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Large-scale Dike Breach Experiments in Belgium

Data Report Wijmeers & Outlook future experiments

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Abstract

Within the frame work of the realization of the Sigmaplan for the river Scheldt in Flanders (Belgium), a series of in situ dike breach experiments caused by overflow are executed. The first breach tests were organized in 2012 at Lillo along the tidal river Scheldt. In November 2015 another experiment took place at Wijmeers, again along the river Scheldt and more are coming.

The purpose of this report is twofold, i.e. reporting the setup and outcomes of the Wijmeers experiment for further (model) analysis and providing outlook for future experiments.

The height of the dike was around 3 m above the ground level of the hinterland, and the width of the crest was 6 m. However, the initiation gully reached only 1.5 m above ground level. During the experiments the following aspects were monitored: breach growth in width, water levels just upstream and downstream of the dike, water pressures within the dike and (to some extend) flow velocities within the breach. Breach growth in width occurred slowly. Therefore measurements continued for almost 2 months. Outcomes can be used for a better understanding of the complex physical processes of embankment breaching for detailed model development and validation as for the optimization of dike design and maintenance strategies.

Allowing overflow and wave overtopping in time (as a climate resilience measure) introduces an additional failure mechanism to account for when designing and maintaining dikes. Incorporating such strategic choices within dike management will need improved maintenance strategies as well as experience with managed and emergency response measures. In addition to filling gaps of knowledge regarding strength of vegetation cover, breach formation and growth, future dike experiments will allow to train skills and gain experience with state-of-the-art managed and emergency response measures.

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1 Introduction

1.1 Breach growth in real-dikes

International research (e.g., CADAM, IMPACT, FLOODsite, DSIG-project, …) on breach initiation and growth has led to the identification and better understanding of different key processes and the development of prosperous (semi) physical models for predictive purposes (see among others Wahl, 2004; Morris *et al*., 2009a; Wu, 2011). A general consensus regarding stage or phase distinctions for the (whole) breaching process can be found (a.o. Visser, 1998; Hahn *et al.*, 2000; Oumeraci *et al.*, 2005; Temple *et* al., 2005; Zhu, 2006; Morris *et al.*, 2009b).

Present knowledge regarding breach growth over time allow the development of (solid) evacuation strategies. However, optimization of dike design, maintenance strategies and breach growth retarding measures require a sound understanding of the complex physical mechanisms of embankment breaching in composite (real) dikes, which is still lacking. In particular, according to Poesen *et al.* (2003), the relative importance of various sub-processes, e.g. flow detachment by flow shear stresses or by seepage forces, plunge pool erosion, headcutting, tension track development and mass-instability, cannot easily be addressed in real-life cases. Visser (1998) suggests to account for the presence of certain river-side protection measures, e.g. rip rap, tidal march, ... At present, this issue is only dealt with in a qualitative way.

Large scale laboratory and field experiments should be performed for both a better understanding of the complex physical processes of embankment breaching (Wu, 2011) as for detailed model development and validation (Morris et al., 2009a).

Within the frame work of the realization of the updated Sigmaplan, the opportunity is offered to organise in situ breaching experiments caused by overflow through an initiation gully. Giving more space to the river includes the construction of new dikes more landward. Therefore parts of existing dikes lose their defence function and need to be removed or breached, either by excavators or by water flowing through an initial (excavated) gully. The breach experiments on existing dikes along the Scheldt will serve to gain insight into the complex physical processes of embankment breaching and (hopefully) allow for model validation as well.

1.2 Managed realignment ‘Wijmeers’

‘Wijmeers (II)’ is a managed realignment (depoldering) of almost 30 ha along the river Scheldt near Schellebelle in between Antwerp and Ghent (Figure). The maximum width of the breach is limited to 100 m due to the presence of rip rap covered with concrete at both sides of the breach location (Figure 2). Together with the surrounding flood control area (FCA) Wijmeers (I), it is part of the cluster Kalkense Meersen of the updated Sigmaplan.

The dike seperating Wijmeers II from Wijmeers I will act as an overflow dike. As a consequence, the breaching experiment at Wijmeers needed to wait upon completion of the ring dike of FCA Wijmeers I.

Figure 1 – Overview of managed realignment Wijmeers

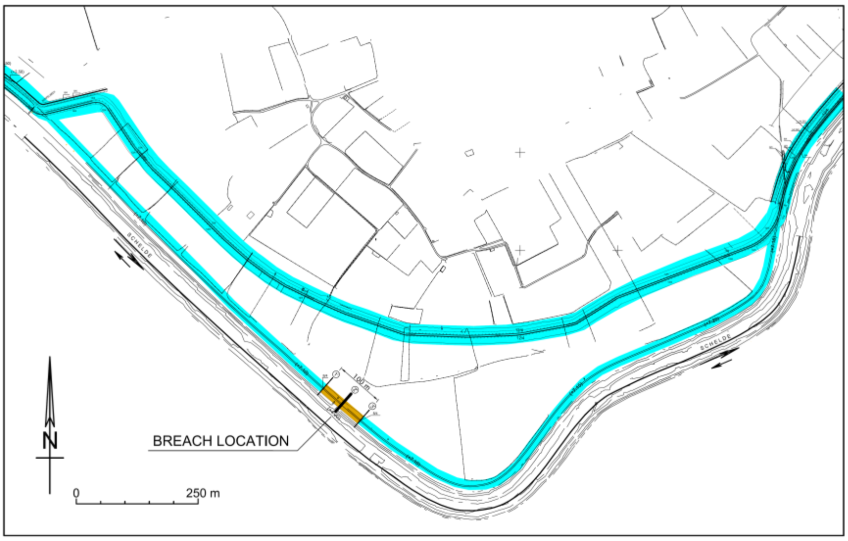

Figure 2 – View of rip rap revetment at the outer limit of the breach location at Wijmeers

1.3 Acknowledgement

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2 Wijmeers experiments – tell the story

2.1 Preparatory phase

In the beginning of 2012, a field trip and technical meeting took place with people from Flemish and Dutch research institutes to discuss the survey program and monitoring of the breach experiments at Wijmeers (Peeters *et al*., 2012b).

At the time, the available data consisted of topographical data of the dike, geotechnical soundings and drillings just outside the breach location. In addition, the core material of the dike (following a grain size analysis of some samples near the upstream edge of the breach location) was considered sandy.

In between November 2012 and August 2013, geophysical measurements (EM, ERT, GPR) of the landside slope and accompanying hand drillings were executed (G-tec, 2014). Next, the Institute for Nature and Forest Research (INBO) expanded the vegetation research for the Sea-Scheldt with a grass cover survey of the breach location at Wijmeers, first in 2012 and again in 2015. The erodibility of the top layer was assessed based on jet and hole erosion tests (JET/HET) following soil sampling in February 2013 (IRSTEA, 2016). Finally, 9 additional geotechnical soundings (CPT) within the breach location (2 at the crest and 1 near the landward side toe) were carried out in September-October 2015 by the Geotechnical division (De Vos & Vincke, 2017).

