A.G., Kok, M. & van Rijswick, H.F.M.W. (2019). Meer zoden aan de dijk met resultaatgerichte normering van waterveiligheid in de Omgevingswet. Tijdschrift voor Bouwrecht 2019(12), pp. 1021-1035.

Hartmann, T., van Doorn-Hoekveld, W.J., van Rijswick, H.F.M.W. & Spit, T.J.M. (2019). Editorial : Special Issue: Flood resilience of private properties. Doi: 10.1080/02508060.2019.1671464

Locations of the main implementation cases that we advise.

Photo by Waterschap Noorderzijlvest.

Project Summary

E2 - Cross-sector collaboration

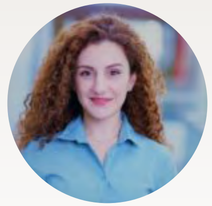
Challenges and benefits from dike reinforcement projects

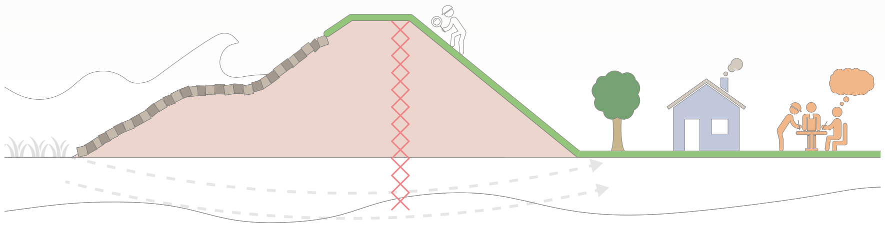
By Emma Avoyan

Radboud University

Project start: 05/2017

Project end: 05/2021





Promotors

Prof. dr. S.V. Meijerink

Radboud University

Prof. P.M. Ache

Radboud University

Outcome

This project provides a better understanding of cross-sector collaboration during the exploration phases of dike reinforcement projects. Despite the growing interdependences, existing power relations between the sectors are characterised by the dominance of the water sector. Cross-sector collaboration can develop as long as it does not compromise flood safety. This configuration mostly resulted in the good performance of collaborative projects characterised by integrative plans and innovative solutions. A number of factors are identified to be important for good performance: the role of connective project managers, the willingness of collaborating parties to contribute financially along with a good engagement process, high motivation,

Figure 1: The Ooijpolder during high water. Photo by Emma Avoyan.

innovation enabling institutional design and the necessary expertise and knowledge.

Motivation and practical challenge

In the Netherlands and abroad, large-scale infrastructure projects, such as dike reinforcement projects, often trigger complex interactions between diverse actors and organisations working together. These actors bring to the process their interests and solutions to the problem. They may collaborate intensively during the exploratory project phases to explore and identify opportunities for linking flood safety with spatial and environmental solutions on and around dikes. The time and resources invested in these exploratory phases imply that the chosen collaborative approach is likely to make a difference. Still, there are concerns about the efficiency and effectiveness of the intensive collaborative processes organised during these projects. Yet, this knowledge would allow management organisations to prioritise cross-sector collaboration when and if needed. This is the reason why as a researcher and a former environmental planner, I am intrigued by the phenomenon of collaboration.

Research challenge

To understand the challenges and benefits of cross-sector collaboration, I investigate how and to what extent different collaborative process factors lead to integrative and innovative solutions for achieving integrative flood protection projects.

Innovative components

My research mixes different research methods to better understand the effectiveness and efficiency of cross-sector collaboration. I have first synthesised the literature on Dutch flood risk governance to look closely at cross-sector collaboration efforts since the flooding disaster of 1953

Figure 2: **Top:** Grebbedijk's development area; **Middle:** 'Dijkdenkers' discussing ambitions for the dike reinforcement; **Bottom:** Grebbedijk's section that allows for recreational and economic activities. Photos by Grebbedijk project en Waterschap Vallei en Veluwe.

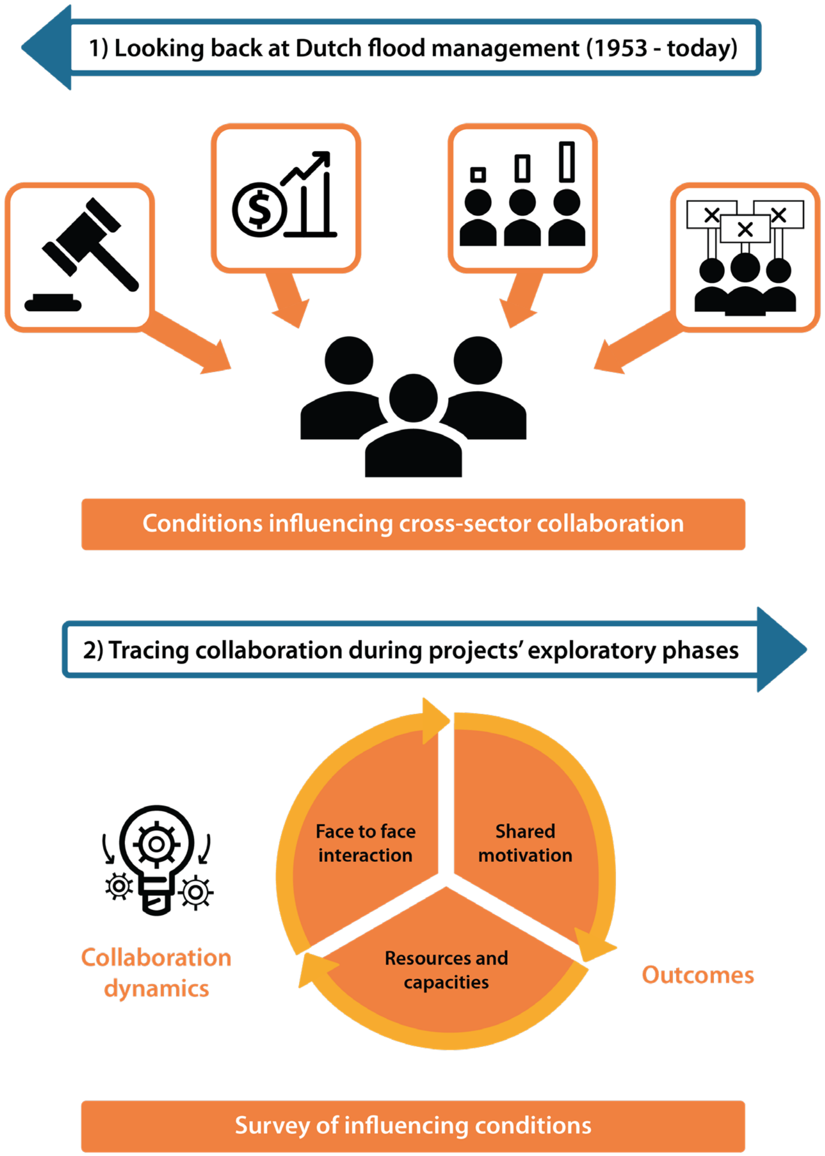


Figure 3: Overview of the innovative components of the research. Based on schemes from Emma Avoyan.

until the recent developments. Then, I examined qualitatively key factors and mechanisms of collaborative processes based on an in-depth case study of the dike reinforcement project: the Grebbedijk project. Finally, I compared multiple projects, including from abroad, to identify different combinations of factors within successful large-scale infrastructure projects: pathways to success. For this, I used the method of qualitative configurational analysis (QCA), which is a promising approach in examining the complex phenomena of cross-sector collaboration.

