WATER2014

Project Title:

SAFElevee: Improving the reliability of flood defence systems by a better understanding of their failure mechanisms

Figure 1: Levee Failure (Breitenhagen, Germany, June 2013).
Left: initial stage of the failure process, probable cause was instability. Right: breach in progress.

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1. Contact details

1.1 Main applicant

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Postion, part-time %	:	100%
permanent position	:	yes

1.2 Co-applicant(s)

Not applicable.

1.3 Title

SAFElevee: Improving the reliability of flood defence systems by a better understanding of their failure mechanisms.

1.4 Keywords

flood defences, levees, failures, breaches, uncertainty, reliability, flood risk, (Bayesian) forensic analysis, performance database, remote sensing

2. Summary

2.1 Research Summary

Failures of flood defences (here also named levees) cause major catastrophes in terms of loss of life, and economic damage. Despite extensive research on geotechnical failure mechanisms such as instability, piping or overflow- induced breaching, considerable uncertainties in failure modelling and prediction remain. The **objectives** of the proposed project – SAFElevee - are (a) to improve the understanding of (geotechnical) failure mechanisms and breaching of flood defence systems, (b) to enhance reliability analysis and design of safe levee systems, and c) to provide systematically collected datasets for future scientific research.

The project is structured within four work packages. The first work package analyses data of levee performance and failure at a macro-scale to identify system failure patterns and its most important causal factors. Innovative combinations of Bayesian analysis, remote sensing and hydraulic engineering are used to reveal how factors such as levee type, geometry, orientation and vegetation will affect performance. The second work package focuses on a more detailed analysis and hindcasting of individual levee failures for which sufficient data is available. Geotechnical and probabilistic analysis will be used to improve our capability to model these events, also taking into account heterogeneity and uncertainty in soil conditions. The third work package addresses the breaching of levees and aims to develop more accurate models and theories of breach initiation and formation. It utilizes information from historical breaches and large-scale field experiments. The fourth joint work package is setting up the international levee performance database which will document failure and performance data on flood defence systems. It will be compiled and used by all researchers in the project, also in collaboration with international academic institutes with the SAFElevee project. Thereby a cooperative knowledge platform on levee safety will be created, which is also a basis for future research and cooperation. SAFElevee is expected to result in better insights in levee failure and performance, thereby complementing existing approaches for assessing levee failures (e.g. expensive field tests) and contributing to cost effective and innovative levee design and reinforcement.

2.2 Utilisation Summary

The majority of the global population is located in flood prone coastal and delta areas. Failures of flood defences cause major catastrophes in terms of loss of life, and economic damage that easily amounts to billions of euros per disaster. Improved flood defence measures are required to safeguard flood prone areas from floods in order to save many lives and considerable damage costs. For example, in the Netherlands, up to 1 billion Euros per year will be invested in the coming year in flood defences. Innovative and cost effective levee reinforcements cannot be applied at a large scale yet, as our understanding of levee failure mechanisms is limited.

SAFElevee will contribute to utilization in the field of delta technology in various ways. The project will complement existing approaches for assessing levee failures (e.g. expensive field tests) at relatively low cost. The research be applicable for future Dutch and international projects that aim to develop models and tools for levee design and safety assessment. The project is aiming to contribute to more effective and innovative levee reinforcements and large potential cost savings, through a better understanding of performance and failure modes. To maximize utilization potential, the SAFElevee project is positioned within a collaborative network of academia, governmental organisations, and private companies. A dissemination workshop with partners on findings on future opportunities will be organized as part of the project. Overall, the SAFElevee project will establish a cooperative data and knowledge platform for governments, researchers and companies in the field of levee safety in a broad range of programs, now and in the future.

2.3 Summary STW's website

The SAFElevee project (led by Delft University of Technology) enhances the safety of flood prone areas by improving the understanding of failure and breaching of levee systems. Systematic documentation and analyses of international levee performance data enables the development of accurate techniques for the innovative, and cost-effective designs of flood defence systems. Work packages in the project focus on macro-scale analysis of levee failure patterns, hindcasting of individual failures, and models for levee breach formation. A cooperative data and knowledge platform on levee performance will be created through the close involvement of end users from governmental bodies, research institutes and private sectors. Thereby, the SAFElevee partners foresee to strengthen their international network and position in the field of flood risk management and levee safety.

3. Current composition of the research group

The SAFElevee research team consists of a Postdoc and two PhD researchers, a technical assistant (0.2 FTE), and several senior scientists from Delft University of Technology, the knowledge institute Deltares, and the private companies Fugro and HKV. The table below gives an overview of the SAFElevee work packages, its core disciplines, senior supervisors, and the end-users involved through in-kind support.

