Interreg
2 Seas Mers Zeeën
Polder2C's
European Regional Development Fund

Overflow tests on Belgian levees

Foto: Vilda-Yves Adams

Adaptation to climate change

Continuous Overflow tests on Belgian levees

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INTERREG Polder2C's project

The INTERREG Polder2C's is an international research project within the framework of the updated Sigmaplan for the river Schelde. The Hedwige-Prosperpolder will be transformed into tidal nature. Depoldering of Hedwige-Prosperpolder offers a unique testing ground, the Living Lab Hedwige-Prosperpolder, for flood defence and emergency response experts. In this environment current and innovative techniques, processes, methods and products can be tested for practical validation. Thirteen project partners, led by the Dutch Foundation of Applied Water Research (STOWA) and the Flemish Department of Mobility and Public Works (DMOW, Flanders Hydraulics Research), are working together. Together, they aim to improve the 2 Seas regions' capacity to adapt to the challenges caused by climate change.

Flood Defence

The rising sea level is a serious threat to the countries in 2 Seas region. How strong are our current flood defences? What is the impact of environmental elements such as the weather, the presence of vegetation or man-made objects on our flo-1od defences? To answer these questions numerous destructive field tests are carried out in the Living Lab to validate flood defence practices. The project entails in situ testing, guidance on levee maintenance and validation of flood defence infrastructure.

Emergency Response

We aim to improve emergency response by developing the right tools for inspection of water defences, risk evaluation and solutions for flooding. If our water defences do not operate as designed, we must take the right measures to prevent flooding of valuable areas. The Hedwige-Prosperpolder Living Lab offers unique possibilities to exercise emergency management in the event of calamities under controlled but realistic circumstances. Activities that are part of the programme are levee surveillance and monitoring, emergency response exercises, breach initiation and the large European exercise.

Knowledge Infrastructure

We aim to develop a knowledge infrastructure through which existing and new to be developed knowledge will become available and accessible. A necessary success factor for any initiative to improve knowledge is to have its outcomes integrated in practices of a wider community. Knowledge Infrastructure focuses therefore on the consolidation of knowledge acquired in the Living Lab with a variety of activities. Accessibility of data in a user-friendly manner, educational activities in the field and incorporation of knowledge in educational curricula are considered key elements.

Field Station

How can we make sure that both experts in the field and the local public benefit from our project and the learnings about climate change, flood resilience, emergency response and the unique environment of the Hedwige-Prosperpolder? An important and unique way of reaching this goal is realising a Field Station at the project site. It will be used during and after the project for educational purposes, research and as a special meeting place for exclusive occasions.

1 Introduction

Continuous overflow tests on levees are designed and executed to test the strength of levees and levee covers under the load of a continuously overflowing discharge of water. For this purpose, Flanders Hydraulics has designed and built an Overflow Generator (Vercruysse et al., 2022) within the framework of the Interreg Polder2C's project. This device allows to generate a controlled and homogenous discharge of water flowing over the levee crest and slopes.

Within the Polder2C's project, 27 overflow tests on Belgian and Dutch levee stretches have been executed in 3 episodes from 30/10/20 to 28/11/20, 17/02/21 to 31/03/21 and 16/11/21 to 20/12/21. Different test goals have been addressed, to understand the normal performance of a levee cover, and the influence of different anomalies and/or deviations from the 'standard' levee:

Name	Category
- B-OF01 Reference (low discharge)	Reference
- B-OF02 Short Grass + Artif. Anom	Alternative vegetation + Slope anomaly
- B-OF03 Mid High Discharge	High Discharge
- B-OF04 Tree	Tree
- B-OF05 Cliff	Slope anomaly
- B-OF05B/C Damage repair	Damage repair
- B-OF06 Clay Erosion	Clay Erosion
- B-OF07A/B Levee Challenge	Damage repair
- B-OF08 Mid Low Discharge	Reference
- B-OF09 Mid High Discharge	High Discharge
- B-OF10 High Discharge	High Discharge
- B-OF11 Tree bis	Tree
- N-OF01 Reference	Reference
- N-OF02 Clay Erosion	Clay Erosion
- N-OF03 Reference	Reference
- N-OF04 Reference	Reference
- N-OF05 Burrow	Burrow
- N-OF05B Damage repair with clay?	Damage repair
- N-OF05C Damage repair with RTM	RTM (Reinforced Turf Mat) type I
- N-OF06 RTM	RTM type I
- N-OF07 RTM	RTM type II
- N-OF08 Grass sods	Nature-based solution
- N-OF09 Burrow protection	Burrow protection
- N-OF10 Reed vegetation	Alternative vegetation
- N-OF11 Reed vegetation	Alternative vegetation

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2 Test overview

2.1 Situation

On the Belgian part of the levee at the Prosperpolder, 14 overflow tests have been conducted on 12 sections. The location of these 12 sections is depicted below (Figure 1) and the coordinates of the crest location shown in Table 1. All tests have been conducted on the landward side slope in the direction of the polder. For each of the given locations, more details are given in the subsequent chapters per test.

Figure 1 - Overview image of the overflow tests performed on the Belgian part of the HPP Living Lab. The background image (PDOK aerial photo) is from 2021 (postdating the tests).

Table 1 - Overflow test coordinates of crest position.

Test ID	X (m L72)[1]	Y (m L72)[1]	Lon (°E WGS84)	Lon (°N WGS84)
B-OF01	140 944.80	225 726.50	4.23881	51.34125
B-OF02	140 935.80	225 735.88	4.23859	51.34134
B-OF03	140 929.50	225 742.40	4.23859	51.34140
B-OF04	140 870.10	225 804.40	4.23774	51.34195
B-OF05(B/C)	140 862.90	225 811.90	4.23764	51.34202
B-OF06	140 961.37	225 709.23	4.23905	51.34110
B-OF07a	140 968.50	225 701.82	4.23916	51.34103
B-OF07	140 971.74	225 698.34	4.23920	51.34100
B-OF08	140 978.55	225 691.39	4.23930	51.34094
B-OF09	140 986.70	225 682.80	4.23942	51.34086
B-OF10	140 994.60	225 673.50	4.23953	51.34078
B-OF11	140 900.53	225 773.62	4.23818	51.34168

[1] L72: The Lambert'72 coordinates are related to the Belgian reference system. Projection details are given at https://www.ngi.be/website/de-lambert-kaartprojectie-2/.

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In general, the levee has a crest elevation of ca. 11.2 m TAW (Belgian reference level) and a toe elevation on the polder side of +/- 4 m TAW. The marsh in front of the levee on the river side is higher (5 to 6 m TAW). Note that the marsh elevation is higher than the polder elevation. The crest is typically 10 m wide and has a landward slope of 11/4 or ca. 19°. For the Belgium levee an asphalt service road with a width of 3.5 m is located on the crest. At the far end of the toe, a drainage gully is present. A 3D render illustrates the levee and its surroundings, and an example profile is presented in Figure 3.

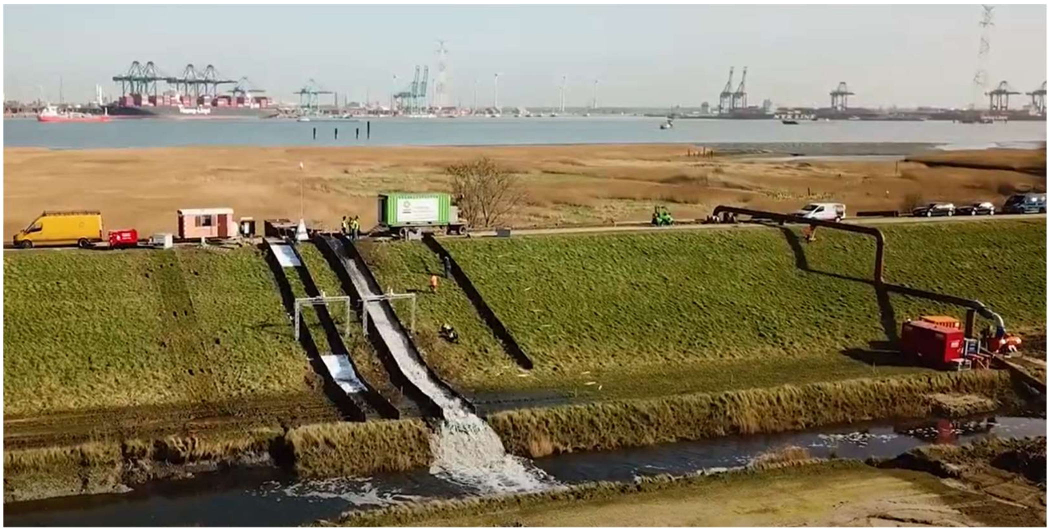

Figure 2 - View on a test setup (B-OF07) consisting of side boardings, camera portals and other equipment.

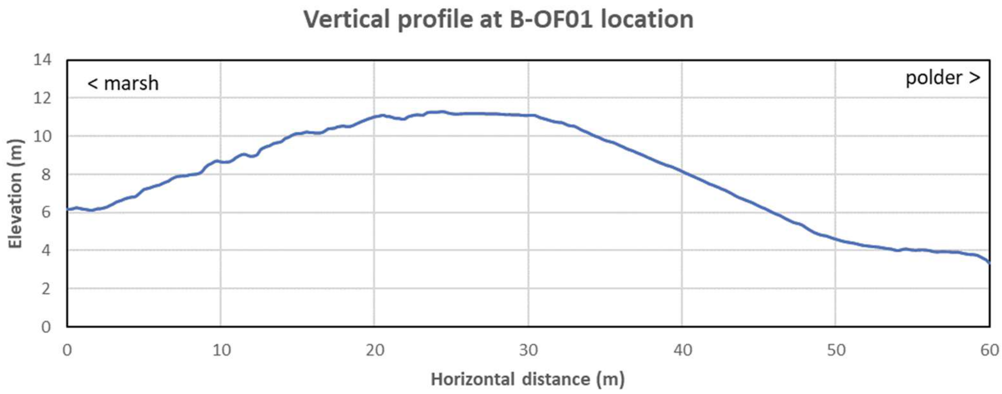

Figure 3 - Elevation profile over the levee at test site B-OF01.