Relevant for whom and where?

Policymakers, advisory organisations and scholars interested in project performance assessments, cross-sector collaboration and collaborative governance of large-scale infrastructure projects involving multiple functions and private and public organisations.

Progress and practical application

Collaboration between organisations creates opportunities for developing integrative, innovative and legitimate solutions. However, as power relations and political/administrative circumstances are generally decisive, the quality of these solutions varies depending on how cross-sector collaboration evolves throughout exploratory phases, because in these phases the solution path is determined. There may be different pathways to success with different combinations of factors. Although there is no single recipe for success, the factors identified in this research (good engagement process, shared motivation, connective manager, resource contribution willingness, knowledge and expertise, and institutional design for innovation) can be used as an evaluation framework. Regular reflection on the presence or absence of success factors may help project managers to learn more about factors that would need to be improved. For details about findings, see the project outputs on the next page.

Recommendations for practice

- Use the success factors as an evaluation framework of collaborative processes within dike reinforcement among other area development projects.
- Recruit project managers with connective capacity and experience in designing and implementing integrated multidisciplinary and complex infrastructure projects.
- Engage and collaborate with area partners as early as possible in the exploration phase.
- Co-develop innovative solutions via specific procedural arrangements (e.g. design approach).

Key project outputs

Avoyan, E. & Meijerink, S.V. (2019). Cross-sector collaboration within Dutch flood risk governance: historical analysis of external triggers. Doi: 10.1080/07900627.2019.1707070

Avoyan, E. (2021). Inside the black box of collaboration: a process-tracing study of collaborative flood risk governance in the Netherlands. Doi: 10.1080/1523908X.2021.2000380

Avoyan, E., Lagendijk, A., Meijerink, S.V. & Kaufmann, M. (Forthcoming). Examining necessary and sufficient collaborative conditions for achieving output performance of the Dutch Flood Protection Programme.

On the map, the Grebbedijk project in Wageningen, which is one of the ongoing projects of the Flood Protection Programme studied within this project.

Photo by HWBP.

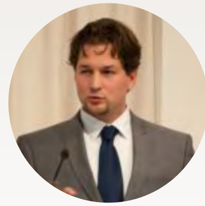
Project Summary

E3 - Understanding knowledge arrangements

Insights into how and why combining knowledge types benefits flood risk management interventions

By Martijn van Staveren

Wageningen University & Research

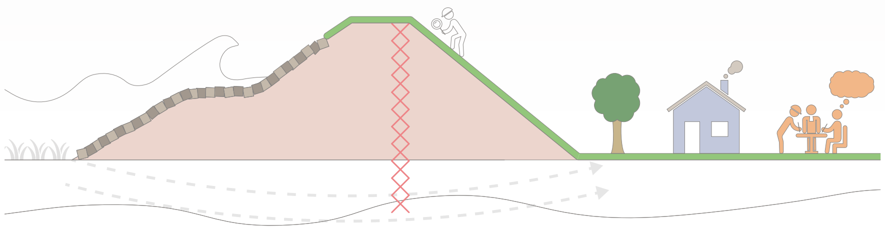


Project start: 08/2018
Project end: 08/2021

Contributors

Prof. dr. ir. M. Kok

Delft University of Technology



Outcome

This project has yielded insights into why and how combining different kinds of knowledge can be beneficial for designing effective and accepted flood risk management interventions. For example, residents near the Grebbedijk in Wageningen could indicate risk zones for piping based on earlier experiences. This example argues for the involvement of stakeholders in dike improvement projects and for purposefully engaging with knowledge types other than purely scientific. However, reaching out to and appreciating different forms of knowledge on their potential contribution to better flood risk management interventions is sometimes challenging. Working procedures and project management arrangements are biased to particular types of knowledge, which are

Figure 1: Grebbeberg seen from the Grebbedijk. Photo by Michiel Verbeek from Wikimedia Commons, CC BY-SA 4.0.

already operational and standardised. Therefore, a recommendation to project managers and policymakers is to be creative and search for new possibilities and inspiration for collaboration.

Motivation and practical challenge

Dealing with flood risks in densely populated and low-lying deltas is one of the global challenges for a sustainable future. I learned from earlier research projects that various forms of knowledge can contribute to improved flood risk management. These various knowledge forms include government guidelines and norms, engineering applications and local spatial planning ideas. Although sometimes depicted as competitors, various knowledge forms can contribute to better grounded and more accepted flood risk management interventions. However, project managers often struggle to combine knowledge without overstepping efficiency, formality, and ownership boundaries. Engaging actively with stakeholders also creates expectations. In short, it is important to balance formal roles and responsibilities with constructive engagement with stakeholders involved in a dike reinforcement initiative.

Figure 2: Grebbedijk is a project between Rhenen and Wageningen in which the Regional Water Authority works with multiple stakeholders to decide the preferred combination of dike reinforcements as well as spatial planning measures. Photo by Martijn van Staveren.

Research challenge

The main challenge is to investigate to which extent knowledge arrangements designed to engage different forms of flood risk management are in place and provide recommendations for knowledge integration.

Innovative components

The innovative approach is to look at the existence of knowledge arrangements and assess how this helps to engage with different kinds of knowledge in flood risk management. It is relevant to mention that the project is not set up as an evaluation study. Instead, it aims to identify lessons learned and provide recommendations from other research conducted, case studies, etc. In terms of methodology, the project has enabled us to look at how knowledge arrangements are shaped during a prolonged project development trajectory: from exploratory studies to participatory work, designing options, to a final decision making step.

Relevant for whom and where?

The specific recommendations are useful for project managers, but the general insights are also relevant for the wider stakeholder network involved in, or interesting to engage in, flood risk management initiatives.

Progress and practical application

Local knowledge is obtained via participatory processes. A sometimes slightly 'overlooked' form of knowledge is spatial planning and visual designing. These disciplines have the challenging task to turn discussions and explorations into practical options and visual presentations of flood risk management interventions.