Figure 3 presents an overview of these preparatory survey activities.

Figure 3 – Overview of some preparatory survey activities (in clockwise sense): JET, EM, GPR and ERT

2.2 November 1 – 15, 2015

Along the dike, at one side of the (foreseen) initial breach centre, piezometers were installed for measuring pore water pressures at TAW +4,5 m, which is around the level of the breach pilot channel (De Vos & Vincke, 2017).

On the land side slope, a 1x1m grid was drawn (Figure 4). In addition, small pickets were placed on the crest. Water level gauges were installed within the polder as well as in the river. The elevation of numerous points in the polder can be used to derive elevation/area-relationships.

On Sunday, November 15, the preparation works for the breach initiation gully took place. At the river side, only about 1 meter of the original dike crest was left in place. The top and bottom width of the pilot channel are resp. 6 m (at ~TAW +7,1 m) and 1 m (at ~TAW +4,5 m). The XYZ-coordinates were measured by colleagues from ATO.

Colleagues from the Geotechnical division performed an infiltration test using a double ring infiltrometer to obtain the saturated hydraulic conductivity of the core material of the dike. In addition, (un)disturbed soil samples were taken for further lab testing, a.o. determination of friction angle and cohesion as well as grain size analyse (De Vos & Vincke, 2017).

Finally, a small earthen embankment served as an access path to the platform for frontal video recordings from the landward side of the breach (Figure 5).

Figure 4 – 1x1m grid at both sides of the breach initiation gully

Figure 5 – Breach experiment setup (Courtesy: Dieter Boone)

2.3 November 16, 2015

First, the remaining 1 m of the original dike crest at the river side was removed at low tide. Next, a small earthen embankment with a height of approximate 0,5 m was put in place in the middle of the pilot channel (Figure 6).

At 7:51 h (UTC+1), when the water level in the river reached ~TAW +4,7 m, the breach experiment was initiated by a sudden removal of this bump of soil. Around 8:30 h (UTC+1), the water level in the Schelde reached the maximum level of (only) TAW +5,0 m. Around 10 h (UTC+1) the first breach experiment was ended.

Figure 6 – Small earthen embankment in the pilot channel (Courtsey: Lode De Vriese)

During the test, the flow velocity in the breach channel was measured using GPS floats (Figure 7). Although the accuracy of the measurements was low, the measurements indicate flow velocities in between 1,0 and 1,2 m/s.

During the breach the breach channel eroded to approximately TAW +4,2 m, showing some emerging clayey material, and widened with 1 m.

Figure 7 – Flow velocity measurements in the breach channel using GPS floats

After the test, the breach channel was deepened further with the help of an excavator to TAW +4,0 m. The side walls were steepened accordingly. A temporary dike was installed to prevent flow through the breach during the following high tide in the evening of November 16.

Along the river, upstream of the breach channel, the riprap protection at the river side was removed.

2.4 November 17, 2015

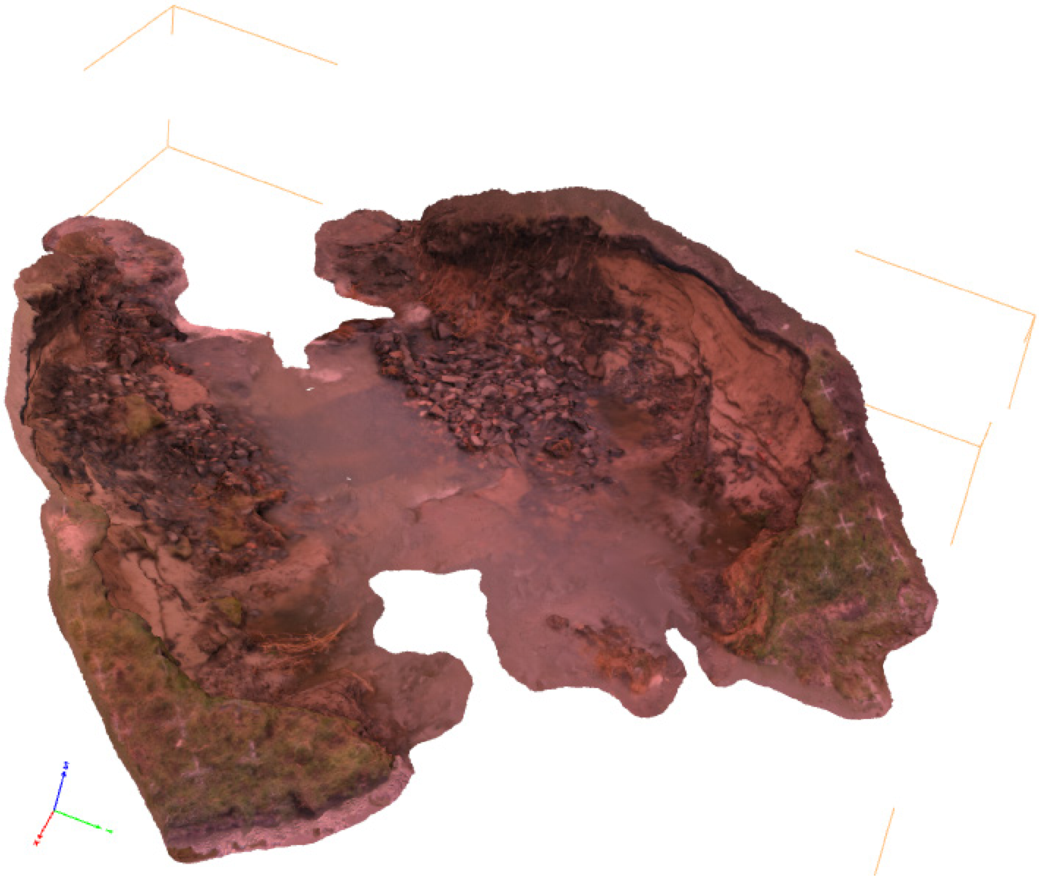
At 8:01 h (UTC+1), when the water level in the river reached ~TAW +4,6 m, the (second) breach experiment was initiated (again) by the removal of the small embankment in the (new) pilot channel. The maximum water level in the Scheldt at high tide only slightly exceed TAW +5,2 m. Around 10:45 h (UTC+1), the water level of the Scheldt dropped below the levels within the polder.

Because the bottom of the new pilot channel was dug out into a clay layer, deepening of the breach channel by erosion was negligible. Also only limited breach growth in width took place. Erosion at the toe of the breach side slopes followed by superficial sliding was noticed, especially of the sandy core material. Both the landward and river sides suffered less erosion and slope instability. Presumably due to the presence of more clayey material, through root-reinforcement by reed and trees as well as rip rap protection at the river side and by grass at the land side. As a result, in plan view, an ‘O’-shaped breach was formed with a top width of about 8 m (Figure 8). Measured flow velocities using GPS floats showed an order of magnitude of 1,5 - 2,0 m/s. Video recordings yielded flow velocities ranging in between 1,4 and 1,5 m/s.

Detailed topographic data are available every 15 à 30 minutes following stereophotogrammetric analysis of photographic images taken from different positions by ATO (Figure 9).