2.2 Test series goals

For each test, a specific goal was formulated before the start of the test.

B-OF01 Reference: The first test was conducted on a 'test section with a good visual condition', i.e. well maintained, and would serve as a reference. The length of the vegetation is about 30 cm.

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B-OF02 Short Vegetation: This test was conducted on a test section from which the vegetation was cut to a length of +/- 10 cm. At the end of the test, an artificial anomaly (step) was implemented.

B-OF03 High Discharge: This test was executed on a test section of only 1 m wide, so that the discharge per m width would be increased in comparison to the reference section B-OF01, given the same pump capacity.

B-OF04 Tree: The effect of the presence of a tree at the levee toe was investigated on this section.

B-OF05 cliff: A cliff due to sheep activity (steepening of the slope) at the lower part of the levee slope was investigated. The experiment resulted in a large damage, which was repaired with an impervious geotextile that was further investigated at a later stage, then subsequently repaired with rock bags and further investigated at a later stage.

B-OF06 Clay Erosion: Students of KULeuven performed an experiment to measure the erosion of the top layer under impacting/flowing water on patches with removed vegetation.

B-OF07 Levee Challenge: Two (sub)sections were artificialy damaged, repaired by student teams of KULeuven and TUDelft within a certain timeframe and subsequently, these repair measures were put to the test.

B-OF08 New reference: An additional reference test was conducted.

B-OF09 High Discharge: A test with high discharges on a levee slope in good visual condition.

B-OF10 Higher Discharge: A repetition of the test with a narrower width of 1 m, to simulate very high discharges on the levee slope.

B-OF11 Tree: A repetition of the test with presence of a tree near the toe of the levee, comparable to B-OF04. In addition to the tree, a small cliff was present along the lower part of the landward side slope.

2.3 Naming convention

The overflow tests have been executed on Belgian and Dutch parts of the levee system in the Hedwige-Prosper polder. The naming of the sections, as already applied above, consist of the code '*X*-OF*YY*(*Z*)' in which *X* is the country initial (B, N(L)) and *YY* is the test section per country. Sometimes, a suffix *Z* is part of the test name, to indicate test repetitions on a given section, typically after a damage repair.

Besides the test names, files and (sub)folders will contain a reference to the nominal discharge applied (if known) by an identifier such as Q360 or Q720. If no nominal discharge is known, only the letter Q may appear in the name.

Tests are executed in periods of typically 1 or 2 hours. This means that overflow is executed during this period and then halted to assess the levee state, take images and/or, perform measurements. Breaks typically take 10 to 20 minutes during a day and multiple hours after a workday (no overflow is carried out at night time). The periods of active overflow are referred to as 'Blocks' and receive a consecutive block number as 'B*nn*' with *nn* being an ascending integer.

During the test runs, images are taken by overhead portals at low frequency. During this time, the timeseries are also recorded. The file name of images and timeseries during the active overflow are therefore also referenced with a suffix _LF to indicate the LF setting of the camera system.

During the breaks, surface state images are taken by the same cameras. These images are referenced by a suffix S.

In order to ensure uniqueness, an additional integer is added to the naming. This integer increments through all of the tests and test periods.

Due to varying operators and practices, and errors during the field acquisition, naming conventions are not applied strictly but should be clear none the less. This leads to the following types of names of timeseries and images.

Test identifiers, e.g. N-OF01 or NL-OF01 or B-OF01 or B-OF1 are self-explanatory now.

The **overflow image folders** are organized per block, with names as e.g.

- B_OF1_Q360_B14_LF_47 : Belgian test OF01, with a nominal discharge of 360 L/s, block B14 during which Low Frequent images are taken, identifier 47.
- NL_OF5_Q180_B9_LF_171: Dutch test OF05, with a nominal discharge of 180 L/s, block B9 during which Low Frequent images are taken, identifier 171.

Within this folder, the **individual overflow images** are stored in Portable Network Graphics format (.png). The file name is structured as follows: the name described above, a camera number (1 to 4, for crest to toe), a machine timestamp and a readable date-timestamp. This yields a file format as:

- B_OF1_Q360_B16_LF_53_1_618893621_2020-11-03-15-25-19-312.png
- NL_OF5_Q180_B1_LF_155_1_326173357_2020-11-23-10-20-50-962.png

The structure of the **timeseries** filenames is somewhat different: a timestamp is located at the front of the filename followed by the name. The raw timeseries are TDMS files (National Instruments Labview format; readable within e.g. Python), the preprocessed data is stored in JSON and a subsampled version is stored in CSV, and obtain file names such as:

- 2020_11_07_09_24_23_B_OF2_Q360_B17_LF_92.tdms(_index)
- 2020_11_27_11_52_45_NL_OF1_Q360_B21_LF_260.json or .csv

The structure of the data inside the JSON files is described in a technical note stored with the actual timeseries.

The structure of the **surface state image folders** is similar to that of the overflow image folders and have names as e.g.

- B_OF1_Q360_B6_S_32 : Belgian test OF01 with a nominal discharge of Q360, surface state image after Block 6, continuous id 32.
- NL_OF1_Q360_B20_S_259: Dutch test OF01 with a nominal discharge of Q360, surface state image after Block 20, continuous id 259.

Inside this folder, the **individual surface state images** are stored in Portable Network Graphics format (.png) and contain besides the folder name a camera number (1 to 4, for crest to toe), a machine timestamp and a readable date-timestamp. Furthermore, the images have

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been acquired at different illumination values (from a value of 100 to 70000)[2]. This is also added to the filename. This yields a file format as:

- 0,100_NL_OF1_Q360_B16_S_251_1_21688914_2020-11-26-15-35-02-537
- 20,000_B_OF2_Q360_B12_S_82_3_75237950_2020-11-06-14-02-46-296.png

2.4 Data repository

The data produced during is disclosed via the Polder2C's Data Wizard (via https://www.polder2cs.eu).

Questions about methodologies and the experimental data presented in this report can be addressed at Flanders Hydraulics Research.

2.5 Test conditions summary

The general test conditions of all tests performed on Belgian levees are summarized in Table 2. The *discharge range* given in Table 2 is the minimum resp. maximum average applied flow during a test block. If no discharge measurement is available, a nominal discharge is shown in brackets. A *block B* refers to a period of typically 1 or 2 hours during which overflow is occurring. In between consecutive blocks, a pause is present to assess damage, make photographs, etc. The total duration refers to the accumulated overflow duration. Note that no details are listed for the damage repair tests on B-OF05B/C. Reference to Hölscher et al. (2021) is made for these tests.

Note that the term **discharge** (Q) is the volumetric rate of flow, i.e. the total amount of water (l or m^3) pumped into the overflow generator per unit of time (s). Therefore, discharge will always be reported in $l.s^{-1}$ or $m^3.s^{-1}$.

The **specific discharge** (q) is the discharge per unit width of the test section. Because most test sections have a width of 2 m, the magnitude of the specific discharge is typically half the magnitude of the discharge. Specific discharge will always be reported in $l.s^{-1}.m^{-1}$.

The design and setup of the overflow generator, monitoring techniques (and their validation) are discussed in Vercruysse et al. (2022).

[2] Note that not all values are available for each photo set, because data has been reduced to eliminate over- and undersaturated images. This was performed by an automated routine that take into account the average luminosity of the image. Because of this, the actual stored photo illumination values are variable because of varying daylight conditions.

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Table 2 - Test conditions

Test	Date	Specific discharge ($l.s^{-1}.m^{-1}$)	# blocks	Total duration
B-OF01	31/10 – 03/11/20	160 – 180	19	20h 55'
B-OF02	05/11 – 07/11/20	160 – 170	20	19h 24'
B-OF03	10/11 – 11/11/20	320-340	10	9h 55'
B-OF04	16/11/20	(180)	3	1h 10'
B-OF05	13/11 – 14/11/20	(180)	19	17h 04'
B-OF06	19/02 – 23/02/21	100 – 200	20	18h 51'
B-OF07	25/02 – 26/02/21	110 – 315	2 x 6	2 x 3h 30'
B-OF08	01/03 – 04/03/21	55 – 340	15	24h 12'
B-OF09	06/03 – 08/03/21	375	12	18h 08'
B-OF10	09/03 – 10/03/21	80 – 550	11	5h 40'
B-OF11	17/02 – 18/02/21	135 – 250	9	13h 03'

2.6 Available data

A description of the test and monitoring setup is discussed in Vercruysse et al. (2022). The table below summarizes the data available per overflow test.

Test	Surface photo[3]	Velocity	Water level	Dis-charge	2D LiDAR	PTV	LSPIV	Other
B-OF01	✓	✓	✓	✓				A, B
B-OF02	✓	✓	✓	✓				
B-OF03		✓	✓	✓				
B-OF04	✓	✓	✓	✓				
B-OF05	✓	✓	✓	✓				
B-OF06	✓	✓	✓	✓	✓		✓	
B-OF07	✓	✓	✓	✓				
B-OF08	✓	✓	✓	✓	✓	✓	✓	
B-OF09	✓	✓	✓	✓	✓			
B-OF10	✓	✓	✓	✓				
B-OF11	✓	✓	✓	✓	✓		✓	

A: Field sketches/drawings of damage made during test breaks.

B: Vegetation cover counts in small patches.

[3] S = images of levee slope surface without water flow; LF = images of the water flow.

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2.7 Test results

In the subsequent chapters, the outcomes obtained and insights gained from each test are shown. In Depreiter et al. (2022), an integrated view is given on the different overflow tests, executed on both Dutch and Belgian levees. Other relevant reports related to the tests and investigations within the Work Package 1 & 2 of the Polder2C's project, are given in the reference list.

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3 B-OF01 Reference

3.1 Goal

The B-OF01 overflow test was the first overflow test executed in the Polder2C's project. Apart from gaining a first experience with the overflow generator developed by Flanders Hydraulics, the main goal was to obtain results that could serve as a reference test section on a Belgian levee. For this purpose, a test section was sought that contained no visual anomalies, defects, burrows etc and could be considered as a 'well-maintained' levee.