Nr	Work package	Research team	Core disciplines
1	Understanding levee failure patterns	**PhD1** Prof. dr. ir. S.N. Jonkman[1,2] Prof. dr. ir. R.F Hanssen[3,4]	Hydraulic[1] and coastal[2] engineering, Geosciences[3], Remote sensing[4]
2	analysis and hindcasting of individual levee failures	**PhD2** Prof. dr. ir. S.N. Jonkman[1,6] Prof. dr. C. Jommi[5] Dr.ir. T. Schweckendiek*[1,5,6] Senior staff from Deltares[1,5,6], Fugro[1,5]	Hydraulic[1] and geotechnical[5] engineering, Reliability analysis[6]
3	Breach patterns and breach growth modelling based on historical failures	**Postdoc$** Prof. dr. ir. S.N. Jonkman[1] Prof. dr. ir. C. van Rhee[7,8] Dr. P.J.Visser[7,8]	Hydraulic[1] engineering, Fluid mechanics[7], breach growth modelling[8]
4	International Levee Performance Database (ILPD)	**Technical assistant (0,2 fte) with the other researchers** Prof. dr. ir. S.N. Jonkman[1] Dr.ir. T. Schweckendiek[1,5] Senior staff from HKV[5,9], Fugro[5,9]	Data management[9], hydraulic[1] and geotechnical[5] –engineering

** The PhD defence date of T. Schweckendiek is July 4, 2014, he will remain affiliated with TU Delft in a tenure track position.*
$ the Postdoc will also play a leading role in the communication and dissemination of the ILPD and project results.

4. Scientific description

4.1 Research contents/Introduction

Background and objectives

Failure of flood defences (here referred to as levees, in other documents also named dikes or embankments) during extreme events can lead to enormous damage and loss of life (Jonkman, 2005). Past events, such as the 1953 floods, the failure of the levee system around New Orleans (2005) and the recent floods in Germany (2013) have shown that failure mechanisms other than overtopping are an important cause of these disasters (see e.g. Bea *et al*., 2009; Seed *et al*., 2008; Horlacher *et al.*, 2008).

Currently, there are considerable uncertainties in modelling and predicting the failure mechanisms such as instability, internal erosion or overflow-induced breaching. Our understanding of geotechnical failures can be significantly improved by hindcasting historical levee failures (e.g. Rajabalinejad *et al*., 2010; Kanning *et al.*, 2008) and other performance observations such as monitored near-failures or field observations during extreme loading (Schweckendiek, 2014). Individual efforts have been undertaken to document failures of flood defences after disasters (e.g. Seed *et al*. 2008 a and b; Heyer and Horlacher, 2007), but no systematically gathered large-scale datasets are available for thorough scientific research. This results in a lack of calibration and validation data for levee failure and performance models.

The **objectives** of the proposed research program are (i) to improve the understanding of (geotechnical) failure mechanisms and breaching of flood defence systems, (ii) to enhance failure models, reliability analyses and designs of flood defences; (iii) to provide systematically collected datasets for future scientific research.

Research approach and activities

SAFElevee focuses on levee performance and failure, and analyses the interrelated processes of (initial) failure of a levee and breach development, both at a system-macro scale as well as for individual failures. The essential elements of the research approach are:

1. To **systematically collect levee performance data,** and compile this in an international levee performance database (ILPD).
2. To **analyse levee failures and performance observations** (e.g. near misses, mitigated sand boils) in order to improve the understanding of the physical processes as well as safety assessment and design models, both in terms of **geotechnical performance and breaching**.

The research is structured within four work packages (figure 2), which are described in more detail below.

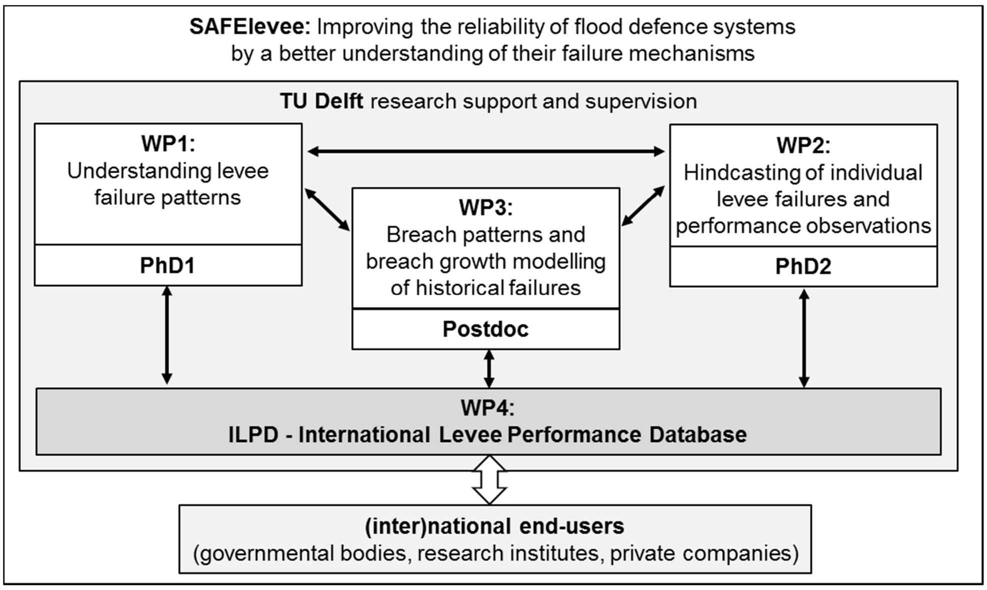

Figure 2 : Research approach and organization of the SAFElevee project.