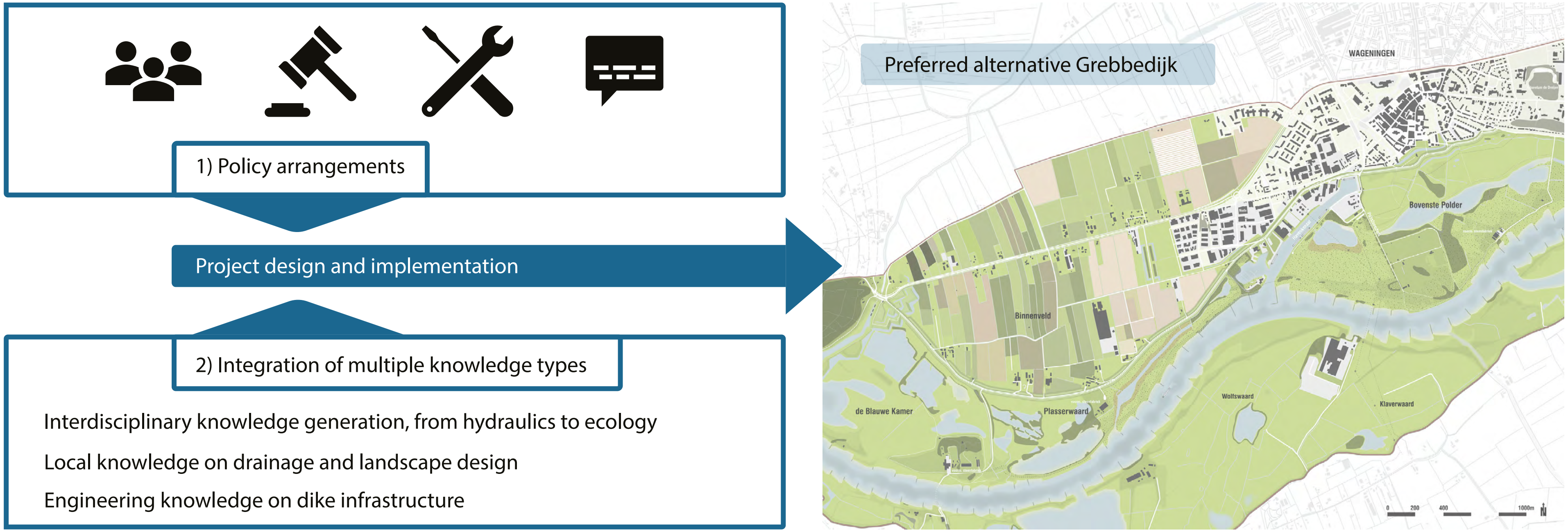


Figure 3: Overview of the innovative components including **(1)** policy arrangements such as actors' coalitions, rules and regulations, resource and capacities, and discourses as well as **(2)** different kinds of knowledge. Based on schemes by Martijn van Staveren. Source of the preferred alternative: Province of Gelderland (2019).

Recommendations for practice

- Reach out to and appreciate different forms of knowledge on their potential contribution to better flood risk management interventions.
- Be creative and search for new possibilities as well as inspiration for collaboration.

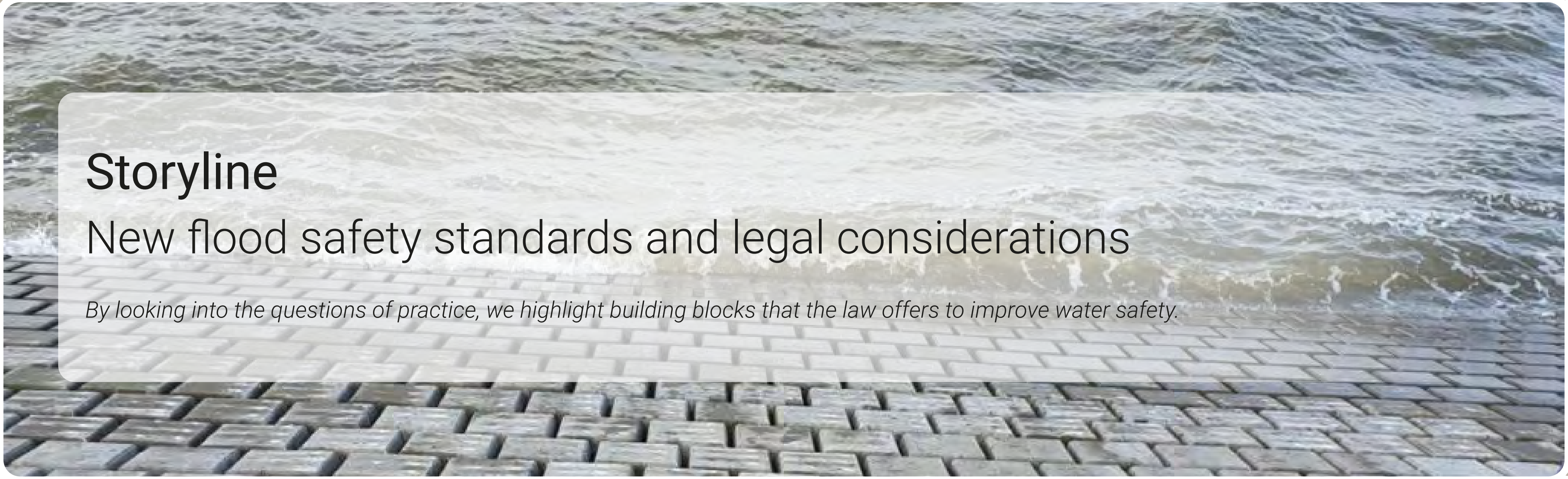
Key project outputs

van Staveren M.F. (2019) Commentary: Dike Relocation from an Environmental Policy Perspective. In: Hartmann T., Slavíková L., McCarthy S. (eds) Nature-Based Flood Risk Management on Private Land. Doi: 10.1007/978-3-030-23842-1_19

van Staveren M.F. (2019). We moeten de delta niet helemaal dichttimmeren. NRC [Newspaper] 22 May 2019.

The Grebbedijk dike reinforcement in Wageningen is the main location studied on this research.

Photo by HWBP.



Storyline

New flood safety standards and legal considerations

By looking into the questions of practice, we highlight building blocks that the law offers to improve water safety.

By Willemijn van Doorn-Hoekveld and Monica Lanz
Utrecht University

How it all started. Lulea (Sweden), 2015, midsummer. An email from Matthijs Kok, the now All-Risk research programme coordinator during a consortium meeting of a European research project (STAR-FLOOD). Whether we wanted to look into the upcoming changes to the Dutch flood protection legislation (*Waterwet*). Our joint reaction followed. The broad outlines of this reaction were incorporated in a new version of the legislative proposal. After that, the new safety standards came into effect in 2017, resulting in a multitude of questions and uncertainties for practice. That we would try to contribute to the implementation of this standard, seemed very logical to us! This storyline brings forth some of the emerging questions, along with the building blocks that the law offers to implement the new safety standards, address the legal responsibilities, and allow innovations in the field of water safety.

To what do the new standards apply?
A basic yet important question. The Water Act or *Waterwet* (in Dutch) provides safety standards for the primary flood defences. The majority of these defences are dikes that protect us against flooding from the North Sea and the major lakes and rivers.

In the Netherlands, water systems are managed by the State and 21 regional water authorities (**numbers on the map on the**

Cover photo: Detail of the dike revetment of the Lauwersmeerdijk near the Wadden Sea. Photo by Monica Lanz.

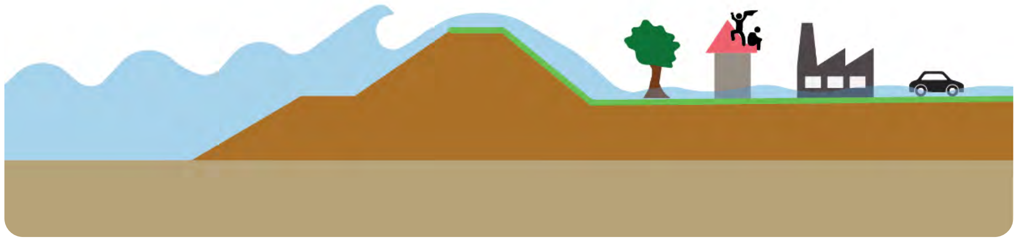
next page). The State manages the North Sea, the Wadden Sea, the large lakes, the major rivers and canals, a single primary flood defence, and a number of large structures which close automatically when the sea levels are extremely high. The regional water authorities manage the other waters (**grey fills on the map**) and defences; this involves more than 95% of the about 3,000 km of dikes (**black lines on the map**).