3.2 Test setup

The B-OF01 Reference overflow test has been executed on the landward side of a Belgian levee in the Hedwige-ProsperPolder (X=140944.8 m; Y = 225726.5 m). The elevation of the crest is 11.2 m TAW, while the landward toe is situated at +/- 4 m TAW. The slope angle is 19° halfway the levee slope (which equals to a "11/4 slope").

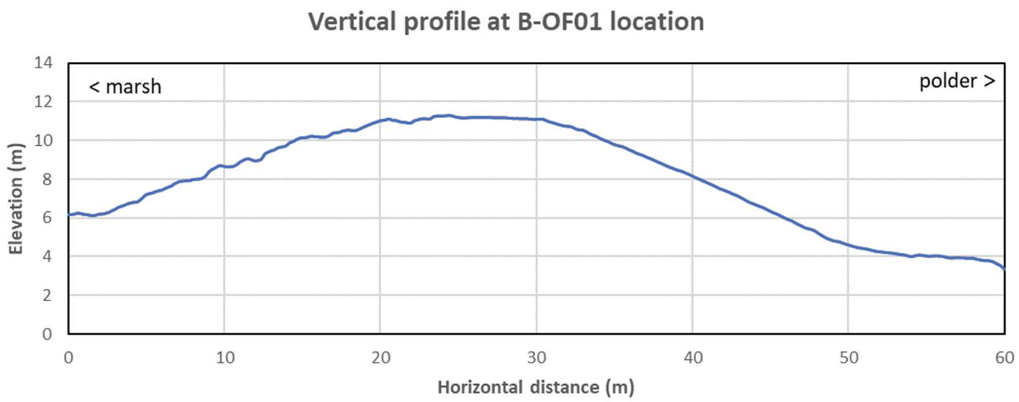

Figure 4 - Elevation profile over the B-OF01 Reference site.

The test section is 2 m wide, fenced by wooden side boarding, and considered to be in a good condition without any visible anomalies. The vegetation state is considered in a state after normal (good) maintenance, with grass lengths of ca. 20 to 40 cm.

Note that the vegetation may have suffered from the extended dry period from April to September '20. Detailed vegetation survey has been performed on Belgian and Dutch levee stretches, reported in Vandevoorde & Lierop (2022). The granulometry analysis (see the integration report in Depreiter et al., 2022) indicates a clayey-silty top layer, which is typically 40 to 50 cm thick. The sand core below the top layer consists of medium sand. An 3.5 m wide asphalt road is present on the levee crest.

The default monitoring setup has been applied and is described in Vercruysse et al. (2022): discharge monitoring, water height monitoring at different locations (by default on the levee crest, upper, middle and lower slope) and velocity monitoring (by default on the upper, middle and lower slope). Camera frames allow to make images of the surface to assess damage evolution, and movies to visualize current patterns. Drawings of the damage have been made, as well as regular photographs by the test operators. The sensor location coordinates are given in Table 3.

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Figure 5 - Sensor locations on B-OF01.

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Table 3 - Sensor locations (approximate) (Lambert '72 coordinates)

SENSOR	X (m)	Y (m)
WH CREST	140944.52	225727.12
WH + VEL UPPER	140940.6	225723.00
WH + VEL MOBILE	140935.45	225717.77
WH + VEL LOWER	140930.16	225712.58
CAMERA UPPER	140939.16	225721.56
CAMERA LOWER	140932.00	225714.61

The pump employed to generate the discharge was a twin parallel Hidrostal F10K-HD submerged pump system supplied by Eekels BV. The theoretical capacity of a single F10K-HD is 970 m³/hour. Taking into account the head difference of >10 m and the conduit length, practical maximum discharge appeared not to surpass +/- 1500 m³/h for the two pumps combined which equals to 416 $l.s^{-1}$. In practice, the maximum discharge appeared to be around 350 $l.s^{-1}$.

Figure 6 - Section B-OF01 with and without overflow ongoing.

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Figure 7 - Overflow generator and piping system test period I (Nov-Dec'20) .

3.3 Execution

The overflow experiment was executed in 'blocks' or periods of typically 1 hour long. In between blocks, a short break was held to monitor damage evolution, repair the section and take photographs. The overflow tests were only conducted at day time.

At the B-OF01 test site, 19 blocks were executed[4] between 31/10/20 and 03/11/20. Short test runs were also conducted on 30/10/20. The total duration of overflow amounted to 20 hours and 55 minutes. The typical discharge applied was 360 $l.s^{-1}$.

Issues with the pump on 30/10 prevented to continue after some test runs. The system became fully operational as of 01/11/20.

3.4 Test results

3.4.1 Description & visual observations

An interrupted start due to technical problems on October 30, 2020 with only 1 hour of testing, was followed by 3 days of testing with a pump discharge of ca. 350 $l.s^{-1}$ or a specific discharge of 175 $l.s^{-1}.m^{-1}$. This corresponds to a theoretical overflow height of 25 cm (river level) and a critical water height of 15 cm (in a broad crested weir situation). The measured water height on the crest was typically 20 cm.

At the start of the runs, some small anomalies are present: 1 noticeable spot without vegetation at 4-5m from the crest, occasional small bare patches, a few mice/moll holes at 5-7 m, 12-13m & 17-18m; caterpillar tracks of a crane about 2 to 3 m away from the toe transition.

At the upstream part of the crest, a hydraulic jump occurred. At the centre of the crest, subcritical flow was accelerated and fairly uniformly spread over the entire width before flow conditions become supercritical. Aeration of the flow started around 4m from the crest, near the measurement location 'UPPER'.

[4] *Due to testing at the start of this first overflow test experiment, the block numbering was restarted during the tests. For 18 blocks, there are recorded data timeseries.*

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During the experiment, bare patches become more prominent, and vegetation roots became increasingly exposed. However, during the course of the test, no critical damage or failure occurred.

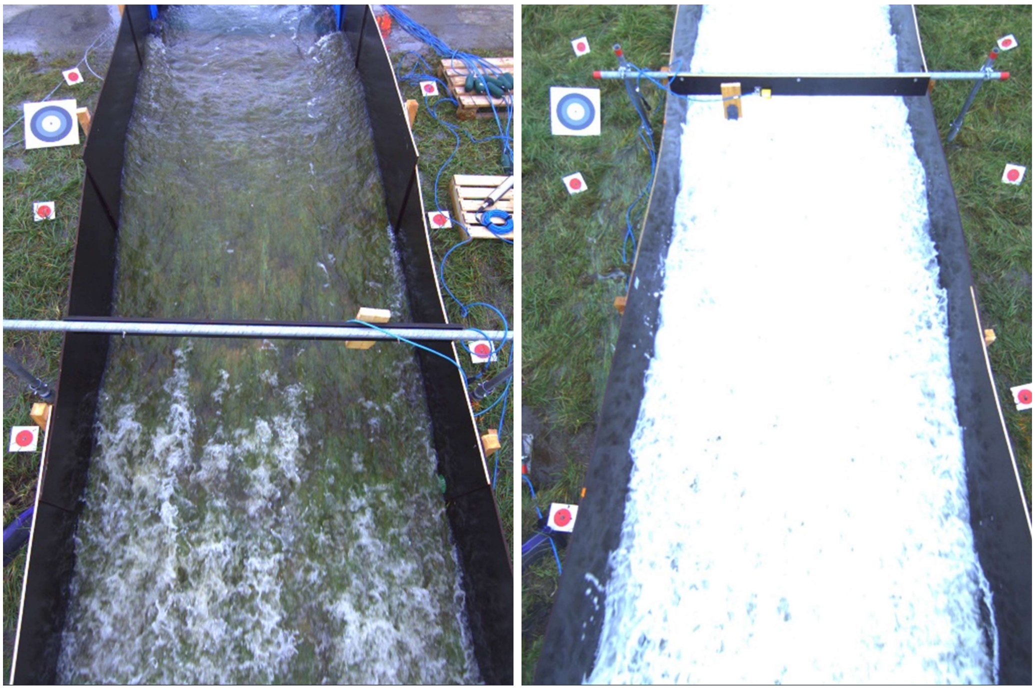

Figure 8 - Left: View of the crest to slope transition and generation of aeration. Right: aerated flow further down the slope.

3.4.2 Video and photo imagery

Images of flow patterns along the slope are available at different parts of the test, and surface state pictures have been made in between blocks of overflow. Table 4 summarizes the identifiers of the image folders (see §2.3 and §2.4 for more information on naming conventions and data retrieval).

Example images at upper part of slope (upper sensor in image), and 3/4 looking down the slope (lower sensor in image) are shown in Figure 8.

The images have been stitched together and are also available on the data repository. Examples are shown in Figure 9.