Figure 8 – ‘O’-shaped breach (Courtesy: Dieter Boone)

Figure 9 – 3D visualization of the breach (Courtesy: Wim Van Calster)



2.5 November, 2015 – March, 2016

The development of the breach was further monitored using photographic images on the following dates:

- November 20, 25 and 27, 2015
- December 2, 4 and 9, 2015

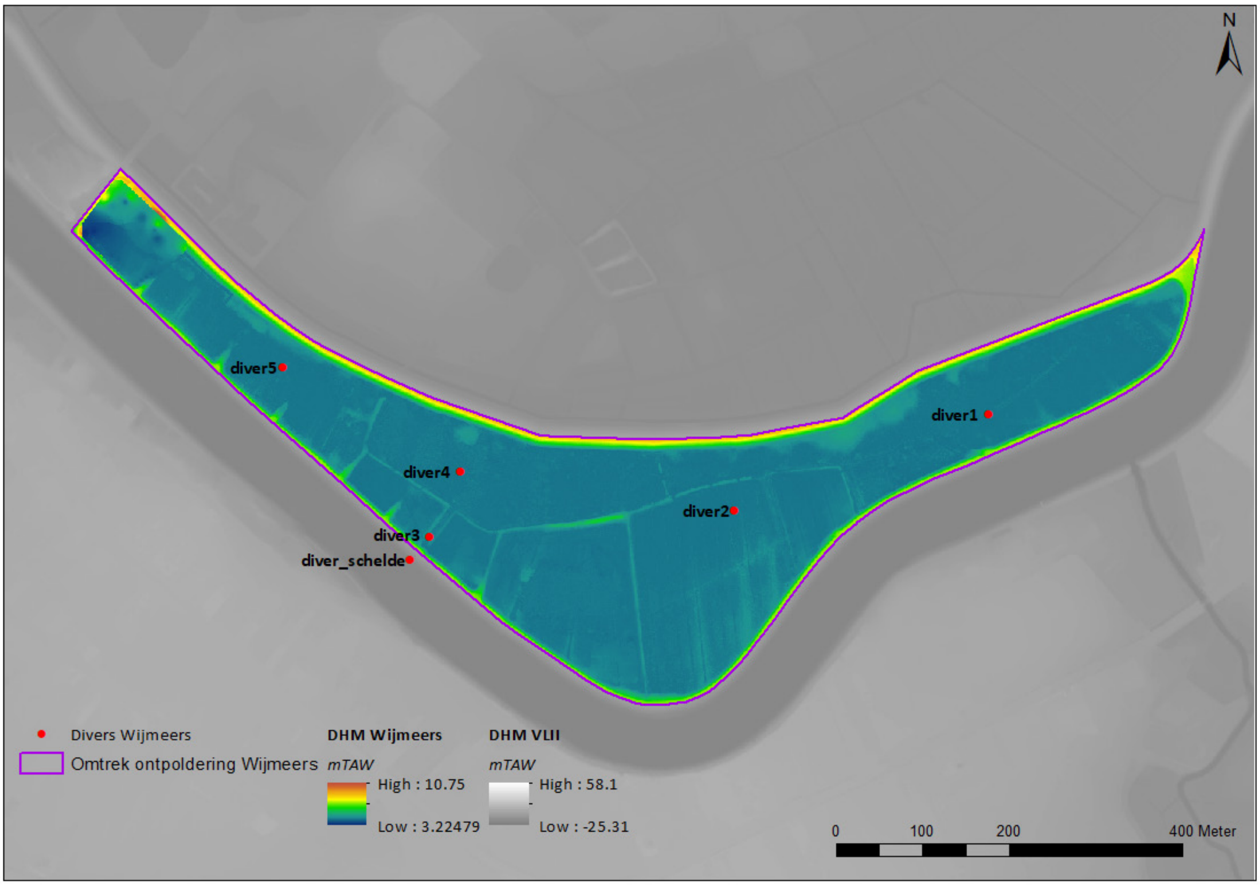
Detailed topographic data are available. The topographic data of December 9, 2015 are based on images from a drone flight (operated by ILVO).

At different locations along the dike crest, GEO continued the piezometric measurements until Jan. 12, 2016.

Pressure sensors within the managed realignment provided water level data (Figure 10).

On March 15, 2016, colleagues from FHR executed discharge measurements during in- and outflow.

Figure 10– Location of pressure sensors within within managed realignment Wijmeers (Courtesy: Leen Coen)



3 Breach dimensions

Combining RTK-GPS data with stereophotogrammetric analysis allowed to produce detailed consecutive Digital Elevation Models (DEMs) of the breach. The first DEM contains the pilot channel to initiate overflow (Figure 11). Besides the grid-points (1x1m) on the dike, Figure 11 also shows 14 cross-sections of the breach location from river- (1) to landside (14) with cross-sections 2 to 8 representing the original dike crest around TAW +7,1 m.

Breach profiles over time at cross-sections 2, 5 and 8 are shown in Figure 12 to Figure 14 (top: 17/11/15; bottom: 17/11-9/12/15). The arrow in Figure 11 illustrates the line of sight of the breach profiles shown (X=0m: downstream along the Schelde).

Figure 11 – DEM of the breach initiation gully (T0)