As a result, the new safety standards are the concern of both the State and regional water authorities who must coordinate their efforts to better ensure and regularly assess the status of the water systems and primary flood defences.

What do the new standards mean?
The European Floods Directive obliges Member States to assess the flood risk, to map the extent and assets and humans at risk and to reduce these risks by taking adequate and coordinated measures. The Directive does not prescribe specific safety standards, so the Netherlands (as any other Member state) is free to design its flood risk management standards.

Since 2017, the Dutch legislation established into the Annexes II and III of the *Waterwet* concrete safety standards for each dike segment based on the potential consequences of a flood and the costs of limiting the flood risks by dike strengthening. The consequences differ quite a lot from place to place. Therefore, these safety standards take several factors into account, such as the maximum water depth of the inundated area, the rate at which the water rises, the ability to evacuate from a specific area and other relevant features of the area. Overall, the safety standards aim at: (a) providing a basic level of protection for the population living behind the dike (probability of dying due to a flood of 1 in 100,000 years), (b) limiting the total casualties, and (c) preventing substantial economic damage. The more serious the consequences of a flood, the stricter the target probability of a dike failure (**see map legend**).

Map data: Esri, HERE, Garmin, NOAA FAO, USGS. Map layers: National Georegister, Unie van Waterschappen.



Simplified schematisation of a flood and its consequences. Adapted from STOWA (2017, Figure 3).

A visit to one of the dike sections in the Lauwersmeerdijken, near the Wadden Sea, that is now reinforced as a result of the implementation of the new safety standards. Photo by Monica Lanz.

Between 2017 and 2023, the responsible authorities are assessing all dike segments against the above standards. Where necessary, a dike reinforcement is planned with support of the Dutch Flood Protection Programme (HWBP in Dutch) so that by 2050 all dikes will be up to the safety standards. Meanwhile, the Water Safety portal gives an annual overview based on the available assessment results and the ongoing reinforcement projects per dike segment.

How to meet the standards?

The dike sections must also be periodically inspected and assessed. The advisors of the responsible authorities must apply the most recent technical guidelines for the assessment of the dike failure probabilities. The technical guidelines include considerations such as the (expected) sea-level rise, river discharges and distribution over the river branches. In addition, every 12 years, the responsible authority must report the results of these periodic assessments to the minister. The effectiveness of the safety standards themselves should also be reviewed once every 12 years. Together these measures should result in sufficiently low flood risk.

What is next?

The new *Omgevingswet* or Environment and Planning Act – in which the *Waterwet* will be included – helps to improve the landscape quality and the coordination between multiple environmental agencies. The new Act integrates into one framework scattered legislation on environment and planning (see figure). Remarkable changes to the legislation include that the water safety standards will now be part of an environmental value, which is a benchmark for the state or quality of the environment. To illustrate these changes, we adapted the infographic of the Environment and Planning Act of the Ministry of Interior and Kingdom Relations (see next page). This Ministry cooperates closely with the Ministry of Infrastructure and Water

Management in order to simplify and reduce the number of rules in one act concerning different aspects of the environment.

By order in council (in the Decree on the quality of the living environment), the responsible authority will determine the sites in which the environmental value applies. Such order will result in an obligation for that the responsible authorities must reach within a certain period of time, and such obligation may not be exceeded once it has been reached.

Limited exceptions

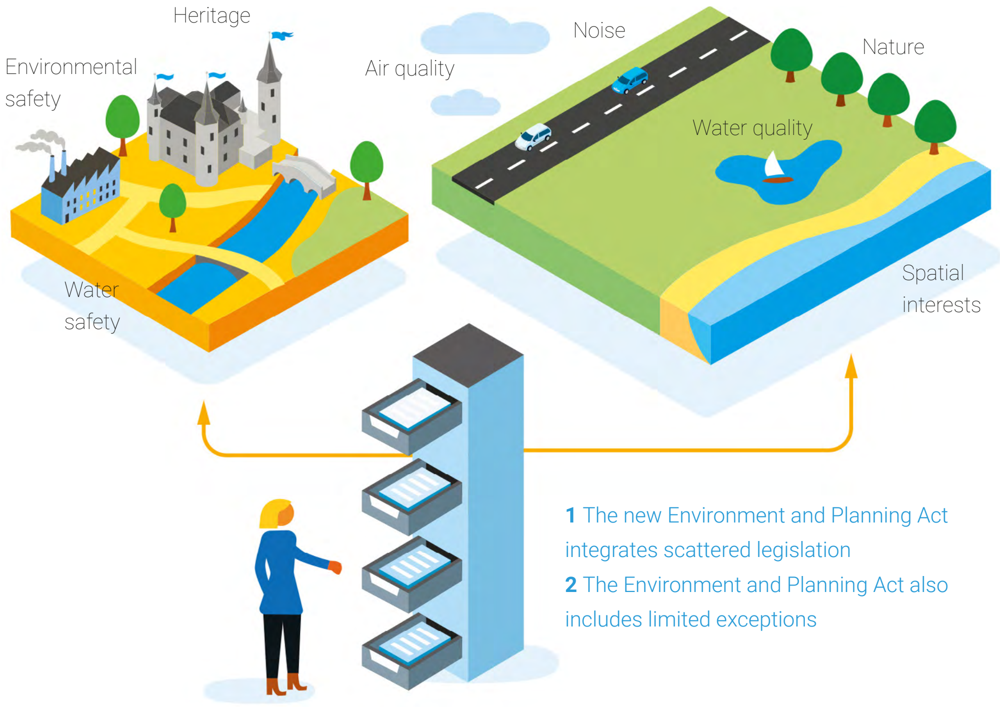
The new act also includes a number of exceptions to achieve the legal obligation within the given period of time. In short, the exceptions come down to (1) changes in the standards or assessment system; (2) disproportionately costly measures; (3) changed circumstances outside the sphere of influence of the responsible authorities; and (4) long lead times for measures. The latter particularly implies that everything within the power of the responsible authority is done to meet the obligation, but the long lead time for taking the measures is causing a delay.

If the responsible authority can appeal to one of these exceptions, a postponement can be granted for the outcome of the obligation.

WHAT IF SOMETHING GOES WRONG?

The liability (or legal responsibility)

Despite the ambitions of the basic protection level, flood defences never guarantee 100% protection. Luckily, there have been just a few flood disasters in the Netherlands. The last flood disaster occurred in 2003 and it's known as the Wilnis dike breach. Although this peat dike was not part of a primary flood defence, its collapse caused extensive damage for the Municipality of Wilnis, but who had to pay this damage? The answer to



Source: Adapted from infographic of the Ministery of Foreign Affairs.

A sudden horizontal dike slide in August 2003 due to a hole of 60 metres in the dike flooded Wilnis. Photo © ANP.

this question was not trivial so it was raised to and finally answered by the Supreme Court.