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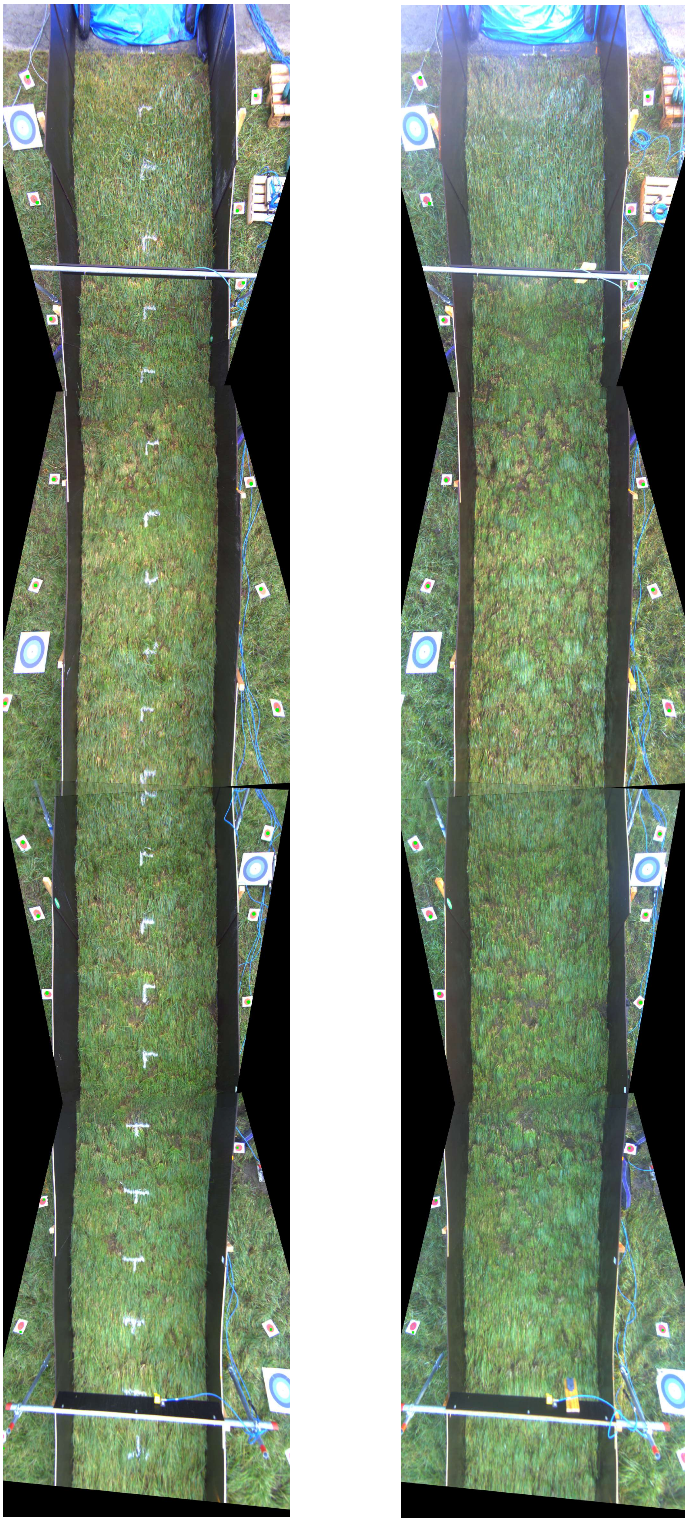

Figure 9 - Stitched surface image of B-OF01 at the start of the experiment (left, block B0) and at the end of the experiment (right, block B17).

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Data files

The complete list of blocks for which imagery is available is shown in Table 4.

Table 4 - Overview of imagery data availble per block in B-OF01. The numers refer to file id's.

Block	Surface images	Flow images
0	12; 13;19	14
1	15; 20; 21; 23	22
2	17; 18; 25	16; 24
3	27	26
4	28	28
5	30	29
6	32	31
7	34;	33
8	36	35
9		37
10	39	40
11	41; 42	43
12		45; 47
13	48	
14	50	49
15	52	51
16	54	53
17	56; 57	55

3.4.3 Timeseries

During the experiment, the monitoring sensor data was acquired as described in Vercruysse et al. (2022). The timeseries plots and statistics per overflow block are given in the Annexes.

The overall statistics for the monitoring timeseries are:

- Total discharge 356.0 l.s-1.(= specific discharge: 178 $l.s^{-1}.m^{-1}$)
- Water height CREST 18.3 cm
- Water height UPPER SLOPE 7.3 cm
- Water height MID SLOPE (MOBILE) 6.1 cm
- Water height LOWER SLOPE 10.3 cm
- Velocity UPPER SLOPE 4.00 m/s
- Velocity MID SLOPE 1.82 m/s
- Velocity LOWER SLOPE 2.50 m/s

The statistics per overflow block (Figure 10) show that the measured discharges and water heights are fairly consistent. For the velocities however, for the velocities are less consistent and should be used or interpreted with care.

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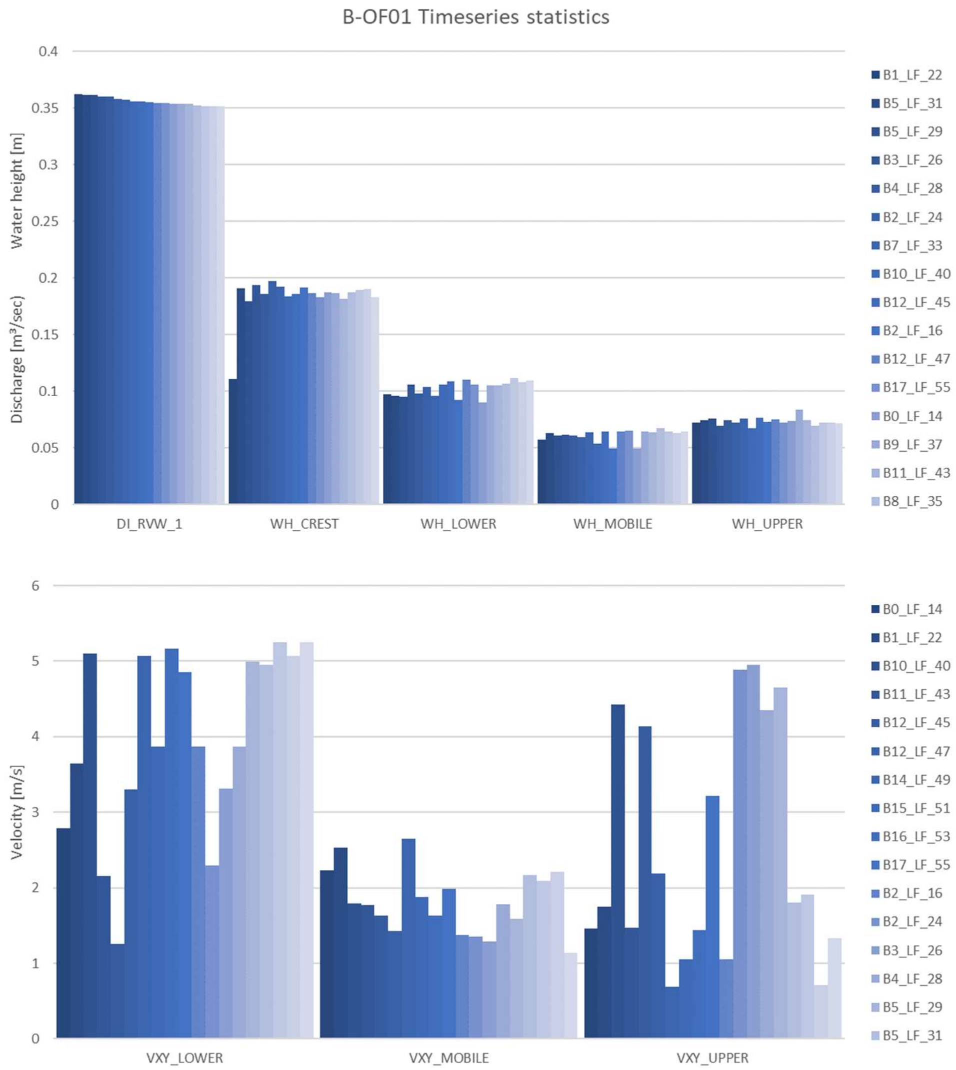

Figure 10 - Timeseries statistics per block, sorted according discharge.

Data files

Table 5 - Overview of raw timeseries data file numbers for block B-01.

Block	Timeseries	Block	Timeseries
0	14 + 19	*11*	*43*
1	20 + 21 + 22	*12*	*45*
2	16 + 24	13	47
3	26	14	49
4	28	15	51
5	29	16	53
6	31	17	55
7	33		
8	35		
9	37		
10	40		

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3.4.4 Discharge variations

In block B2, discharge variations were briefly executed. This allows to set up relations between discharge and water heights. Given the uncertainty on the velocity measurements, it is chosen not to do this for this parameter.

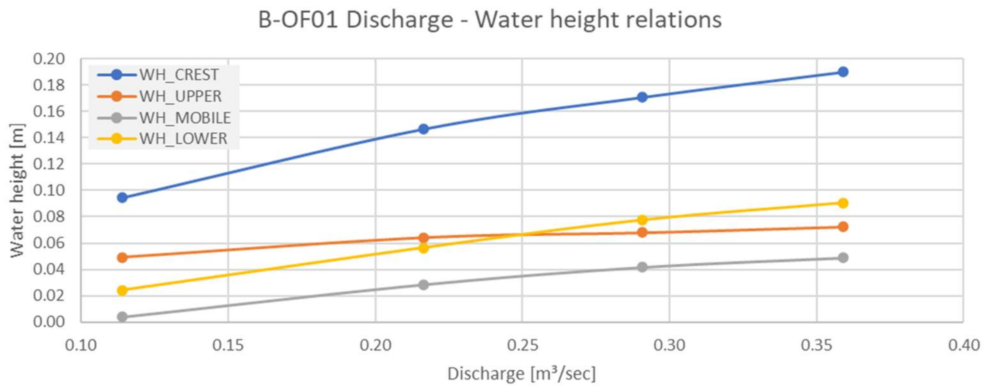

Figure 11 - Discharge - Water height relations for B-OF01 based on block B2.

From this analysis, it appears that WH_UPPER does not respond to the discharge variations as the other sensor positions. It is unclear why this happens. The effect can also be seen on the timeseries plots in the Annex document (Annex A.2 B-OF01: Block 2).

For the crest, this can be fitted to the Francis formula for broad crested weirs $Q = C.L.H^{3/2}$ with C the weir coefficient, L the width (here 2 m) and H the overflow flow height. Based on this, we obtain a value C = 2.08 if Q in [m³/sec] and H in [m].

3.4.5 Field sketches of cover state

During the tests, field sketches were made at different timesteps. In retrospect these sketches appear to be difficult to reference and as a consequence to interpret and have therefore not been processed or analysed further.

3.4.6 Vegetation counts

Vegetation type counts have been made during the B-OF01 test at different times. These data have not been included in this report.

3.5 First insights

Based on the test results described in this chapter, first insights and conclusions can be formulated:

- The overflow generator is able to generate a steady flow pattern over the levee crest with a discharge up to at least 350 $l.s^{-1}$ (over a width of 2 m).
- A levee cover in a good condition, 20 hours of overflow with a specific discharge of 180 $l.s^{-1}.m^{-1}$ leads to some soil erosion and vegetation root exposure, but it does not lead to major or critical damage.