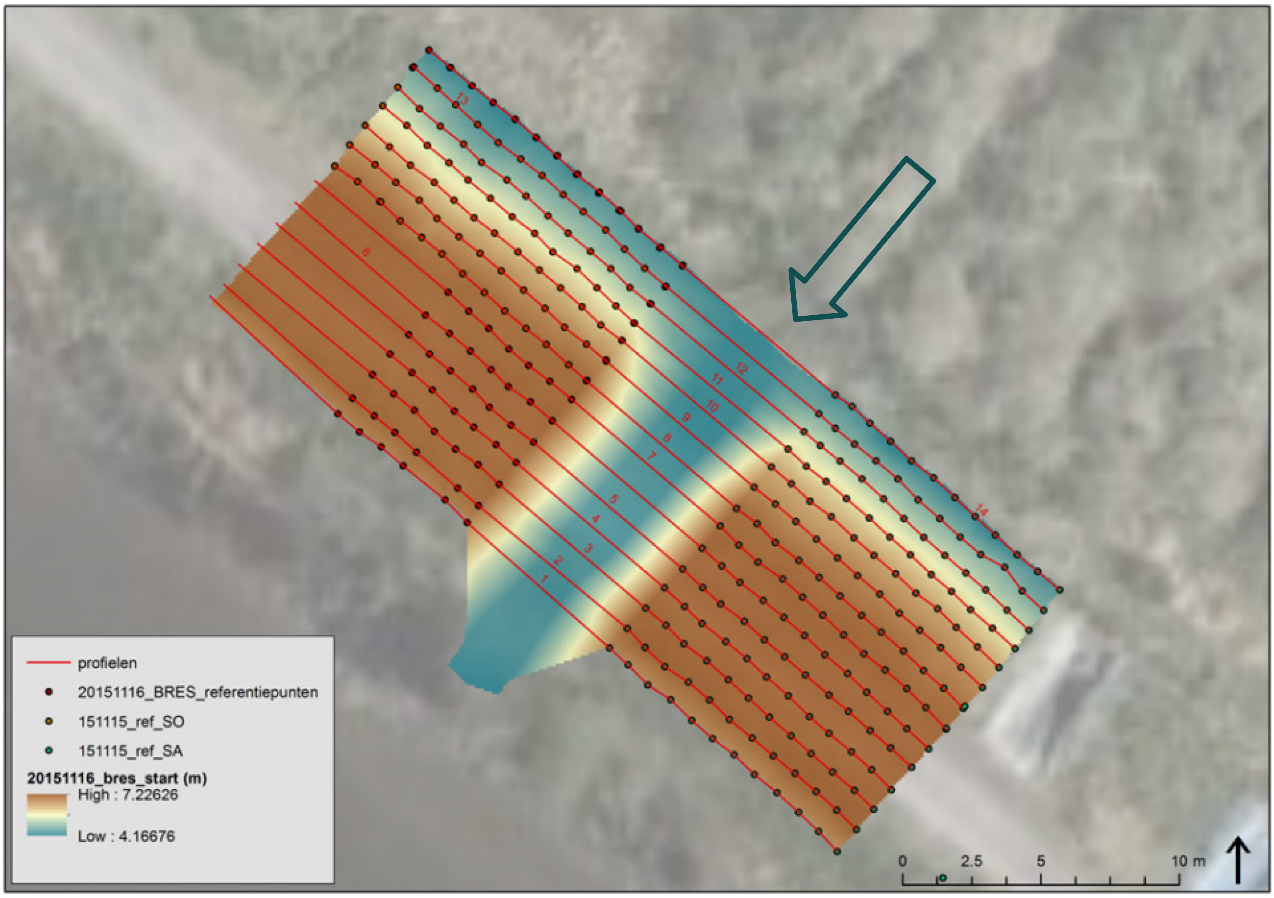
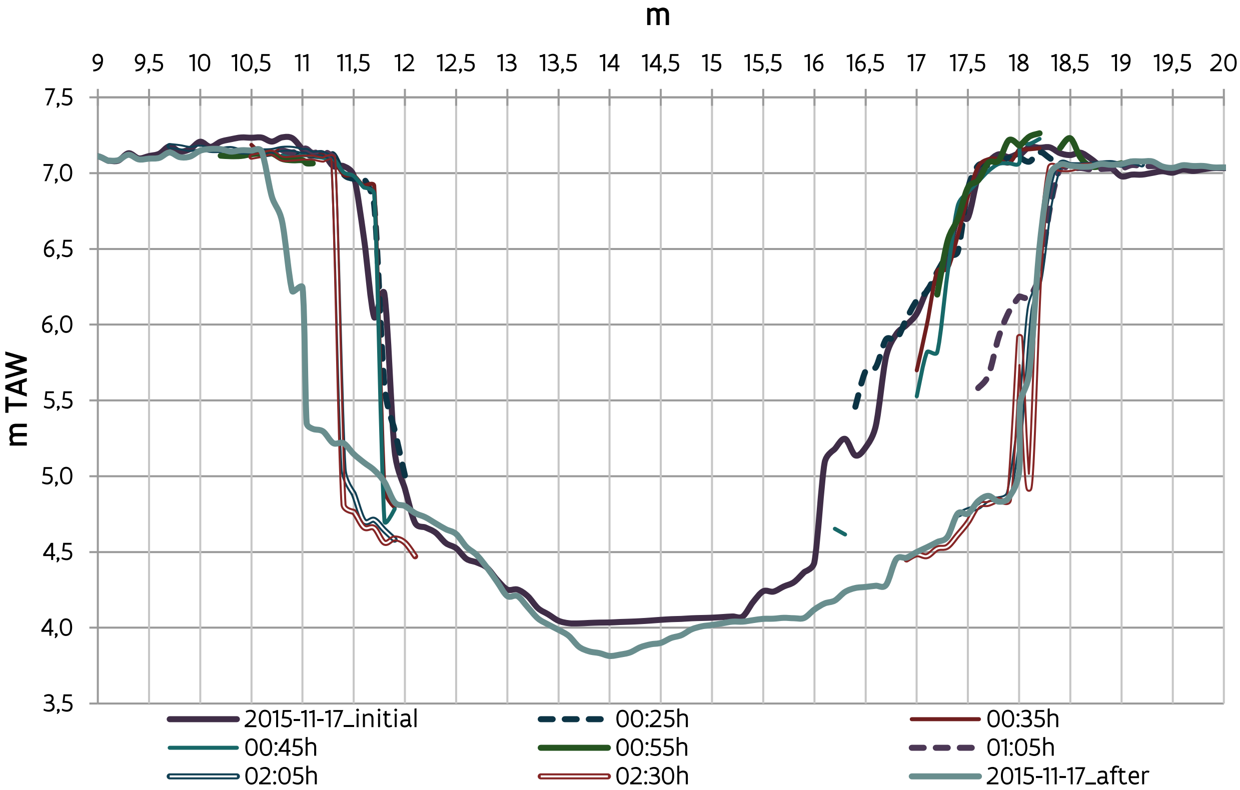


Figure 12– Breach profiles for section 2 (river side)