The liability and the dike deficiency

The Supreme Court ruled that the dike was an *opstal* (a constructed immovable) of the Water Authority. Therefore, the strict liability of article 6:174 Dutch Civil Code was applicable. In such case, the question the Supreme Court needed to answer, applying article 6:174 Civil Code was: "whether the dike does or does not meet the standards which may be set for such a thing in the prevailing circumstances."

Given that the drought caused the peat dike to collapse, the Water Authority argued that it was an unknown risk factor under the quality requirements back in 2003. The Supreme Court agreed to this because of factors such as the state of science and technology and the financial scope of the Water Authority. Consequently, the dike was not defective and the Water Authority was not held liable.

Such argument will probably be less successful if a dike collapses due to drought in the future. Today, preventing dikes from drying out is a permanent part of the duties and management practices of water authorities.

Will the liability increase with the new standards?

The legal responsibility of Water Authorities might increase because the possible exceptions are now limited in the Environment and Planning Act. In the event of any future dike breaches, responsible Water Authorities need to prove that they comply with the new risk standards or that they can appeal to one of the statutory grounds for exception. Otherwise, they might be held liable for any damage as a result of the dike breach (ex art. 6:174 Dutch Civil Code).

In case of a flood, the Disaster Compensation Act (*Wet tegemoetkoming schade bij rampen*) could help by setting up a regulation to partially compensate for damage caused by a specific disaster. This can only be done when insurance coverage or other compensations are not possible. Flood damage could fall under the scope of this Act, since fresh water floods could be designated as a disaster and insuring flood damage is not yet possible in general. In case this act is enacted, it determines who is to be compensated (the circle of victims) and what is compensated (which damage). Victims will in principle only be partially compensated. For each disaster a separate regulation is drafted for the details on the possible compensation. Even partial compensation will not be possible without such specific regulation for the disaster in place.

What to do with innovative projects?

The Environmental and Planning Act also acknowledges the need to balance flood safety with other societal needs. This integrated flood risk management perspective often requires innovative and pilot solutions. Some of these projects are also studied in the All-Risk programme such as the Double Dike and the Wide Green Dike. Current law does not provide a clear answer to decisive questions that exist in practice, but usually this does not hinder the realisation of such an innovation.

Questions that arise with such projects are, for instance, which authority is responsible, not only for the construction, but also for management, maintenance and any liability (Double Dike). Integration with other jurisdictions, such as nature conservation legislation, also plays a role (Wide Green Dike).

Remaining challenges

Despite our initial enthusiasm, what we see is that lawyers are often – but unnecessarily – viewed with fear. The law is seen as creating obstacles, while much more appears to be possible upon closer examination, as we saw in the Double Dike project for questions with regard to responsibilities of different governmental parties and the Wide Green Dike, where the law proved to be more flexible than was expected. This will not be different under the Environment and Planning Act. We hope to continue to be involved in many innovations and thereby highlight the possibilities and preconditions that the law offers and thus help Water Authorities to continue to innovate in the field of water safety.

In our field, and especially in the field of innovative water projects, it appears that the questions from practice cannot be figured out in advance. We depend on practical questions for our work and the development of our legal area. Within All-Risk we have already been able to contribute in this way to various projects (**see some of the publications below**) and we hope that this way of cooperation may lead to many good results.

Interested to read more?

Click or scan the QR Code to view the online version of this storyline. Or view:

This storyline is based on the results of the following open access publications:

- W.J. van Doorn-Hoekveld, H.K. Gilissen, F.A.G. Groothuijse & J. Kevelam, 'Kroniek aansprakelijkheid en schadevergoeding in het waterbeheer', *Overheid en Aansprakelijkheid* 2020/5, p. 11-25. https://envir-advocaten.com/nl/publicaties/kroniek-aansprakelijkheid-en-schadevergoeding-in-het-waterbeheer/
- W.J. van Doorn-Hoekveld, H.K. Gilissen, F.A.G. Groothuijse, H.F.M.W. van Rijswick, 'Meer zoden aan de dijk met de resultaatgerichte normering van waterveiligheid in de Omgevingswet', *Tijdschrift voor Bouwrecht* 2019/165. https://dspace.library.uu.nl/handle/1874/390196
- W.J. van Doorn-Hoekveld, H.K. Gilissen, F.A.G. Groothuijse & H.F.M.W. van Rijswick (18-02-2019), '*Advies: Beheer 'tussengebied' van het project dubbele dijk*', Utrecht Centre for Water, Oceans and Sustainability Law, Utrecht University.
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- Water Safety Portal (in Dutch): https://waterveiligheidsportaal.nl/#/home

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Storyline

What makes collaboration a success?

To ensure integrated solutions, responsible actors should turn success factors of dike reinforcement projects into an established practice.

By Emma Avoyan
Radboud University

In many Dutch Flood Protection Programme projects, public authorities engage with each other and stakeholders to develop flood risk management solutions that integrate different societal values. To increase the chances for a successful collaboration, project initiators should recruit project managers with connective skills, provide incentives for the parties to contribute with resources and facilitate a collaborative process that motivates parties to work together and acquire the necessary knowledge and expertise.

I believe the Netherlands is an exemplary country when it comes to working together and managing the environment in an integrated way. But then it fascinates me that the government and public agencies seek to do even better, obviously because of the limited space to accommodate competing societal values and the alarming climate change scenarios. As a PhD researcher in the All-Risk programme (see project E2), I explore how to improve the collaborative practices that are already well thought to recommend improvements for even better management results. These recommendations are especially timely considering the ongoing debate around the Environment and planning act (*Omgevingswet*) and the objective of the Cabinet to improve the links between different projects and activities in the field of spatial planning and development.

Cover photo: The Ooijpolder during high water. Photo by Emma Avoyan.