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4 B-OF02 Short vegetation

4.1 Goal

The B-OF02 Short Grass overflow test was performed to identify the impact of shorter grass (and other vegetation) that was mowed to a length of +/- 10 cm, compared to the normal length of 20 to 40 cm. On top of that, on the third day of testing on this section, an artificial anomaly was applied.

Note that the mowing of the vegetation was executed only 2 days before the test execution. It is therefore believed that the root system of the vegetation was not significantly impacted to that of the 'normal' length vegetation (as in B-OF01).

4.2 Setup

The B-OF02 Short Grass overflow test has been executed on the landward side of a Belgian levee in the Hedwige-Prosper Polder (X = 140935.80 m, Y = 225735.88 m, or 4.23869°E, 51.34134°N). The elevation of the crest is 11.2 m TAW while the landward toe is situated at 4 to 4.5 m. The slope angle is 19° halfway the levee slope (which equals to a "11/4 slope"). At the far end of the toe, a gully is present. Note that the marsh elevation is higher than the polder elevation.

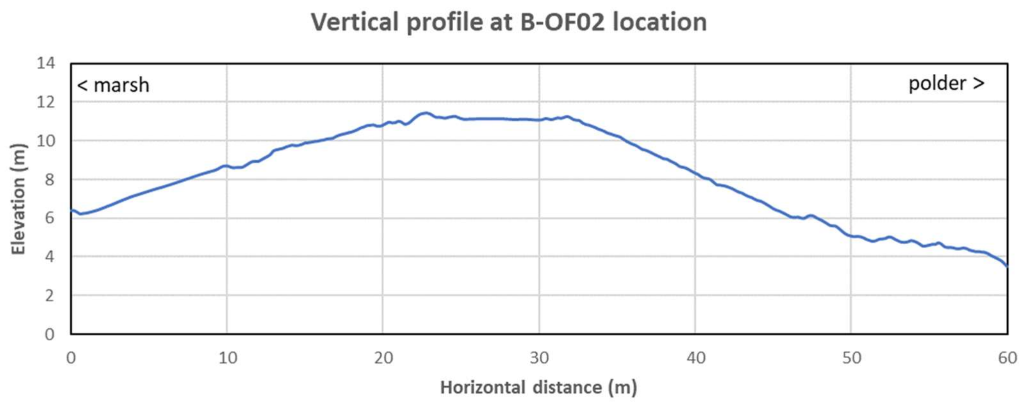

Figure 12 - Vertical profile of the B-OF02 overflow test section.

The test section is 2 m wide, sided by wooden boarding, and considered to be in a good conditions without any visible anomalies. The vegetation state is considered in an altered state compared to a normal maintenance stated (with grass lengths of ca. 20 to 40 cm): in this case the vegetation has been cut by use of a brush cutter to a length of +/- 10 cm. Note that the grass may have suffered from the extended dry period from April to September '20. Detailed vegetation survey has been performed on Belgian and Dutch levee stretches, reported in Vandevoorde & Van Lierop (2022). No other anomalies or obstacles were observed on the section at the onset of the test.

A granulometry analysis indicates a silty top layer, which is typically 40 to 50 cm thick. The sand core below the top layer consists of medium sand. An asphalt road is present on the levee crest.

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On the third test day, an artificial anomaly was applied: a step-shaped incision in the levee slope was made to evaluate the occurrence of erosion of the clay cover. The step was incrementally deepened in between the blocks up to the point the sand core was visible in the inner corner of the step (see the full description below).

The default monitoring setup has been applied and is described in Vercruysse et al. (2022): discharge monitoring, water height monitoring at different locations (levee crest, upper, middle and lower slope) and velocity monitoring (upper, middle and lower slope). Camera frames allow to make images of the surface to assess damage evolution, and movies to visualize current patterns. Drawings of the damage have been made, as well as regular photographs by the test operators.

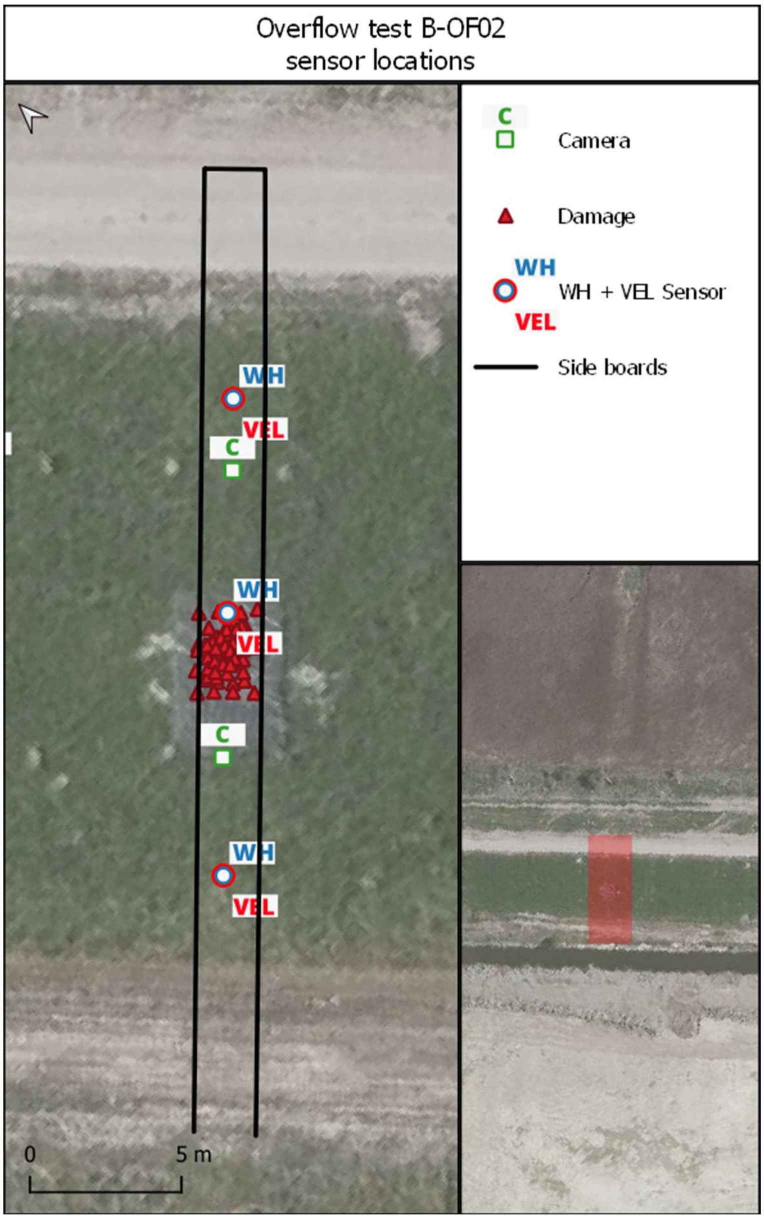

Figure 13 - Location map of overflow test B-OF02.

Table 6 - Sensor locations (Lambert '72 coordinates)

SENSOR	X	Y
WH CREST	Not measured	
WH + VEL UPPER	140931.76	225732.05
WH + VEL MOBILE	140926.61	225727.17
WH + VEL LOWER	140920.37	225721.12
CAMERA UPPER	140930.06	225730.39
CAMERA LOWER	140923.11	225723.90

The pump setup of test period 1 is in place (see §3.2).

4.3 Execution

The overflow experiment was executed in 'blocks' or periods of typically 1 hour long. In between blocks, a short break was held to monitor damage evolution, repair the section and take photographs. The overflow tests were only conducted at day time.

At the B-OF02 test site, 20 blocks were executed between 05/11/20 and 07/11/20. Especially on the last day, some shorter 'blocks' were performed to monitor progression of erosion on artificially created damage (see further). This damage was applied between block 15 and 16, and the damage was increased before block 20. The total duration of overflow amounted to 20 hours and 55 minutes. The typical discharge applied was 360 $l.s^{-1}$.

Figure 14 - Ongoing overflow test on 5/11/2020.

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4.4 Results

4.4.1 Visual observations

November 5th 2020

The start of the overflow test was somewhat delayed because of slight problems with the flow rate monitor on the water pipeline during the morning. It proved to be complicated to get it installed well to yield reliable data of the flow rate. The first overflow session started around 10:00. In total 6 blocks followed that day.

During the overflow runs every hour damage inspection took place via the camera system mounted on the portals and every two hours visual inspection took place of which the results were noted. The test site was continuously monitored to determine unwanted leakage at the boarding, which was countered by placing sandbags when needed.

November 6th 2020

The experiments started around 8 o'clock after some necessary preparations. In the afternoon we managed to complete 14 blocks (cumulative with those on the 5th of November).

Damage proved to increase but not in high speed. Clearly mole burrows transported water from the flow path underneath the boarding to the 'dry' levee cover adjacent (outside test section).

At the end of the day, the options to deliberately increase the damage by excavating a small cliff manually on the 7th of November 2020 were discussed. A cliff (width 135 cm, cliff height 30 cm, step length 90 cm) was to be excavated halfway the slope in the middle of the test section.

November 7th 2020

The day started by excavating the cliff as mentioned above (Figure 15). The clay cover on the test site (loamy/silty/sandy-clay composition) had a well-developed root structure to a depth of at least 30 cm.

Some animal corridors or burrows could clearly be seen in the clay cover. The flora consisted of different species of gras, herbs and other plants (possibly chives, wild garlic, onions-like plants).

It was decided to start with two times 30 minutes run with a pause in between (instead of the previous runs of 60 minutes) and determine the progress of damage. The main reason to do so was that the experiment enabled to really monitor the progress of damage of the overflow by stopping just that process. After two runs it became clear that erosion increased but not that sufficiently that intervals of 30 minutes should be continued. After two blocks of 30 minutes each, 3 more one-hour blocks were conducted again, so in total 5 blocks .

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Figure 15 - Excavated cliff, dimension: 130 cm - 90 cm - 30 cm

After the third run of 1 hour (totaling in 4 hours of overflow after the step was dug), damage was increasing, but not to that extent that failure was deemed imminent. It was therefore decided to increase the depth of the cliff by 10 cm to a depth of 40 cm. On a few small spots the cover layer of sandy-clay was dug away completely and a few cm^2 sandy core became visible. Roots of grass and herbs proved to extend beyond depth of 40 cm. Sand underneath the cover layer was a kind of silty sand. Note that the maximum volume of damage that was allowed was 1 m^3 of eroded soil.