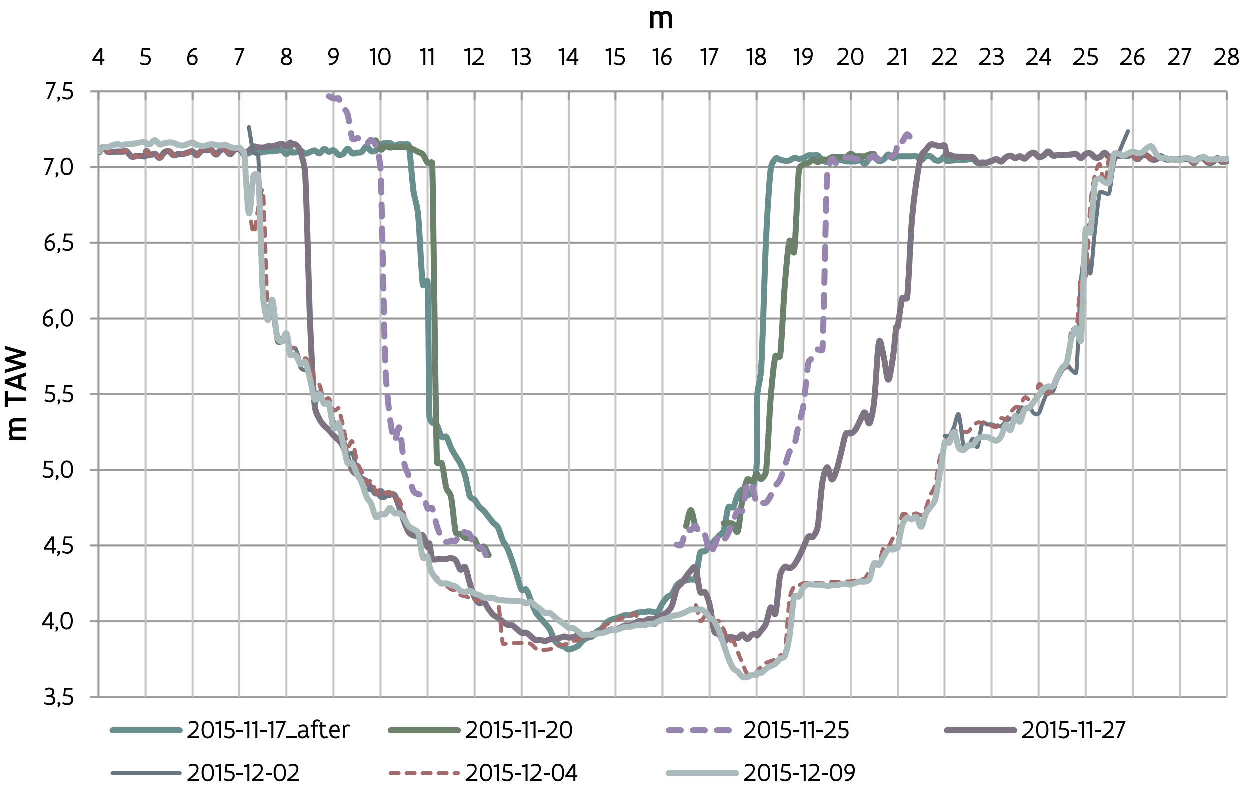
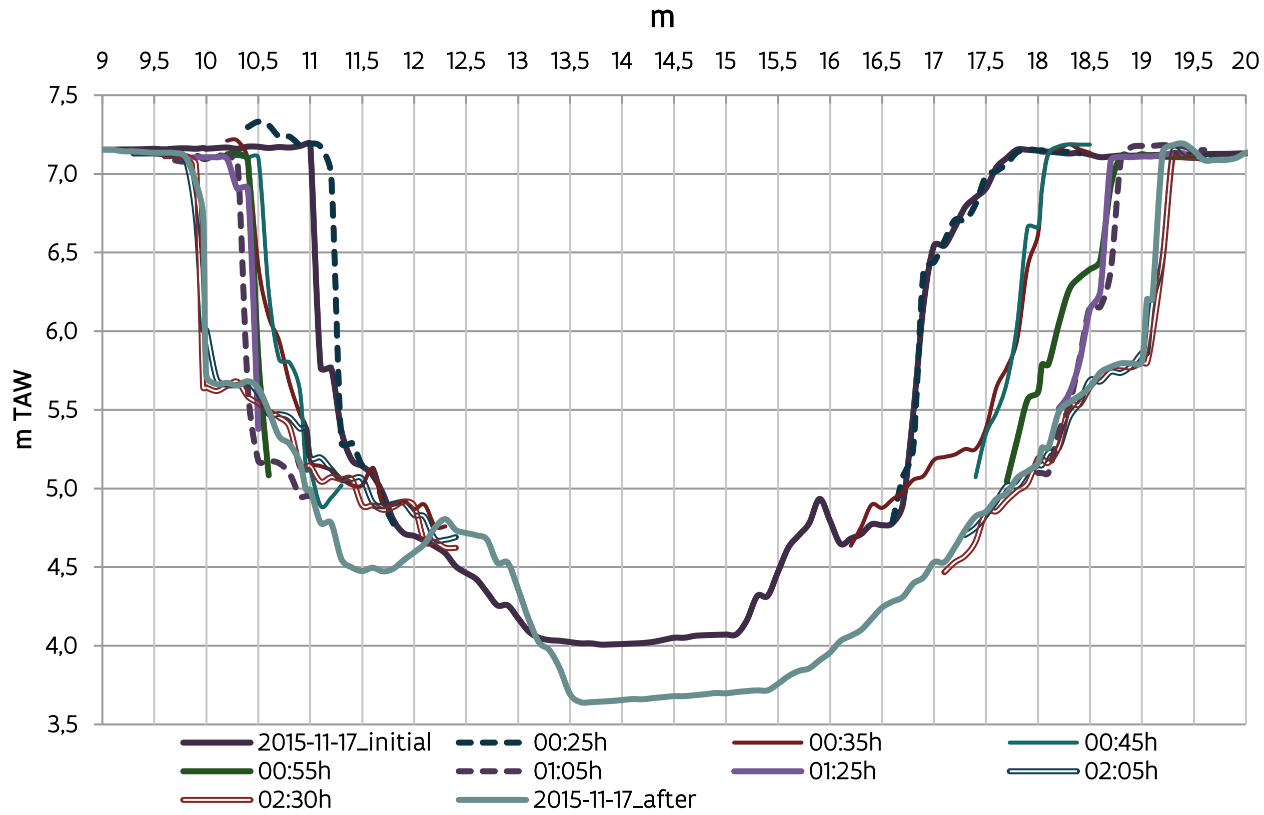


Figure 13– Breach profiles for section 5 (center of crest)