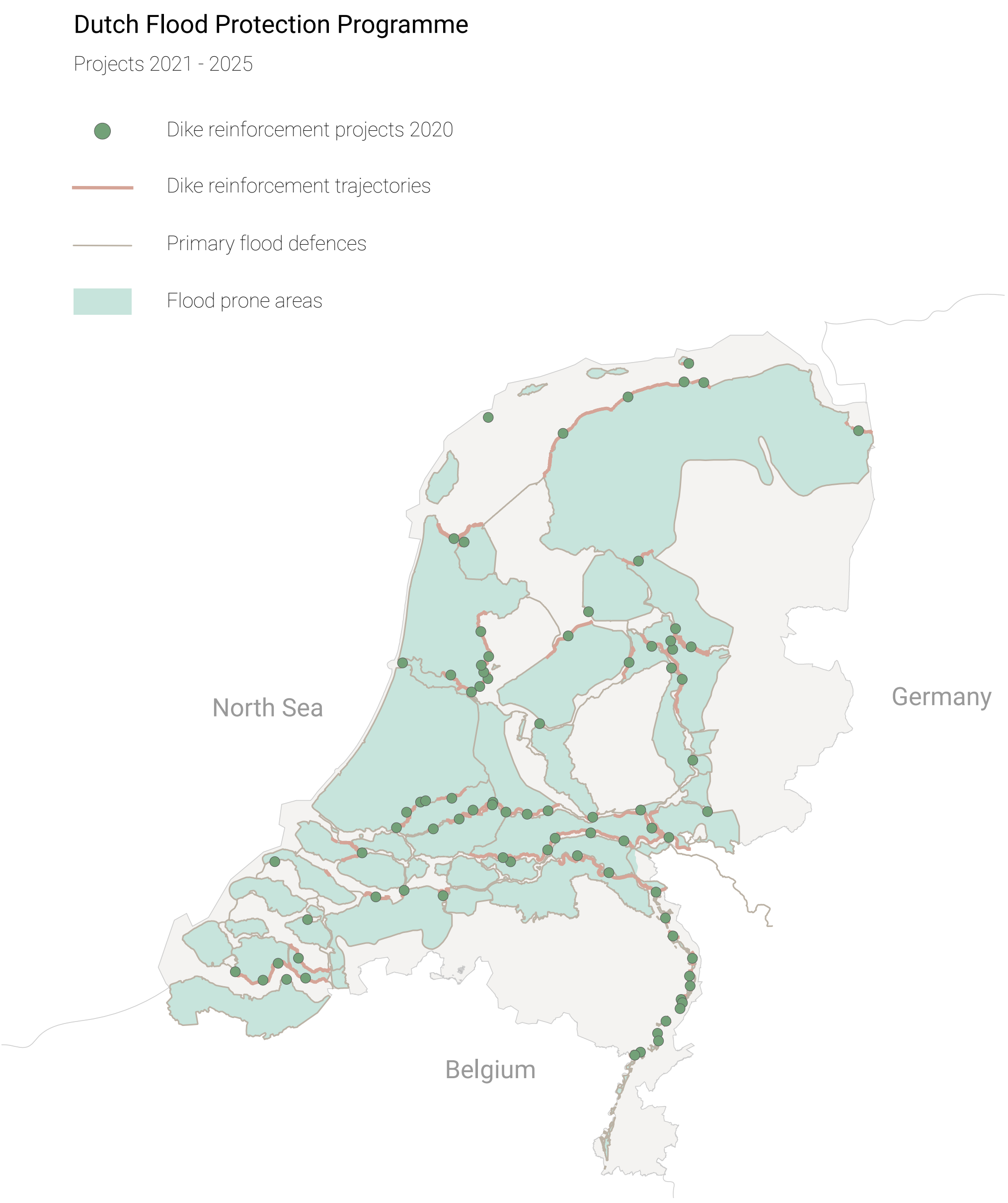
WHY IS COLLABORATION NEEDED?

Implementing dike reinforcement projects requires the early involvement of many interested parties such as public and private organisations, various governmental actors and agencies. By working together, these actors explore "smart combinations" of solutions that allow integrating flood safety with other societal values, such as spatial quality and sustainability. This integrated strategy was initially disputed as there were concerns regarding the "*sober en doelmatig*" (modest and effective) approach of the Dutch Flood Protection Programme. The sober part implies stricter deadlines and resources for no other than dike reinforcement measures. Many linking opportunities could be missed for developing the area in a way that addresses multiple societal and environmental values linked to flood safety. Moreover, the collaboration process and results also have an essential role in the success of these integrated and collaborative projects.

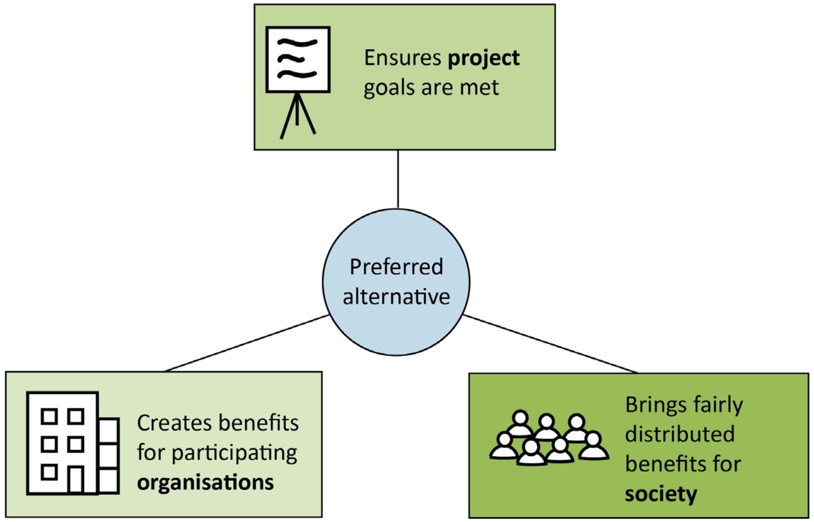
As a researcher, I was challenged to identify different combinations of factors within successful collaborative flood defence projects: pathways to success.

BUT FIRST: WHAT IS A SUCCESSFUL COLLABORATION?

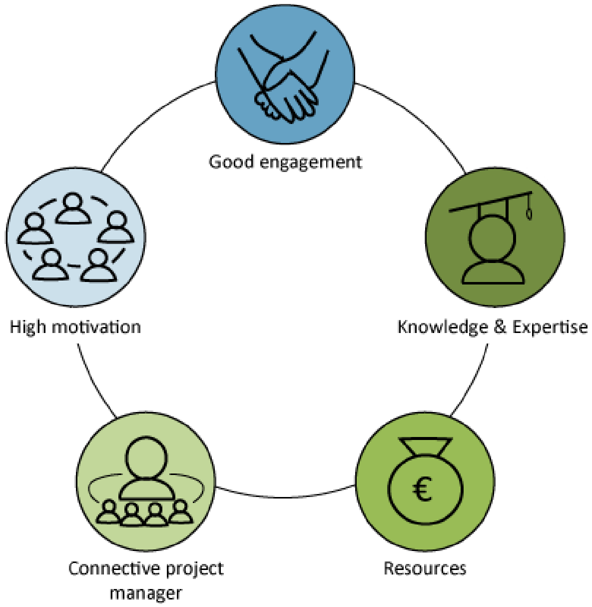
When do we conclude that the project collaboration was successful? Is it when actors reach a consensus? Or is it when actors achieve the agreed goals? Or when all involved actors benefit from the results of the collaboration? As usual, there is no simple answer to when, how and for whom collaboration is successful. Indeed, it is challenging to assess the success of the collaboration as well as the factors that feed this success. Therefore, for this research, I combined three criteria to measure the success of collaborative exploration phases of dike reinforcement projects leading to the (implementation of) a preferred alternative that:



The Flood Protection Programme project locations. Source: Adapted from Flood Protection Programme Map. Layers retrieved from the National Georegister and Flood Protection Programme. Illustration by Juliette Cortes Arevalo and Martijn Vos



The three criteria to identify successful collaborative projects in the context of this research. Based on schemes by Emma Avoyan.



The factors of successful collaborations. Based on schemes by Emma Avoyan.

- creates benefits for collaborating organisations.
- ensures meeting the jointly agreed project goals.
- warrants equally distributed benefits among the beneficiaries (the society as a whole).

SURVEY STUDY

I conducted a survey study to first identify the successful projects based on the above three criteria and then determine the success factors that fed this project success. The survey was distributed between September and November in 2020 and had around **350 respondents** from eventually **26 ongoing dike reinforcement projects**. In the survey, I asked different questions regarding the collaborative process and the results. Respondents represented various groups of stakeholders, although most worked in governmental organisations: national government, provincial and local governments, and water authorities. The water authorities comprise more than 47% of the total responses, which can be explained by their important managing role in the Dutch flood risk governance. I have then carried out a qualitative comparative analysis (QCA) to systematically compare the projects and examine the relationships between different factors and the results of these projects. Survey findings show that five factors are important to successful collaboration, although to differing degrees and in different combinations (pathways).