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Figure 16 - Excavated cliff, dimension: 130 cm - 90 cm - 40 cm

It was expected that damage would increase rapidly so runs of 15 minutes were decided upon with continuous presence of the experiment team executing visual inspections continuously. After the first 15 minutes erosion increased significantly. A second run was started planned for 10 minutes, again with prudent and in combination with on spot visual inspection. After 6:30 minutes the color of the water suddenly changed from white to brownish and the pumps were stopped immediately (around 7:00 minutes effectively). Damage increased very significantly in these few minutes and the experiment was stopped.

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Figure 17 - Increasing damage to the top of the excavated cliff. Sand eroded from underneath the top layer causing this layer to crack and be flushed away.

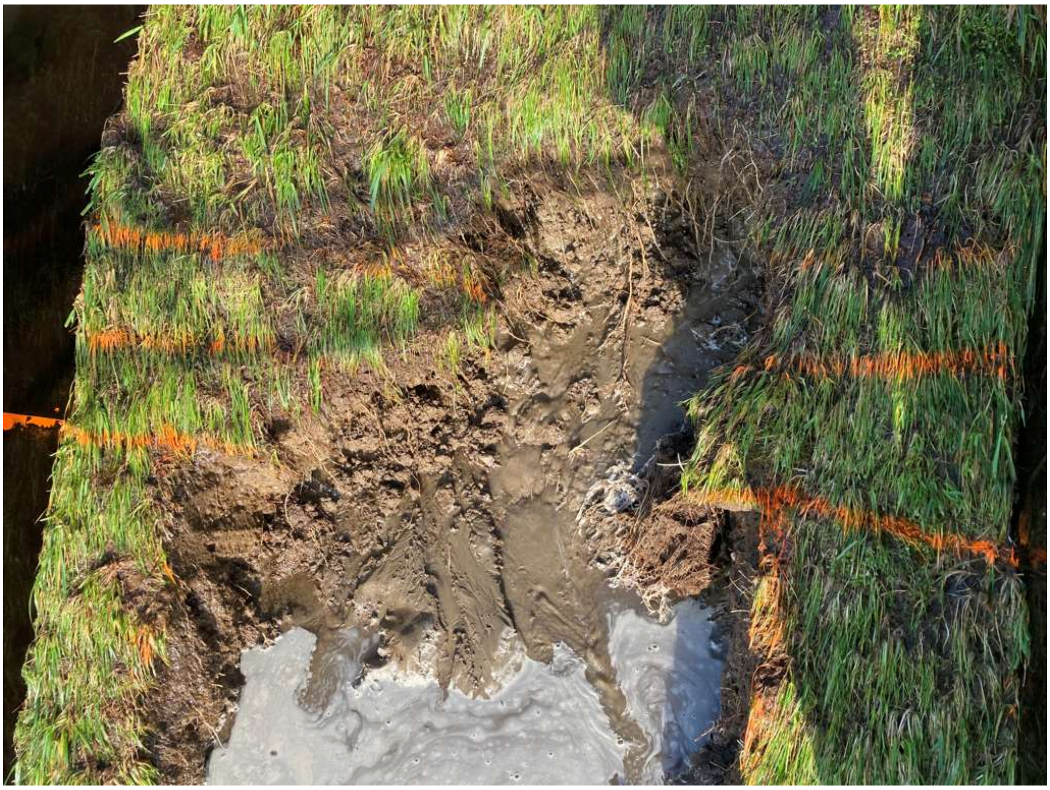

Figure 18 - Close up from the damage on the top side of the excavated cliff.

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4.4.2 Video and photo imagery

Images of flow patterns along the slope are available at different parts of the test, and surface state pictures have been made in between blocks of overflow. Table 7 summarizes the identifiers of the image folders (see §2.3 and §2.4 for more information on naming conventions and data retrieval).

The images have been stitched together and are also available on the data repository. Examples are shown in Figure 19.

Figure 19 - Stitched surface image of B-OF02 at the start of the experiment (left, block B1) and at the end of the experiment (right, block B20). The two middle images are taken at B15 before and after the creation of artificial damage.

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Data files

The complete list of blocks for which imagery is available is shown in Table 7.

Table 7 – Overview of imagery data availble per block in B-OF02. The numers refer to file id's.

Block	Surface images	Flow images
0	58	
1	60	59
2	62	61
3	64	63
4	66	65
5	68	67
6	70	69
7	71	71
8	74	73
9		75
10	76; 78	77
11	80	79
12	82	81
13	84	83
14	86	85
15	87;89	87
16	91:93	90
17	95	92; 94
18	97	96
19	99	98
20	101; 103; 104	100; 102

4.4.3 Monitoring timeseries

During the experiment, the monitoring sensor data was acquired as described in Vercruysse et al. (2022). The timeseries plots and statistics per overflow block are given in the Annexes.

The overall statistics for the monitoring timeseries are:

- Total discharge 333.0 l.s-1 (specific discharge 166.5 l.s-1.m-1)
- Water height CREST 12.2 cm
- Water height UPPER SLOPE 9.1 cm
- Water height MID SLOPE (MOBILE) 7.9 cm
- Water height LOWER SLOPE 16.9 cm

Velocity measurements are only available for a limited number of Blocks.

- Velocity UPPER SLOPE 2.86 m/s
- Velocity MID SLOPE (MOBILE) 3.28 m/s (excl. B1 and B2)
- Velocity LOWER SLOPE 2.69 m/s

The statistics per overflow block (Figure 20) show that the measured discharges and water heights are fairly consistent. The velocities however are less consistent and should be used or interpreted with care. A detailed presentation of each block is presented in Annex B (separate document).

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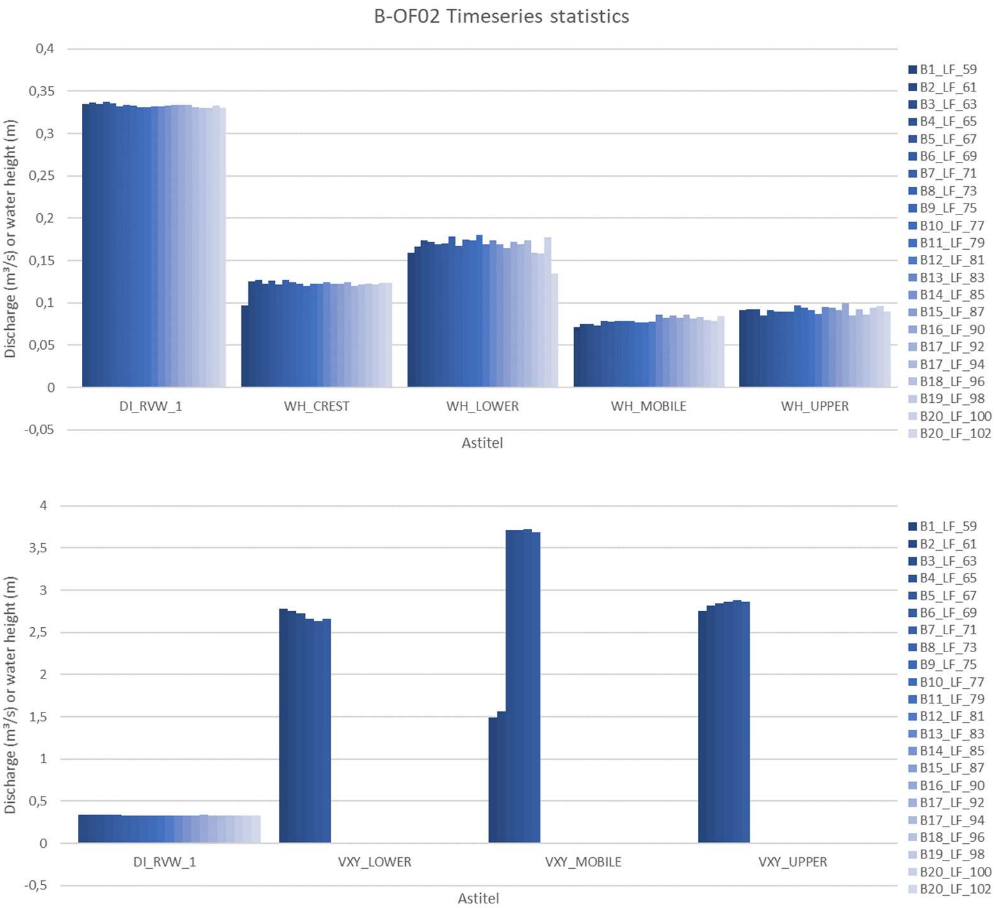

Figure 20 - Timeseries statistics per block, sorted according to block number.

Data files

Table 8 - Overview of raw timeseries data file numbers for block B-02.

Block	Timeseries	Block	Timeseries
1	59	11	79
2	61	12	81
3	63	13	83
4	65	14	85
5	67	15	87
6	69	16	90
7	71	17	92; 94
8	73	18	96
9	75	19	98
10	77	20	100

4.4.4 Other data

Field sketches of damage occurrence have been reported in an Excel file, but have not been further processed or analysed.

4.5 First insights

Based on the test results described this section, first insights and conclusions can be formulated:

- Based on the visual observations, the presence of shorter grass did not lead to fast(er) erosion or failure than the reference case with normal length grass. It must be noted that the vegetation root system corresponded to that of 'long vegetation' because the vegetation was mowed only shortly before the test execution.
- The creation of an artificial (step-shaped) damage did show some evolution but was not expected to yield fast erosion. Increasing the step depth until the sand core was reached, did however resulted in fast (within minutes) erosion and damage evolution.

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5 B-OF03 High discharge

5.1 Goal

The B-OF03 overflow test aimed at performing a high(er)-discharge test. The pump setup yielded a discharge of ~330 $l.s^{-1}$ on the first two tests (B-OF01 and B-OF02). In order to double this to a specific discharge of 330 $l.s^{-1}.m^{-1}$, the section width was reduced to 1 m (compared to 2 m in a standard section). The goal of the test was to evaluate the impact of a higher discharge on the erosion and damage evolution.