Work package 1: Understanding levee failure patterns
PhD with supervisors prof. dr. ir. S.N. Jonkman (Hydraulic Engineering) and prof. dr. ir. R.F Hanssen (Geoscience and Remote Sensing)

Little is known of what determines failure patterns (i.e. number of failures, types, and locations) of flood defences at a system level during extreme events. The **objective** of this work package is to analyse data of levee performance and failure at a macro-scale, to identify system failure patterns and its most important causal factors (e.g. type and shape of a levee, vegetation etc.). This requires an innovative combination of techniques and data sources from hydraulic and geotechnical engineering and remote sensing.

The first activity (A1.1) is to analyse patterns in the International Levee Performance Database (ILPD, see WP4) at a macro-scale, in order to investigate which failures occur for certain types of flood defences and regions, and which failure mechanisms and underlying factors (e.g. state, maintenance, geotechnical factors) are important. Such patterns at macro-scale are not easily detected by conventional methods. Therefore, techniques such as neural and Bayesian networks will be used for the analysis. These techniques have proven its usefulness when dam failure patterns were systematically collected and analysed (Peng and Zhang, 2012), and in research on breakwaters in coastal engineering (e.g. Panizzo and Briganti, 2007).

The second activity (A1.2) concerns the analysis of spatial patterns of levee failure of data from past flood events. Large flood events, such as 'New Orleans' (25 failures; Bernitt and Lynett, 2011) and '1953' (more than 150 failures) are characterized by multiple failures. In case of multiple breaches the impact of flooding can increase significantly (Jonkman *et al*., 2008). There is limited knowledge of the factors that drive the number of failures and their locations. Spatial patterns in loading and strength of flood defences will be investigated and compared with actual failure patterns. Particular focus will be given to deformation, as it is an important indicator for many of the levee failure mechanisms. Using satellite radar interferometry (archives going back to 1992), the (pre-failure) deformation of levee systems will be analysed in retrospect (Hanssen and van Leijen, 2008). A particularly data-rich case is the 2002 flood event in Saxony, Germany (Heyer and Horlacher, 2007) with more than 70 levee failures and breaches. A stay of two-months at TU Dresden is foreseen for data collection and collaboration on the analysis (A1.3). As part of this exchange activity a researcher from Dresden will visit TU Delft for a similar period for information exchange and research cooperation.

As a final activity (A1.4) it will be investigated how landscape features, such as foreshores, wetlands and vegetation, can influence levee safety. For example, foreshores and wetlands in front of levees can reduce loads, and vegetation behind levees can indicate seepage. Such relationships will be analysed more systematically using remote sensing data on presence, change and state of landscape features (wetlands, vegetation, water bodies). Since observations on these landscape features have been available for the last several decades for many locations, spatial and deformation patterns in time can be linked to levee system performance and failure.

Work package 2: Hindcasting of individual levee failures and performance observations
Supervisors: prof. dr. ir. S.N. Jonkman, dr.ir. T. Schweckendiek (reliability analysis and levees), prof. dr. C. Jommi (professor of dikes and embankments in the geotechnical engineering group).

In the Netherlands, (near-)failures of actual flood defences are rare. While experiments on prototype scale are therefore very valuable, actual (non-experimental) levee failures contain additional information which the experiments cannot reproduce. Hence, in order to improve the understanding of levee failures and to the reduce failure model uncertainty, there is a need for "calibration" by means of hindcasting historical (near-)failures.

The **objectives** of this work package are to a) improve our understanding of the physical processes involved in levee failures; b) improve and/or develop computational models that can be used on safety assessment and design of levees. This is done by hindcasting a limited number of data-rich historical (near-)failures. The focus will be on geotechnical failure mechanisms (piping, instability), as these appear to be the dominant threats for levees in flood defences (Vorogushyn *et a*l. 2009).

Data will be collected on detailed characteristics of data-rich historical (near-)failures such as geometry, ground conditions, field observations, hydraulic loads, etc.) as input for the ILPD (A2.0). For specific cases of interest, the available data will be complemented with additional geotechnical site investigation (A2.1).

In first instance, these (near-)failures will be analysed using existing failure models and soil data using a deterministic approach, i.e. by means of safety factors (A2.2). This will give insight in the predictive capabilities of the existing models and will enable the research team to choose the most promising cases for further in-depth study and to judge whether additional data acquisition is necessary.