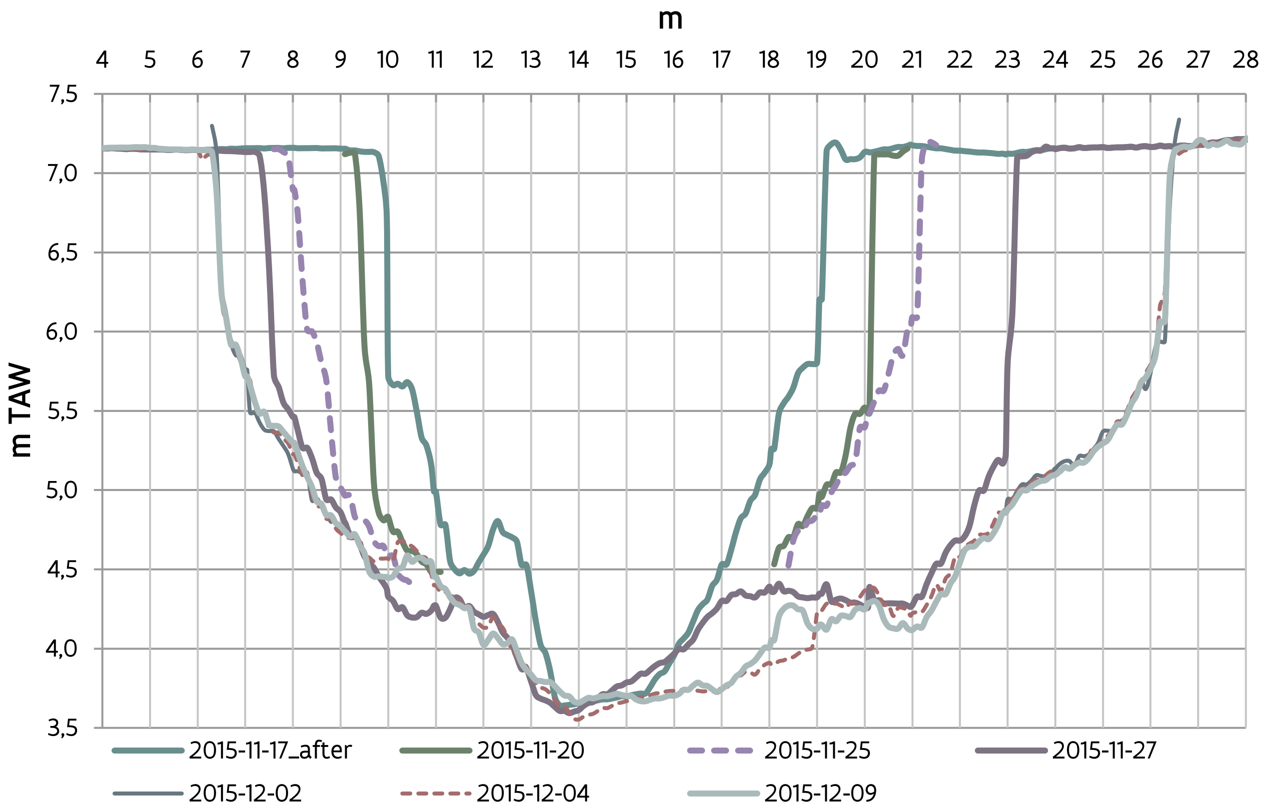
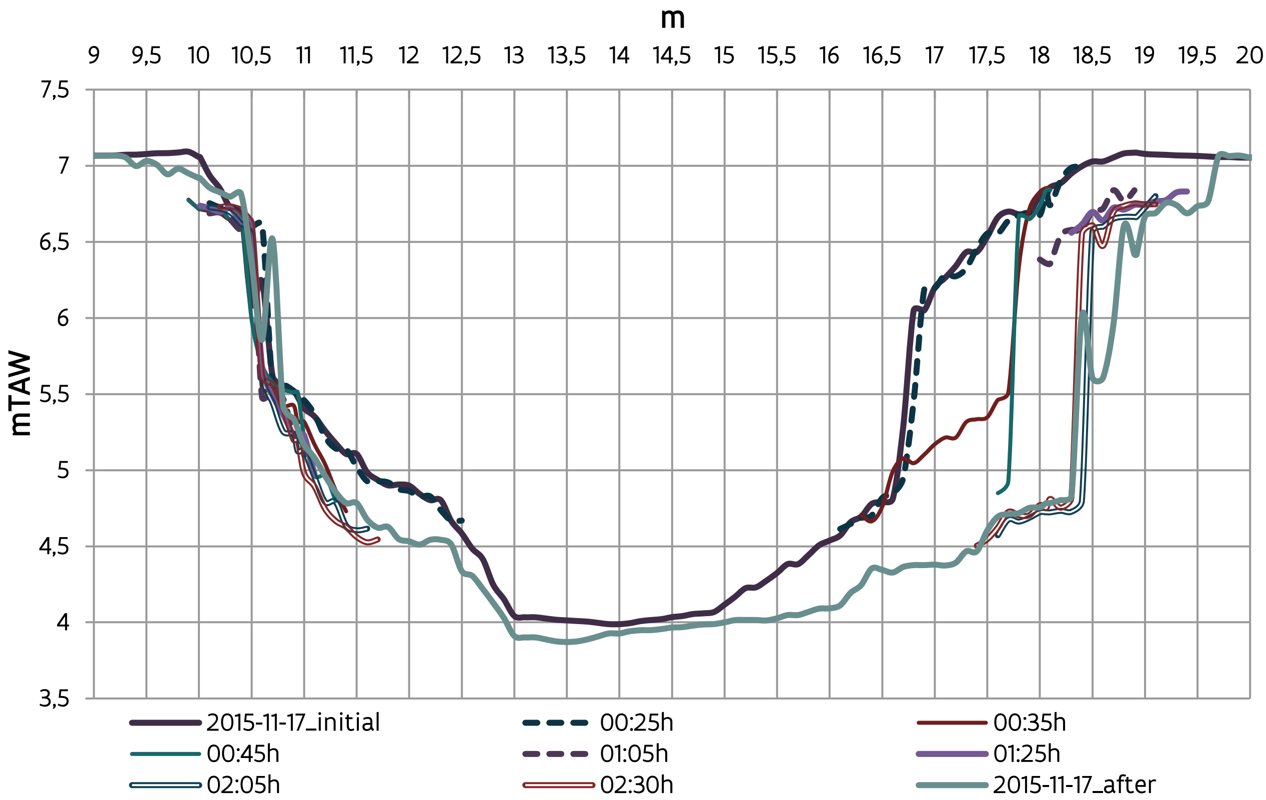
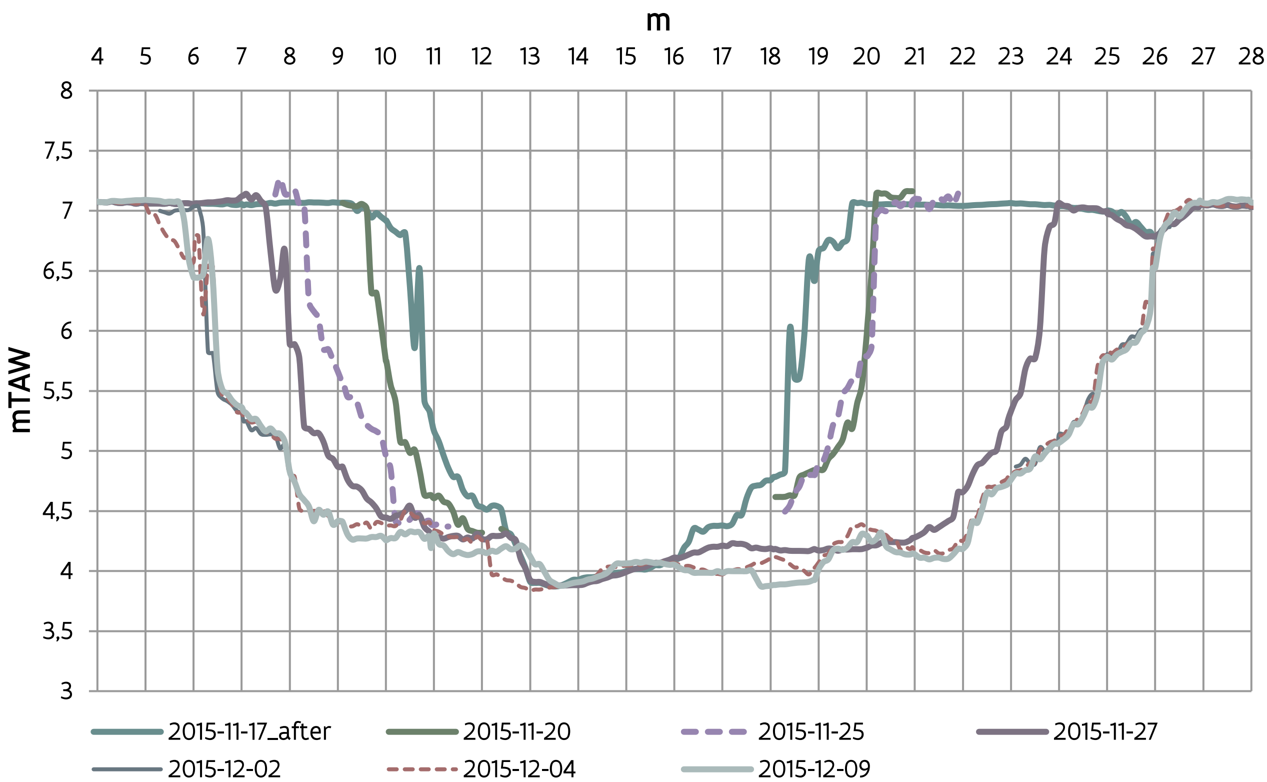