5.2 Setup

The B-OF03 High Discharge overflow test has been executed on the landward side of a Belgian levee in the Hedwige-Prosper Polder (X = 140930.2 m, Y=225741.8 m or 4,23859°E, 51.341395°N). The elevation of the crest is 11.26 m TAW, while the landward toe is situated at +/- 4.5 m TAW. The slope angle is 20° halfway the levee slope (which equals to a "11/4 slope"). At the far end of the toe, a gully is present.

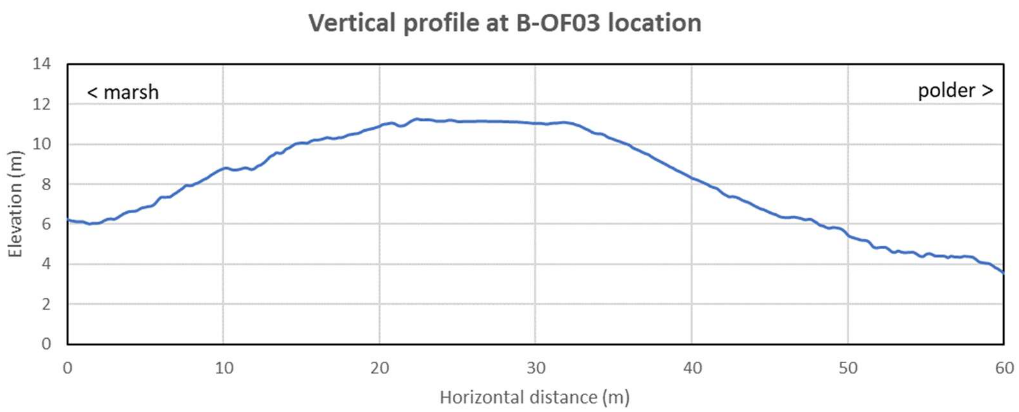

Figure 21 - Elevation profile over the B-OF03 High Discharge site. Data from drone based photogrammetry survey.

The test section comprises of a 1 m wide area fenced by plywood side boarding and considered to be in a good condition without any significant, visible anomalies.

The vegetation state is considered in a state after normal maintenance, with grass lengths of ca. 20 to 40 cm. Note that the grass may have suffered from the extended dry period from April to September '20. Detailed vegetation survey has been performed on Belgian and Dutch levee stretches, reported in Vandevoorde & Van Lierop (2022). The granulometry analysis indicates a silty top layer, which is typically 40 to 50 cm thick. The sand core below the top layer consists of medium sand. An asphalt service road is present on the levee crest.

The monitoring setup has been changed from the general case (described in Vercruysse et al., 2022): discharge monitoring, water height monitoring at different locations (levee crest, upper, middle and lower slope) and velocity monitoring (upper, middle and lower slope). Here, no camera frames were installed to make images of the surface to assess damage evolution, and movies to visualize current patterns.

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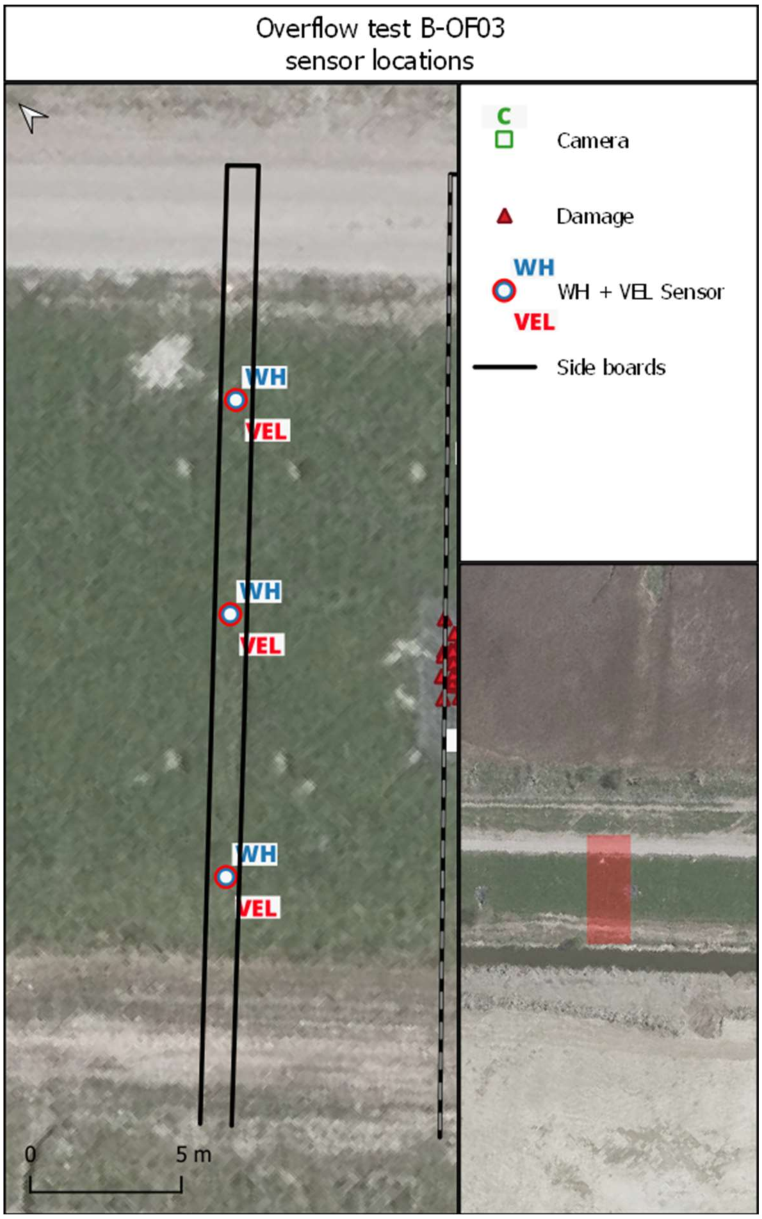

Figure 22 - Sensor locations at B-OF03.

The pump setup the discharge consist of a twin parallel Hidrostal F10K-HD submerged pump system supplied by Eekels BV. The theoretical capacity of a single F10K-HD is 970 m³/hour. Taking into account the head difference of >10 m and the conduit length, practical maximum discharge appeared not to surpass +/- 1500 m³/hour for the two pumps combined. In practice, the maximum discharge appeared to be around 340 $l.s^{-1}.m^{-1}$.

Figure 23 - General view on test section B-OF03. Notice the narrowed section width.

5.3 Execution

The overflow experiment was executed in 'blocks' (or runs) of typically 1 hour long. In between blocks, a short break was held to monitor damage evolution, repair the section and take photographs. The overflow tests were only conducted at day time.

At the B-OF03 test site, 10 blocks were executed on 10/11/20 and 11/11/20. The total duration of overflow amounted to 9 hours and 55 minutes. The typical discharge applied was 337 $l.s^{-1}$.

Note that the logging of file names has been erroneous throughout this test, so care needs to be taken when looking up data.

5.4 Results

5.4.1 Visual observations

On November 10th, the experiment started at 9:00. No camera portals were installed over this section. Due to bad weather and dangerous field conditions (slippery), the first day of testing was ended around 17:00 and continued on November 11th.

During the experiment, it is observed how bare patches appear and erosion occurs and evolves through time. However, no critical damage is present during the entire experiment. Fairly extensive leakage along the boarding was noted, which hampered the execution of the experiment.

5.4.2 Video and photo imagery

No overhead imagery is available for this experiment. The experiment leader made series of photos at blocks B0, B2, B4, B6 and B8. Several short movies were made as a narrative.

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Figure 24 - Comparison of the levee vegetation aspect at B0 (left) and B8 (right) at the upper 3 meter of the levee.

Figure 25 - Comparison of the levee vegetation aspect at B0 (left) and B8 (right) halfway the levee slope (15-17 m).

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5.4.3 Monitoring timeseries

During the experiment, the monitoring sensor data was acquired as described in Vercruysse et al. (2022). The timeseries plots and statistics per overflow block are given in the Annexes.

The time series show several anomalies, so care needs to be taken when interpreting the data.

Discharge data is available for blocks B7, B9 and B10 and indicate a discharge of 337 $l.s^{-1}$.

For the water level data, the lower water level sensor shows spiking behavior and should be considered unreliable. For the other WH sensors, the average levels are:

- Water height CREST 22.0 cm
- Water height UPPER SLOPE 12.4 cm
- Water height MID SLOPE (MOBILE) 16.1 cm

The velocity measurements are generally considered as poorly reliable, especially for the middle and lower slope measurements. Note that the VXY_MOBILE is positioned on the crest starting at block 5 (day 2); this velocity value is shown here.

- Velocity on CREST 1.64 m/s
- Velocity UPPER SLOPE 1.69 m/s

With the velocity and water level sensor placed on the crest, it is possible to calculate an average discharge over the width of 1 m:

Q = A x V = B x H x V = 1 m x 22 cm x 1.64 m/s = 0.361 m^3/s.

This is very close to the observed value of 337 $l.s^{-}1$ and the nominal value of 360 $l.s^{-1}$.

During the experiments, water height measurements were also performed with measuring sticks and averaged 20.7 cm for the runs with discharge measurements. With this value (instead of 22 cm), Q is calculated as Q = 1 m x 20.7 cm x 1.64 m/s = 0.339 m^3/s. This is also very close to the value measured by the discharge meter installed on the feeder conduit, within the 1% range. This observation strengthens the accuracy of the discharge measurement.

Data files

Table 9 - Overview of raw timeseries data file numbers for block B-03.

Block	Timeseries	Block	Timeseries
0 (named: B20)	106	6	112
1	107	7	113
2	108	8	114
3	109	9	115
4	110	10	116
5	111		

A detailed presentation of each block is presented in the Annex document.

5.5 First insights

Based on the test results after almost 10 hours of overflow (which is half the duration of the previous experiments), first insights and conclusions can be formulated:

- The high discharge experiment did not lead to strong(er) erosion or faster damage evolution than observed in other (reference) experiments.
- The data suggests that the discharge measurement on the feeder system is accurate.