In most cases, the exact conditions at the time of the observation are uncertain (e.g. water level, ground conditions). These uncertainties will be accounted for using various techniques for (inverse) probabilistic analyses (A2.3). Specific scientific challenges are dealing with spatial variability and heterogeneity in ground conditions, groundwater flow, and unsaturated soil behaviour. A novel combination of probabilistic analysis and random field modelling will be used to account for uncertainties in both models and site conditions when hindcasting the (near-)failure cases. Given the strong track record of Hong Kong UST in the field of geotechnical modelling (Zhang et al., 2013; Chang and Zhang 2013) a two months travel programme to this institute is foreseen to exchange expertise on the development of computational models for levee failure (A2.4). As part of this exchange activity a researcher from Hong Kong will visit TU Delft for a similar period for information exchange and research cooperation.

The results of the probabilistic analyses will be evaluated in terms of the consequences for safety assessment and design of levees (A2.5). The most important issues to be addressed in this context are to (i) determine which models perform best under which conditions, and (ii) to quantify the model and soil uncertainty we need to account for.

This work package will result in (i) high-quality and high resolution data sets of historical (near-failures), (ii) an improved understanding of levee failure processes, (iii) improved insights in model performance and most suitable modelling approaches, and (iv) recommendations for end-users on failure modelling in safety assessment and design.

Work package 3: Breach patterns and breach growth modelling based on historical failures
Supervisors: dr.ir.P.J. Visser, prof.dr.ir. S.N.Jonkman, prof.dr.ir. C. van Rhee (professor of fluid mechanics and dredging engineering).

The formation of breaches significantly affects the damage due to flooding. Past research has been done on breaching of individual sand levees (Visser, 1998) and cohesive levees (Zhu, 2006). However, the physical processes associated with breach formation are not yet fully understood. Just like for initial failure models, there is a shortage of calibration data on breaching patterns and individual breach characteristics in the form of actual failure cases (Morris *et al*., 2006). The **objective** of this work package is to develop more accurate models and theories of breach initiation and formation using available datasets for calibration and validation.

Figure 3: Full-scale breach experiment near Fort Lilo (Belgium) by Flanders Hydraulics Lab and TU Delft.

The first activity (A3.1) concerns a study of the physical processes of breach initiation and formation. This consists of an extensive review of relevant processes (e.g. erosion), and the effects of changing geotechnical properties with variations in the degree of saturation affect erosion rates, and influence breach formation (Takahashi, 2009; Pickert *et al*., 2011). These issues have not yet been widely researched in a coherent framework. The second parallel activity (A3.2) concerns the analysis of both large-scale experimental data (fig. 3) and field data on breach formation in levees. This will give a better insight in observed processes, the breach formation over time, and the eventual breach characteristics (width and depth) that are most relevant for flood impact analysis. Thirdly, for purposes of validation and model improvement (A3.3) insights in physical processes will be combined with breach observations. Available breach models will be used for validation and to propose improvements to existing breach models. Combining (large-scale) experimental data with field observations on overall breach formation into one dataset will form the standard dataset required for validating all levee breach models (Morris *et al.*, 2008). Work package 3 is expected to lead to new insights in breach formation and a better understanding of how to prevent breaching and how to design breach resistant levees.

Work Package 4: International Levee Performance Database as a common data base ILPD
Management and maintenance by a technical assistant from TU Delft (0,2 fte); the researchers in WP1-3 will contribute to its development; end users will provide guidance for content and user-relevance.

The international levee failure database (ILPD) will be developed to collect and store information in a uniform way on:

i. actual failures during extreme catastrophic events, such as the failure of levees in New Orleans (Seed *et al.*, 2008a) or China (Zhang *et al*., 2013).
ii. failures in large-scale (prototype) experiments, such as breach growth experiments in the Netherlands (Visser, 1998)
iii. general investigations of performance of flood defence systems, e.g. on the case New Orleans (Bea *et al.,* 2008) or on coastal floods in France (Jonkman *et al,* 2012).

The focus is on engineered flood defence systems such as earthen levees, hydraulic structures and flood walls including transitions between them, both in riverine in coastal environments. The database will be set up in such a way that life loss and impact data on actual events (Jonkman *et al*., 2009, Vinet *et al*., 2012) can be added to the ILPD as a future extension initiative. Also, for life loss and damage models there is a very limited data basis for calibration and validation of models and risk estimates.

The ILPD will initially be filled using available information on failures across the world . Cooperation will be set up with international leading academic partners who have done research on relevant failures: TU Dresden, Colorado School of Mines, and Hong Kong UST, (see also section 5.2). The envisaged database is expected to contain initially more than hundred cases documented at different levels of detail. At a high aggregation level, spatial failure patterns and typical causal factors could be found from analysing a larger number of cases and system performance reports (i.e. which sections of the flood defence system did survive or fail and why) as part of WP1. Well-documented cases will be eligible for in-depth hindcasting analyses on the level of individual levees and failure and breaching modes (WP2 and 3). Where relevant, additional data can be added through literature and archive study, and on-site tests.