WHAT ARE THE FACTORS OF SUCCESSFUL COLLABORATIONS?

Good engagement

When the collaborative process offers actors sufficient opportunities and mechanisms to identify, deliberate, and make agreements over the joint preferred alternative.

Knowledge and expertise
When collaborating, actors share or outsource the necessary knowledge and expertise.

Resources
When the actors are willing to acquire and share resources, including logistical and financial to develop and implement the preferred alternative.

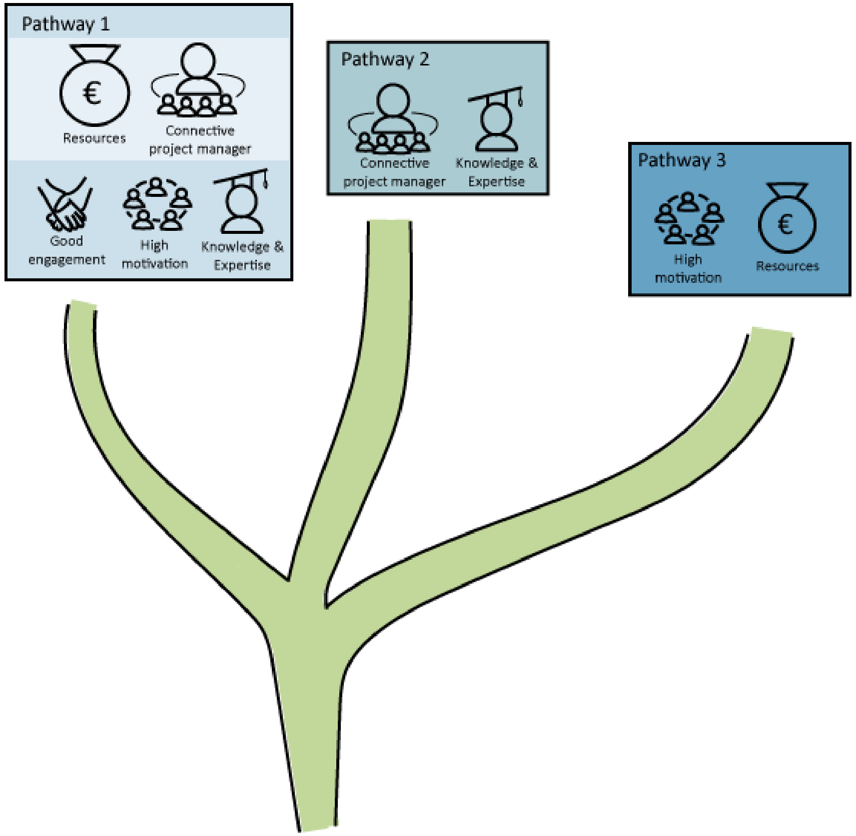
Connective project manager
Project managers with connective management styles or skills that can connect the actors and adapt the project to changing external conditions.

High motivation
The extent to which actors engage in trust-building activities, develop a sense of satisfaction with collaboration and build commitment to collaboration.

PATHWAYS TO SUCCESS IN COLLABORATIVE PROJECTS

Pathway 1: connective project manager and resources
The first pathway revealed that many projects (11 out of 26) were successful due to a combination of a **connective project manager** and **resources** made available by the parties. This combination is then complemented by **good engagement, high motivation** or availability of relevant **knowledge and expertise.**

Pathway 2: limited resources but a connective manager and necessary expertise
The second pathway indicates that a **lack of resources** can be compensated by the simultaneous presence of a **connective project manager**



Pathways to success in collaborative projects. Based on schemes by Emma Avoyan.

and the necessary **knowledge and expertise**. Although this is not a common pathway, at least four projects out of 26 have succeeded in having this configuration of factors.

Pathway 3: high motivation of parties to pool resources

The third pathway is rather an exception (only 2 projects out of 26 had this pathway to success). The **absence of a project manager** with a connective management style and **the lack of necessary knowledge and expertise** can be compensated by the **high motivation** of parties to pool their **resources** for meeting the project goals.

LESSONS LEARNED

Overall, according to the survey respondents, there are already many examples of successful collaborative projects of the Dutch Flood Protection Programme. The role of project managers with skills to connect is essential in achieving this success in the collaborative process. Project initiators could strategically recruit managers with extensive experience in managing large-scale integrated projects. The willingness of collaborating parties to contribute financially is also a critical success factor for the projects. However, these two factors are complemented in most successful projects with a good engagement process, high motivation and the necessary expertise and knowledge. The question now is how can we further develop and promote these success factors for future area development projects? Not all success factors must be present to achieve successful integrative projects. The presence of others may compensate for the absence of some factors. Therefore, project initiators should not be discouraged if they do not have most of these success factors at first. They should instead focus on mechanisms to maintain what they have and promote the missing ones.

Interested to read more?

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This storyline is based on the results of the following open access publications:

- Avoyan, E., Lagendijk, A., Meijerink, S.V. & Kaufmann, M. (Forthcoming). Examining necessary and sufficient collaborative conditions for achieving output performance of the Dutch Flood Protection Programme, *Journal of Public Administration Research and Theory*.
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Photo from a session on area development on the Grebbedijk. Photo by HWBP.

The theme:
Implementing large-scale infrastructure projects for flood risk management requires good collaboration between water authorities, municipalities, land-owners and societal organisations.

Would you like to see the presentations of the researchers? You can view them **by clicking or scanning the QR Code.**

Reflection
Looking beyond reinforcement

Webinar team

Moderator

Sander Meijerink
Radboud University

Speakers

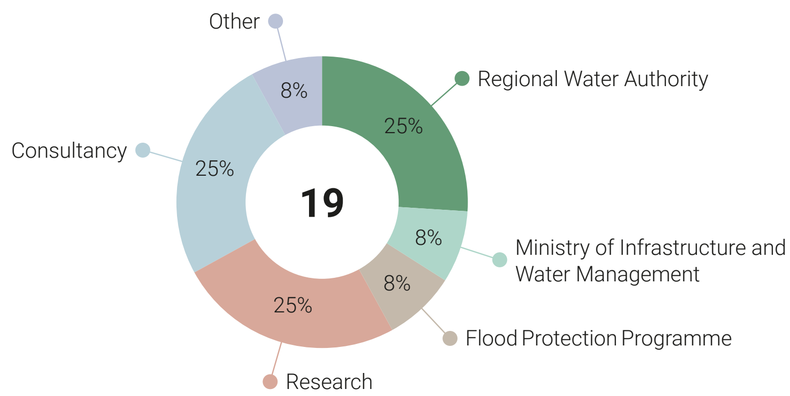
Monica Lanz
Utrecht University

Introduction

Emma Avoyan
Radboud University

Annelies Freriks
Element Advocaten

Participants



Participant responses to the question beyond strengthening, what are important topics?

This reflection emerged from the discussion between researchers and participants during the All-Risk webinar organised on October 13, 2021.