Figure 14– Breach profiles for section 8 (land side)





From the above figures, the following can be noticed:

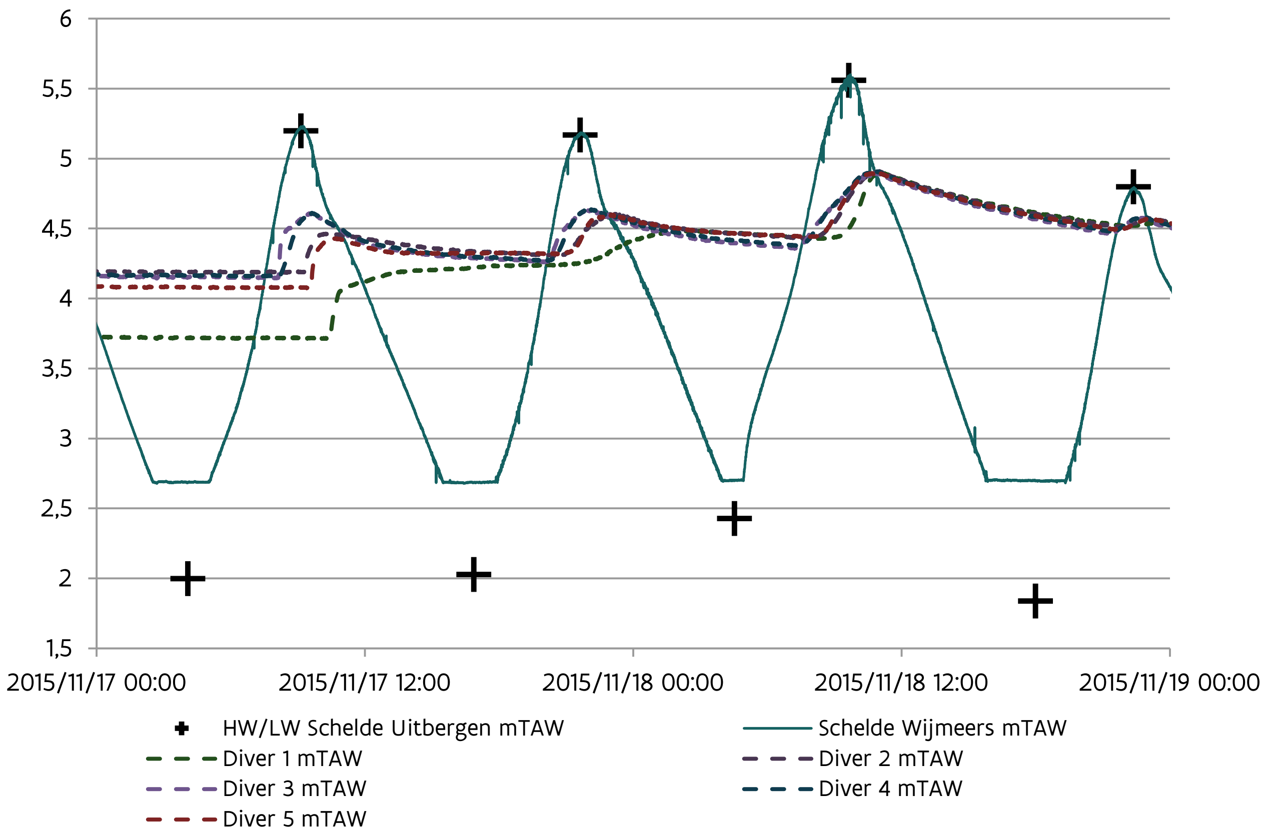
- On November 17, 2015
    - In the beginning, the breach has the tendency the grow symmetrically as well as faster at the centre of the crest
    - After 30 minutes, the land side of the breach channel is trying to catch up with the centre of the crest, but above all at the left side of the breach (looking in breach flow direction)
    - After 1 hour, the river side of the breach channel is now trying to catch up with the centre of the crest, again above all at the left side of the breach (looking in breach flow direction), possibly linked with the removal of the riprap protection at the left side of the breach channel.

- Until December 9, 2015
    - Asymmetric growth in width, again possibly linked with the removal of the riprap protection at the left side of the breach channel, along the river.

4 Measured water levels

Figure 15 shows measured water levels in the Scheldt just upstream of the breach location and within the managed realignment.

Figure 15 – Measured water levels (m TAW)



The limited breach growth yielded relatively small breach flows leading to non-uniform increases in water levels within the polder on November 17, 2015 (Figure 15). As a consequence, changes in water volumes stored in the entire polder cannot be derived easily based on the changing water levels.

5 Outlook for future experiments

In this chapter, first the state-of-the-art body of knowledge regarding breach initiation, formation and growth caused by overflowing/overtopping water is briefly described. Next, challenges for dike management aiming for (more) resilient dikes in order to cope with climate change (to a certain extend) are mentioned. Finally Living Lab Hedwige-Prosperpolder is presented as an opportunity to train skills and gain experience with managed and emergency response measures.

5.1 State-of-the-art

International research (eg. CADAM, IMPACT, FLOODsite, DSIG-project, …) on breach initiation and growth led to the identification and better understanding of different key processes and the development of prosperous (semi) physical models for predictive purposes (a.o. Wahl, 2004; Morris et al., 2009a; Van Hoestenberghe et al, 2010; Peeters et al., 2011).

However, due to the complex interaction between soil, water and structure, model accuracy in predicting the flood hydrograph following breach formation is still low. Therefore prediction of breach formation remains a critical stage of a flood risk assessment that can significantly affect the overall results. As a consequence industry practices for breach prediction vary significantly from effectively guesswork through to detailed numerical modelling (Morris et al., 2009a).

Although the relevance to practice from recent research is significant, gaps in knowledge remain. Large scale laboratory and field experiments should be performed to better understand the complex physical processes of embankment breaching (Wu, 2011) as well as for detailed model development and validation (Morris et al., 2009a).

In recent years, large scale laboratory (e.g. Zhao, 2016) and field experiments (e.g. Peeters et al., 2012b & 2014; Ponsioen & van Damme, 2016; van Damme et al., 2016) were set-up to provide timeseries for breach initiation and growth in depth and width following overflow and wave overtopping.