A technical assistant will closely work with the other researchers in the project to develop a suitable structure and format for the ILPD (A4.0), to collect data on failure and performance (A4.1) and to manage and maintain the data platform (A4.2) throughout the project lifetime. In the final year of the project a longer-term management and maintenance structure (incl. funding arrangements) will be developed together with end-users to ensure that the ILPD can continue to exist after 2017.

Given the relevance of the theme and ILPD for the national and international levee safety community, a discussion and dissemination workshop will be organized in the second year of the project (A4.3). The postdoc (WP3) and technical assistant will play a leading role in the organization.

In short, the ILPD will serve as: a) a research tool for the SAFElevee project, b) an international collaboration and data sharing platform; and c) an important database for a wide range of end-users, applied for model calibration and validation, and R&D on models. The database will be available publicly to the scientific and engineering community for purposes of research and education, and cooperation.

4.2 Existing infrastructure

The research comprises primarily desk studies that will be performed at Delft University of Technology; experimental facilities are not required. Delft University of Technology possesses the IT facilities and software to establish and host the ILPD and to execute all foreseen research analyses. Additional data acquisition (e.g. site investigation) will be contracted externally, if required.

4.3 Time plan and division of tasks

The SAFElevee project aims to start at the beginning of 2015 and to last for 4 years. An overview of the foreseen activities are provided by work package in the table below. Activities that are expected to (journal) publications are marked with "P" in the planning table.

Work packages and Activities	**2015**		**2016**		**2017**		**2018**	
WP1: Understanding levee failure patterns (PhD1)								
A1.0 Data collection and setting up ILPD								
A1.1 Dataset analysis of levee failure factors				P				
A1.2 Spatial patterns of levee failures					P			
A1.3 Data collection and analysis of 2002 failures (TU Dresden)								
A1.4 Effect of landscape features							P	
Reporting / dissertation								
WP2: Hindcasting of individual levee failures and performance observations								
A2.0 Data collection and setting up ILPD								
A2.1 Geotechnical site investigation								
A2.2 Deterministic hindcasting				P				
A2.3 Probabilistic hindcasting (incl. heterogeneity)						P		
A2.4 Exchange of expertise on building computational models								
A2.5 Application to safety assessment and design							P	
Reporting / dissertation								
WP3: Breach patterns and breach growth modelling based on historical failures (Postdoc)								
A3.0 Data collection and setting up ILPD								
A3.1 Study on physical processes			P					
A3.2 Breach data analysis				P				
A3.3 Validation and model improvement						P		
WP4: International Levee Performance Database ILPD (technical assistant)								
A4.0 Data collection and setting up ILPD								
A4.1 Further completion with additional cases								
A4.2 Management and maintenance of ILPD platform								
A4.3 Dissemination workshop				W				

5. Utilisation plan

5.1 The problem and the proposed solution

The majority of the global population is located in flood prone coastal and delta areas. Major catastrophes are often associated with failures of flood defences, such as the failure of the levee system around New Orleans (2005), the floods in Thailand (2011) and the Elbe floods in Germany (2013). The costs of these disasters are enormous, and easily amount to billions of euros per disaster. For the coming decades it is expected that human populations, economic values and risks in the flood prone regions will increase further (Hallegatte *et al*., 2013). New and upgraded flood defence measures are required to safeguard these areas from flood risks. Many lives and considerable costs can be saved if proper precautionary measures against flood risks are taken.

Given the above, a thorough understanding of the performance and failure of flood defence systems is of great societal significance. At a national (Dutch) and global level the investments in levee reinforcements are high (hundreds of millions to 1 billion Euros per year in the Netherlands), whereas government budgets for infrastructure management are under pressure. Through a better understanding of levee performance and failure (the aim of this proposal), better and more effective designs of levee reinforcements can be made and costs can be saved in the major flood defence programs, such as the Dutch national levee reinforcement program (HWBP). For example, reinforcement costs for levees in the Netherlands are between 3 and 20 Million Euro per kilometre. Changes in the design are estimated to save up to 50% of these costs. So, if only one levee reinforcement project in the Netherlands would benefit from the insights of SAFElevee, the savings are already larger than the costs of this project.

Currently, several research methods are applied to improve the insight in levee failures. *Field experiments* on real (decommissioned) levees give valuable insights but cost millions of Euros for a single failure case. E*xperimental lab studies* have lower costs, yet scaling issues will limit the actual validation of real failures. D*esk, literature and (numerical) modelling studies*, give important insights, yet also lacking the actual calibration of real failures. These previous approaches are important and useful, but the acquired knowledge too often fails to be used effectively and to be repeated in similar cases, as it is too widely spread, not properly accessible, and inadequately analysed. The SAFElevee project will create a surplus value of the existing research methods through the collection and evaluation of actual performance and failure data in a systematic and accessible way. Our approach enables a very large expansion of the available validation data for levee systems, and can be applied in ongoing programs that develop new tools for levee designs and reinforcements. An example is the Dutch WTI program which aims at developing new tools for levee design.