One of the objectives of the Dutch Flood Protection Programme (HWBP) is to link other interests and tasks with flood risk management tasking if possible. For this reason, many collaborative processes have been initiated in which parties jointly explore options and develop a preferred alternative. What can we learn from these collaborative projects? What are important conditions for the collaboration to arrive at an effective and broadly supported preferred alternative? And what are the legal possibilities and obstacles (e.g. related to Natura 2000) to realising such a preferred alternative? In this All-Risk webinar, we discussed these and other governance issues.

Discussion

Despite the legal challenges for pursuing integrated flood risk management initiatives and the collaborative governance that is needed, during the webinar, it became clear that many successful projects have managed to organise successful collaboration between the involved parties. Still, there are concerns about the efficiency and effectiveness of the intensive collaborative processes organised during the exploration phase of Dutch Flood Protection Programme projects.

For increasing both efficiency and effectiveness of the efforts, it is important to consider whether the jointly developed preferred alternative creates benefits for collaborating parties, contains a roadmap for achieving jointly agreed project goals and warrants equitable distribution of the costs and benefits of its implementation among the beneficiaries (the public). The likelihood of achieving these performance levels is high when the projects have managers with a connective management style and sufficient (financial) resources are made available by the parties involved. Other success factors are productive engagement, shared motivation and the generation or sharing of relevant knowledge and expertise.

During the discussion participants added relevant success factors for achieving integrative projects, such as clarity about objectives and financing, a long-term vision, sense of urgency, shared responsibilities, and relatively small project scale. It is important to realise that not all these success factors must be present to achieve successful integrative projects. The absence of some factors may be compensated by the presence of others. Therefore, project owners should not be discouraged if they do not have most of these success factors. Instead, they should focus on the conditions they have and promote and further stabilise them. As mentioned by one of the webinar participants: "We often focus on what we could have or could achieve rather than on what we have and have achieved".

How can then parties be stimulated to link their sectoral goals to Flood Protection Programme projects?

Most of the participants mentioned engaging other policy sectors early in the process – so that they have sufficient time to develop ideas around linking opportunities – is crucial. Others also mentioned creative thinking, a design approach, and taking a specific area with concrete problems as a starting point. Whereas policy objectives tend to be abstract or vague, problems and interests in specific cases are not.

Within the Flood Protection Programme, there are also a number of projects that did not manage to organise productive collaborative processes, either because no collaborative process was initiated or because nothing came out of it. During the webinar, there was a lively discussion on the bottlenecks that stand in the way of integrated Flood Protection

Participant responses to the question: Which factors do you think are important for the success of integral HWBP projects (other than in Emma's presentation)?

Programme projects. Some participants mentioned that there is neither capacity nor time for developing integrated solutions. Others mentioned a tight planning schedule and time pressure would hinder the development of integrative projects. Other participants pointed to the slow lead (processing) time or even fear for delays in the management of the Flood Protection Programme that stand in the way of successful collaboration and integrated solutions. Participants also questioned whether the ambition to realise integrative projects may come at the cost of the speed at which a project is realised. Although a majority prioritised integrative solutions above speed, some warned that the Flood Protection Programme should be careful with that. Whereas some flexibility may be acceptable, it should be realised that a delay in project implementation comes at the cost of water safety. Finally, some participants argued that stakeholder participation, too big ambitions of some sectors or limited budgets of municipalities have hindered productive collaboration.

Overall, the success factors and bottlenecks mentioned in the discussion confirm the results of the research into collaboration within Flood Protection Programme projects. One of the interesting research results is that despite the criticism on the Flood Protection Programme for its 'sober and efficient approach', the programme still managed to realise a large number of successful, integrative projects. Overall the strategy of 'meekoppelen' (linking) has been successful.

All-Risk recommendations:

- Use the mentioned success factors together as an evaluation framework for assessing collaborative efforts within the Flood Protection Programme projects. Focusing on these factors will make it possible to assess whether they relate to each other or can be compensated if missed.
- The skillset of project managers deserves attention. When hiring project managers, select people with extensive experience designing and implementing large, integrated multidisciplinary and complex infrastructure projects, next to conventional requirements such as meeting deadlines. They also need competencies to identify and connect stakeholders.
- Engage with area partners as early as possible (from the launching, beginning of the exploration phase, or during the pre-exploration phase). This way, partners may be more willing to invest their resources (people, finances, logistics etc.) to develop the most optimal solution together and have enough time to work out procedures within their organisations.

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Colophon

Towards Improved Flood Defences – Five Years of All-Risk Research into the New Safety Standards

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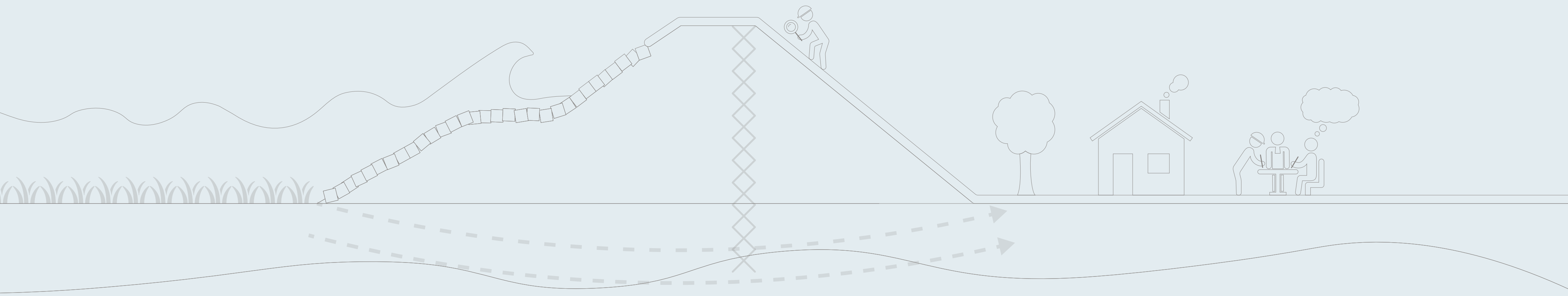


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Towards Improved Flood Defences – Five Years of All-Risk Research into the New Safety Standards

Flood risk reduction is one of humankind's major challenges, especially for the people who live near water. In the Netherlands, the increase in economic activities and the number of people living in vulnerable areas have urged the development of new safety standards to further reduce flooding risks. The national government and regional water authorities are now working towards achieving these standards in the Flood Protection Programme (or HWBP, in Dutch). In this programme, about 2/3 of the 3,500 km of primary flood defences in the Netherlands will be reinforced over the next three decades. The All-Risk research programme, which ran from 2017 to 2022, was carried out to support the implementation of the HWBP.

After five years of research, we are pleased to share the All-Risk legacy contained in this book with dike professionals and everybody else interested in flood risk. The book starts out by sketching the technical and legal implications of the new risk-based approach, and associated challenges and opportunities. Separate chapters then address the five All-Risk themes, ranging from the risk framework to the legal implementation. The text summarises the main outcomes of 15 individual PhD projects from researchers working in five universities, together with over 30 partners from government, research institutes, NGOs and the private sector. The focus lies on their innovative contributions and recommendations. Each chapter further includes storylines of case study applications and concludes with reflections from webinar discussions between representatives from research and practice.

https://www.all-risk-program.nl/