5.1.1 Failure of vegetation cover

A vegetation cover consists of a substrate (soil), a sod (turf zone) and a sward (grass blades with herbaceous crops). A cohesive soil is less prone to erosion. Root presence results in a higher (so-called: apparent) cohesion. Grass blades and other crops, in turn, shields the top soil from direct impact and possibly reduces flow velocities (Figure 16). As a consequence, all three elements enhance the erosion resistance against surface erosion, shallow slip failure as well as headcut formation.

Figure 16– Shielding of top soil by roof tile aligning vegetation

By increasing the (erosion) resistance of the vegetation cover, breach initiation can be prevented or retarded, reducing the probability and even preventing the possibility of breach formation. As a consequence, flood damages are like to reduce. In addition, step-by-step increasing erosion resistances through enhanced management can be seen as a *no regret/building with nature* measure under unpredictable changing climatic conditions.

Until now, laboratory and field experiments have failed in assessing the individual contributions of these elements. However, within the framework of FloodProof Holland, TUDelft will run overflow experiments on a clayey layer, initially without and subsequently with a (grown) vegetation cover. In addition, Living Lab Hedwige-Prosperpolder (LL HPP) will evaluate the possibilities of organising wave overtopping, overflow and/or infiltration experiments on a standard and mown vegetation cover, after having removed the turf zone as well as after 2 years of improved maintenance.

5.1.2 Erosion of landward slope (after failure of vegetation cover)

Provided a dike with a sandy core, steepening of the landward slope or formation of an overall head cut followed by upstream migration will occur rapidly, rule of thumb at a speed of 1 m/s (Figure 17). Therefore, the available time interval (prior to breach widening) depends strongly on the dike core material and its footprint and as a consequence on choices within dike design.

Figure 17– Upstream head cut migration

5.1.3 Breach growt in depth (when head cut reaches river side)

Until now, the flow through the breach is relatively constrained, somehow *in control*. Ones the breach start growing in depth, the flow discharge through the breach can start to increase more rapidly resulting in uncontrolled breach widening and accompanying flows.

It is expected that the presence of a (cohesive) cover layer and revetment at the river side will hinder the transition towards uncontrolled breach growth (Figure 18). In addition, absence or presence of a foreland will likely affect the breach growth in depth as well. Here, choices within dike design come into place. Enhancing the presence of (high) forelands can be seen as a *no regret/building with nature* measure.

Figure 18– Presence of stone debris within the dike at the river side prevented breach growth in width

Within LL HPP a series of experiments are foreseen to evaluate the impact of presence/absence of a foreland on breach growth in depth.

5.1.4 Breach growth in width

Finally, breach growth in width will occur resulting in an even more rapid increase in breach flow. Ones the water levels of the flooded area start to keep up with those in the river, flow velocities will start to decrease. Rapid breach growth will tend to cease.

The process of steepening/undermining of side walls inducing slipping and/or block failure and hence, breach growth in width, is again influenced by the presence of an additional protection at the river side, e.g. riprap or foreland, as well as land side, e.g. vegetation cover. Again dike design and enhanced maintenance (as a management measure) can play their role.

Within LL HPP a series of experiments are foreseen to evaluate the impact of presence/absence of a foreland on breach growth in width.

5.2 Challenges

Dikes are often composite structures rather than uniform structures. In order to evaluate the possibility of the development of a breach, it is necessary to know the dike structure, i.e. core material, cover layer, revetment, … and possible failure mechanisms and to assess of the actual strength of the dike and/or its individual components. Having trained dike managers and inspectors as well as clear (and easy) assessing methods is one the challenges. Methods that allow dividing dike vegetations into 5 (strength!) categories (Vannoppen et al., 2016; Vandevoorde et al., in prep.) and lookup tables for macro stability, internal and external erosion (Peeters et al., 2008) are very useful and should be further developed for specific situations, e.g. presence/absence of a ditch, foreland, paved towing path, …

Allowing overflow and wave overtopping in time introduces an additional failure mechanism to account for when designing (accounting for varying actual strength) and maintaining (aiming for increased actual strength) dikes. Incorporating such strategic choices within dike management will need improved maintenance strategies as well as experience with managed response (standard procedure)/emergency response (just in case) measures.

Finally, whether parallel river flows have an (adverse) effect on breach development is still unknown and therefore is currently not accounted for.

5.3 Opportunities

As mentioned before, Living Lab Hedwige-Prosperpolder will allow to gain (some) insight on the impact of certain features, e.g. maintenance strategy, presence foreland, quality cover layer, …, on the actual strength of a dike withstanding external erosion (surface and headcut erosion, superficial sliding, breach growth in depth and width,…) on the landward slope and crest.

In addition, these in situ experiments offer possibilities to demonstrate failure mechanisms as well as damage images/scenarios to dike managers (professional) and dike patrollers (volunteer). Moreover, managed/emergency response measures can be tested (effectivity?) and trained (efficiency?) under *real life* storm conditions.

Through a close link with educational institutes and their students it will be possible to validate the representability of methods/tools/measures for site characterisation, dike assessment and damage prevention/control.

Among many other, first steps towards validating existing Load-strength-duration curves as well as breach growth model application can be found in Peeters et al. (2012a), Peeters et al. (2016) and Pleijter et al. (2018). Much more work to do…

6 Conclusions

Many authors stress the need for large scale quality data regarding earthen embankments that have developed historically in stages. Within the frame work of the realization of the Sigmaplan for the river Scheldt in Flanders (Belgium), a series of in situ dike breach experiments caused by overflow are executed. In order to maximise outcomes of these full-scale field experiments, Flanders Hydraulics Research (FHR) has joined forces national and international expertise who showed their interests to assist in the preparation of the testing program and/or to participate during the in situ breach test.

Present knowledge regarding breach dimensions over time allow the development of (solid) evacuation strategies. However, optimisation of dike design, maintenance strategies and breach growth retarding measures require sound understanding of the complex physical mechanisms of embankment breaching. The breach tests along the Scheldt will serve to gain insight in the different breach processes and (hopefully) allow detailed model development and validation as well.

In this report, first, the breach experiments at Wijmeers are discussed. Time series of the breach are explained and included. It is hoped for that the data (together with the time series of the Lillo breach experiment) will be further used to develop and validate models by universities.

Next, state-of-the-art knowledge regarding breach development, how to retard and/or prevent, are briefly summarized. An outlook is provided for further expanding the dike breaching body of knowledge. Living Lab Hedwige-Prosperpolder is believed to offer opportunities for filling gaps of knowledge regarding strength of vegetation cover, breach formation and growth, and will allow to train skills and gain experience with state-of-the-art managed and emergency response measures.

Off course, a major drawback of in situ tests on real-dikes will be the lack of repeatability. Therefore, questions can be asked about the representability of the outcomes of the experiments. “Yet is it far better to light the candle than to curse the darkness” (quote by William L. Watkinson, 1907). Furthermore, by lighting a candle not only on dike assessment, but also concerning site characterisation, inspection and response measures, eventually, the world becomes a brighter place.

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