In order to strengthen the utilisation of the project several dissemination activities are foreseen. The project will not only lead to academic publications, but in addition more popular publications and (engineering) media are foreseen. Communication and information materials and a website will be prepared to share the ILPD and research findings with a larger public. Finally, a dissemination workshop in Delft is foreseen in 2016 with scientific partners as well as interested end-users.

Overall, the SAFElevee project is expected to:

- Establish a cooperative data and knowledge platform for governments, researchers and companies in the international field of levee safety.
- Complement existing approaches for assessing levee failures (e.g. expensive field tests) at relatively low cost.
- Be applicable for future Dutch and international projects that aim to develop models and tools for levee design and safety assessment.
- Contribute to more effective levee reinforcements and large potential cost savings, through a better understanding of performance and failure modes;
- Contribute to innovative solutions for levee reinforcement and breach prevention (e.g. breach resistant levees).

5.2 Potential users

Company/Institute	**Contact**	**Full contact details**	**Company size**	**Attendance user committee**	**Support letter**	**Contribution**
Rijkswaterstaat Water, Verkeer en Leefomgeving www.rijkswaterstaat.nl	Dr. ing. F. (Felix) Wolf	P.O. Box 17 | 8200 AA Lelystad | the Netherlands T: +31 (0) 53208729 E: felix.wolf@rws.nl	>250	Yes	Yes	Yes
Ministerie van Infrastructuur & Milieu http://www.rijksoverheid.nl/ministeries/ienm	Ir. F. (Frank) Hallie	P.O. Box 20901 | 2500 EX The Hague | the Netherlands T: +31 (0) 70 - 456 9386 E: frank.hallie@miniem,nl	>250	Yes	Yes	Yes
Stichting Deltares www.deltares.nl	Ir. F. (Frans) Hamer	P.O. Box 177 | 2600 MH Delft | the Netherlands T: +31 (0)88 335 8273 E: frans.hamer@deltares.nl	>250	Yes	Yes	Yes
Fugro N.V. www.fugro.com	Ir. M.T. (Martin) van der Meer	Veurse Achterweg 10 | 2264 SG Leidschendam | the Netherlands T: +31 (0)70 311 1444 E: m.vdmeer@fugro.nl	>250	Yes	Yes	Yes
Stichting Toegepast Onderzoek Waterbeheer (STOWA) www.stowa.nl	ir. L.R. (Ludolph) Wentholt	P.O. Box 2180 | 3800 CD Amersfoort | the Netherlands T: +31 33 460 3200 E: wentholt@stowa.nl	<250	Yes	Yes	Yes

HKV lijn in water www.hkv.nl	Ir. drs. K. (Kees) Vermeer	P.O. Box 2120 | 8203 AC Lelystad | the Netherlands T: +31 320 29 42 42 E: vermeer@hkv.nl	<250	Yes	Yes	Yes
HWBP Hoogwaterbeschermings programma http://www.hoogwaterbeschermingsprogramma.nl/	Ir. J. (Jasper) Tamboer	P.O. Box 93218 | 2509 AE The Hague | the Netherlands T: +31 (0) 6 35 11 94 13 E: jasper.tamboer@ hoogwaterbescherming.nl	<250	No	Yes	No
ENW – Expertise Network for Flood Protection www.enwinfo.nl	Ir. D.P. (Don) de Bake	P.O. Box 17 | 8200 AA Lelystad | the Netherlands T: +31 6 14197288 E: don.de.bake@rws.nl	<250	No	Yes	No
Hong Kong University of Science and Technology Civil & Env Engineering www.ust.hk	Prof. L.M. (Limin) Zhang	Clear Water Bay, Kowloon, Hong Kong T: +852 2358 8720 E: cezhangl@ust.hk	>250	No	Yes	No
Colorado School of Mines Civil & Env Engineering www.mines.edu	Prof. M.A. (Mike) Mooney	1500 Illinois St. | CO 80401 Golden | USA T: +1 303 384 2498 E: mooney@mines.edu	>250	No	Yes	No
Tech. Univ. Dresden Institut Wasserbau und Hydromechanik (IWD) www.iwd.tu-dresden.de	Dr. Ing. T. (Torsten) Heyer	TU Dresden 01062 Dresden, Germany T: +49 351 463 33874 E: torsten.heyer@tu-dresden.de	>250	No	Yes	No

Towards the application of the research results
To maximize utilization potential, the SAFElevee project is positioned within a collaborative network of research institutes, government and private companies, of which the diversity ensures the direct application of the outcomes in a broad range of research and implementation programs.

SAFElevee will deliver to the development of tools for levee design, reliability analysis and safety assessment. At a national level, the findings and ideas generated within the project can be directly put into practice through the involvement of end users from governmental bodies and private companies, and the active involvement of TU Delft within programmes like the Topsector Water, Flood Control IJkdijk initiative.

Academia, research institutes: The main applicant TU Delft combines its expertise on hydraulic, geotechnical engineering and remote sensing. The iinternational academic partners Technical University Dresden (levee failures, Germany), Hong Kong University of Science and Technology (geotechnical expertise and experience with dam failure datasets, China) and Colorado School of Mines (data management for levee failures, USA), have committed themselves to provide data and collaborative actions. The knowledge institute Deltares is an established and active player in the international market for flood risk management, and will provide expertise and support as active research partner and end-user.

Government: The Dutch Ministry of Infrastructure and Environment, Rijkswaterstaat, HWBP, and Water boards (through STOWA) contribute significant experience regarding the practical management aspects of flood defence systems. The SAFElevee project will provide essential input to improve tools and rules for levee design and safety assessment (e.g. WTI 2017, HWBP), leading to more cost effective reinforcement and prioritization. The Dutch network of experts on flood protection (ENW) is involved to review and ensure the knowledge sharing of the project. The main applicant – prof. Jonkman – holds a part time advisory position (0,1 fte) as a strategic advisor at Rijkswaterstaat, enabling sharing of the results.

Private companies: Fugro N.V. is a multinational engineering company that has developed expertise and innovative systems for levee data management which can also be used in the SAFElevee research for cases across the world. HKV Consultants operates globally, providing services and research in water and safety, with specific expertise on innovative tools in this field. Both companies are involved in various levee safety projects in the Netherlands and abroad.

The application of the SAFElevee outcomes will not be limited to the users mentioned above. The cooperation model is “open” and other organizations active in the field of levee safety have shown interest and are welcome to join in a later stage, Examples of such organizations are the United States Army Corps of Engineers (USACE) and Flanders Hydraulics Lab.

Overall, the project aims to maximise the use of its results by establishing an international and cooperative data and knowledge platform, where governments, researchers and companies can publicly exchange their knowledge and expertise on levee safety.

5.3 Past performance

The project is led by the hydraulic engineering group of TU Delft. Over the past decade members of the group have played a major role in the scientific development of methods for several aspects of flood risk analysis, including:

- Levee reliability analysis for several failure mechanisms (Vrijling, 2001), including geotechnical failures (Kanning, 2013; Schweckendiek *et al*., 2014)
- Breach models in sand dikes (Visser, 1998) and cohesive embankments (Zhu, 2006)
- Damage and life loss analysis (Jonkman *et al*., 2008 & 2009)
- Risk acceptance and risk evaluation (Vrijling *et al*., 1995; Jonkman *et al*., 2011)

These methods have been implemented in multiple risk assessment studies in the Netherlands (e.g. VNK “Veiligheid Nederland in Kaart”) and abroad. The group’s research line on geotechnical failure mechanisms and specifically piping has resulted in significant attention for this critical failure mechanism in recent years (Vrijling et al., 2010). Also, the group has been involved in several forensic studies on floods and levee failures in New Orleans (2005), France (2010), Thailand (2011), Japan (2012), and Germany (2013). Furthermore, the risk-based concepts developed at TU Delft constitute now the basis for the new Dutch flood management policy (implemented in 2014) and the prioritization of levee reinforcement in Dutch national programs. These initiatives have resulted in multiple scientific as well as more popular publications, and in the establishment of a solid (inter)national network. The research group is involved in various (inter)national (applied) research projects, e.g. in New Orleans and Texas (USA), Vietnam, China and Singapore. Members of the group (Jonkman, Kok, Schweckendiek, Vrijling) are active in national and international advisory boards, such as the Dutch Expertise Network on Flood Risk (ENW), and international communities on levee safety.

A network of researchers from various disciplines in the field of flood risk at TU Delft is formed by the Delft Flood Risk Center. Active members of that center and the SAFElevee project include several groups at TU Delft. The Geo-engineering section of TU Delft focuses on understanding the physical processes associated with failure of levees and other soil structures. They combine model, experimental and field work. The Geoscience and Remote sensing departments at TU Delft have specific expertise on earth observation methods. They have developed innovative methods to observe deformation in levee systems which has resulted in various publications, and also in a start-up company for infrastructure monitoring, named “Hansje Brinker”.

The research team includes various private partners that will strengthen the utilization potential. Deltares is one of the world’s leading institutes in applied research concerning geotechnical and hydraulic aspects of levee systems. HKV Consultants is a mid-size company that has developed several innovative tools and data systems for flood and water management. Fugro focuses on data analysis and management, is present in many regions over the world, and has developed several innovative research tools, such as Fugro Real.

6. Intellectual property

All data obtained within the SAFElevee project will be made publicly available through the ILPD (International Levee Performance Database). The ILPD will be a free and open source initiative. Therefore, intellectual ownership regulations by means of contracts and patents are not applicable for the SAFElevee project.

6.1 Contracts

Not applicable.

6.2 Patents

Not applicable.

7. Positioning of the project proposal

7.1 Uniqueness of the proposed project

The SAFElevee project fulfils the urgent societal demand to ensure safe living in flood prone areas. Its multidisciplinary research approach provides hands-on solutions that can be applied internationally to improve flood defence systems.

The pillar Delta technology of the Dutch Topsector Water policy aims to enable delta life by clustering innovations in the four themes Eco-engineering, Water Safety, Water management, and Smart Dikes. In order to progress the innovations within these themes and apply them internationally, developments are deemed necessary for:
a) Knowledge building of the functioning of water and soil systems;
b) Knowledge transfer from excellent fundamental research to application in the field;
c) Information and Communication Technology (ICT) for monitoring, analysing and improving databases;
d) Cooperation between the public, private and scientific sectors.
(Source: Innovation contract Deltatechnology 2014 – 2015)

The SAFElevee project foresees in all the above innovation aspects by working on:
- An international levee performance database with public access, in which existing local/regional information and data sources are combined (b,c,d);
- Analyses of macro-scale levee performance patterns with novel data analysis techniques (a,c)
- Hindcasting of actual failures instead of laboratory or field experiments (a,b, d)
- Application of novel (soil) material models and accounting for unsaturated behavior as well as heterogeneity in ground conditions (a,b,c)
- International focus to develop and strengthen valuable international networks in the field of flood risk management and levee safety and to further improve the world-wide visibility and reputation of the Dutch water sector (b,c,d):

7.2 Embedding of the proposed project

SAFElevee fits very well within a number of ongoing initiatives and projects at TU Delft and partner institutes. The hydraulic engineering group of the main application, prof. Jonkman, is leading the initiative of the Delft Flood Risk Centre. This is a multi-disciplinary research centre within TU Delft involving groups and researchers in related fields such as geotechnical engineering, remote sensing and applied mathematics. The project fits very well in this center due to the involvement of researchers of various groups in Delft.

The project is strongly related to ongoing research projects at TU Delft such as the research multifunctional flood defences (supported by STW), and the BE-SAFE project on safety of levees with vegetated foreshores supported by NWO.. Together with the organization of water boards (STOWA) a 4 year research project on safety of primary and regional levees, including the effects of emergency measures, has been initiated in 2013. As part of this project an existing decommissioned levee (Leendert de Boer polder) will be tested to failure limits in 2015. This test will provide additional data for the SAFElevee project. Full-scale levee breaching tests in Belgium are scheduled in 2015, and cooperation on this topic is foreseen with Flanders Hydraulics Lab. At a national level, TU Delft will also be involved in the new Flood Control – IJkdijk consortium.

SAFElevee will also be complementary to recent EU projects that have started in the group, such as the Riskcit project on coastal flood risks and the RAIN project on risk analysis of infrastructures, including levees. Finally, the project will contribute to further formalizing and extending contacts with partner institutes such as Dresden, Hongkong and the Colorado School of Mines.

7.3 Request for support elsewhere

Not applicable.

8. Financial planning

8.1 Personnel positions

Position	Category	Fte	Months	Tariff	Name (optional)
1	Postdoc	1.0	36		
2	PhD	1.0	48		
3	PhD	1.0	48		
4	NSP	0.2	48		

8.2 Consumables

A budget of 1,500 €/year/FTE will be allocated to both PhD's (2 x 4 years) and the Postdoc (3 years) to cover expenses related to domestic travel (to e.g. conferences and meetings), dissemination equipment (e.g. posters), and project specific courses in order to be able to perform the research. In WP2, geotechnical site investigations will be performed (€ 30,000). **The consumables budget totals € 46,500**.

8.3 Travel abroad

A travel budget of 2000 €/year/FTE will be allocated to both PhD's (2 x 4 years) and the Postdoc (3 years) to allow presenting their research results at international conferences and to attend meetings and workshops that are relevant to the project. Within WP1 and WP2 a travel budget is allocated to exchange expertise with foreign universities. The PhD-WP1 will visit UT Dresden (2 months; € 13,000), the PhD-WP2 will attend UST Hong Kong (2 months; € 17,000). In exchange, from both universities a scientist will visit TU Delft to provide information on failure cases and collaboration on research activities (3 months; € 24,500). **The travel budget totals € 76,500**.

8.4 Investments

To host and secure the International Levee Performance Database (ILPD) a budget of 2,500 €/year will be allocated to cover expenses for hardware and software. **The investment budget totals € 10,000.**

8.5 Contribution from users

removed

8.6 Cost breakdown

removed

8.7 Letters of support

Letters of commitment of partners and end-users in which they declare to provide a cash and/or in kind contribution or other type of support to the SAFElevee project, are presented in Annex 1. An overview of supporting partners and end-users is given in section 5.2.

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9.1 Selection of key publications research group

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10. Abbreviations and acronyms

- ILPD: International Levee Performance Database
- STOWA: Stichting Toegepast Onderzoek Waterschappen
- WTI2017: Wettelijk Toetsinstrumentarium 2017 http://www.helpdeskwater.nl/onderwerpen/waterveiligheid/primaire/toetsen/wti2017-ontwikkeling/