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6 B-OF04 Tree

6.1 Goal

The B-OF04 experiment aims at investigating the influence of the presence of a tree near the levee toe. In contrast to a Dutch levee, Belgian levees have typically more shrubbery and trees. The expectation for the experiment is that scour could evolve around the tree trunk, depending on the erosion strength of the soil.

6.2 Setup

The B-OF04 Tree overflow test has been executed on the landward side of a Belgian levee in the Hedwige-Prosper Polder (X=140870.4 m; Y = 225804.7 m or 4.23774°E, 51.34196°N). The elevation of the crest is 11.2 m TAW, while the landward toe is situated at +/- 4 m TAW. The slope angle is 19.5° halfway the levee slope (which equals to a "11/4 slope"). At the far end of the toe, a trench is present.

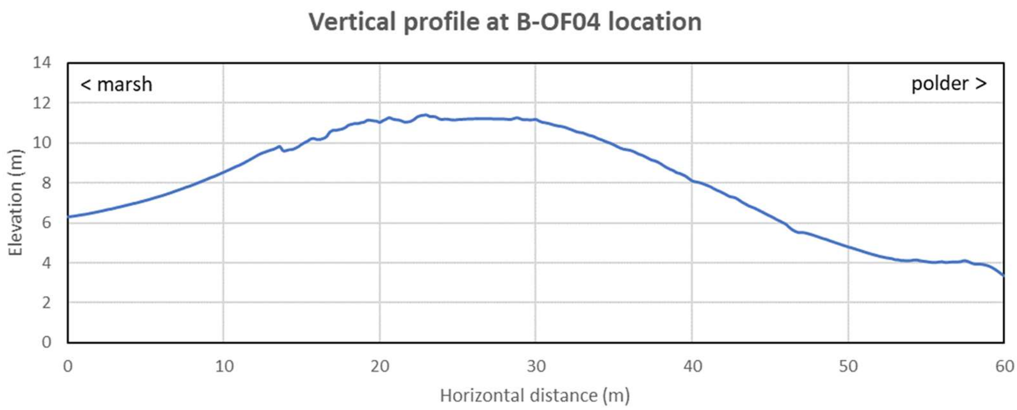

Figure 26 - Topographic profile over the B-OF04 test location.

The test section is 2 m wide, sided by wooden boarding. On the upper part of the slope, there are no visible anomalies. Close to the toe, a small 'cliff'-like structure is present, which is believed to be due to grazing and sleeping sheep here. It is a damaged spot on the lower part of the slope. Near the toe, a small tree is present in the middle of the section.

The vegetation on the larger part of the section is considered in a good state after normal maintenance, with grass lengths of ca. 20 to 40 cm. Note that the grass may have suffered from the extended dry period from April to September '20. Detailed vegetation survey has been performed on Belgian and Dutch levee stretches, reported in Vandevoorde & Lierop (2022). The granulometry analysis (see the integration report in Depreiter et al., 2022) indicates a clayey-silty top layer, which is typically 40 to 50 cm thick. The sand core below the top layer consists of medium sand. An asphalt road is present on the levee crest.

The default monitoring setup has been applied and is described in Vercruysse et al. (2022): discharge monitoring, water height monitoring at different locations (levee crest, upper, middle and lower slope) and velocity monitoring (upper, middle and lower slope). Camera frames allow to make images of the surface to assess damage evolution, and movies to visualize current patterns. For this site, no exact locations of the sensors have been recorded,

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but the approximate positions are shown below. The same pump setup as for B-OF01 was used (see §3.2).

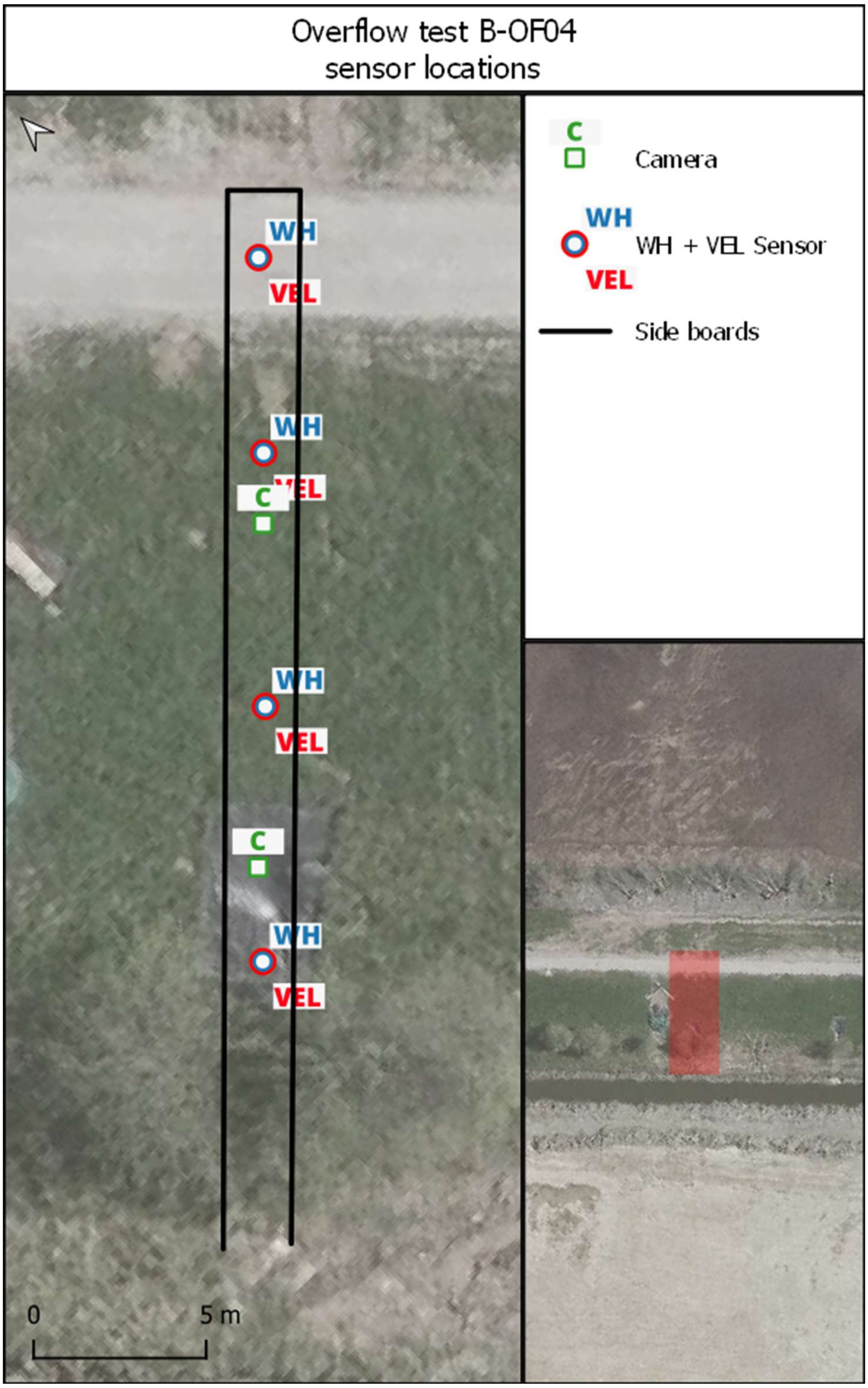

Figure 27 – *Approximate* sensor locations at B-OF04 (no GPS measurement at this test site).

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6.3 Execution

The overflow experiment was executed in 'blocks' that were shorter than regular (regular is 1 hour) due to the observations. In between blocks, a short break was held to monitor damage evolution, repair the section and take photographs.

At the B-OF04 test site, 3 blocks were executed on 16/11/2020. The nominal pump discharge was 360 $l.s^{-1}$.

6.4 Results

6.4.1 Visual observations

A section with a tree situated a few meters outside the levee toe was chosen to be tested to study the influence of the tree presence (under the expectation that some form of scour would occur). Also, a small (minor) cliff (see also the B-OF5 test for a large cliff structure) was present however, it was estimated that it would not affect the experiment significantly. The cliff was also related to the animal activity around the tree area (it is thought that it is the sleeping place of sheep).

Shortly after the start of the experiment, it was observed that 'sand boils' were present outside the test strip. On the left side of the test section (i.e. southwards), water and sand was emerging from small (mice?) holes near the levee toe area.

Figure 28 - Tree at the toe of the levee.

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Figure 29 - Sand emerging from small burrows outside the test section.

Figure 30 - View on the overflow around the tree.

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Besides these sand boils, the normal exposure of grass roots and appearance of bare spots in between sods of grass became visible. This indicates soil erosion, but not to a critical state.

The duration of the experiment was limited. On 16/11/20 at 10:20 am the first testing block started. After 25 minutes, a short break was needed to repair the section and deepen the plywood boardings so that less water would flow underneath outside the test section (at the cliff location). At 10:45, the test resumed to end at 11:43. Damage photos were registered both at 10:45 and at 11:43.

At 11:58, the test resumed for the last time, until 12:05. The total pumping time was only 67 minutes before final damage. The field hypothesis was that sand eroded from under the cover layer (i.e. sand from the levee core is transported, even partially outside the test section) created a mass deficit and destabilized the cover layer (undermining), leading to failure (sudden collapse).

Figure 31 - Initial cover layer collapse.

After the initial collapse, it was observed how the sand core under the cover layer had a fluidized aspect, mobilized and led to a further collapse of the cover layer. After the sand core was sufficiently drained, this collapse process stopped. In this manner, the cliff wall travelled back- and upwards for about 2 meters after the initial collapse.

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Figure 32 - View on the undercut cover layer.

6.4.2 Video and photo imagery

Surface and surface damage pictures have been made after block B1, B2 and B3. No initial state surface images were made. No current pattern images were produced during this test.

Data files

During the field acquisition, the image files of the surface state have been acquired in the "flow image" mode in order to catch damage evolution. As a consequence, the files have been recorded with the incorrect filenames, but can be retrieved under the identifiers 149, 150 and 151 (see §2.3 and 2.4 for more information on the naming convention.)

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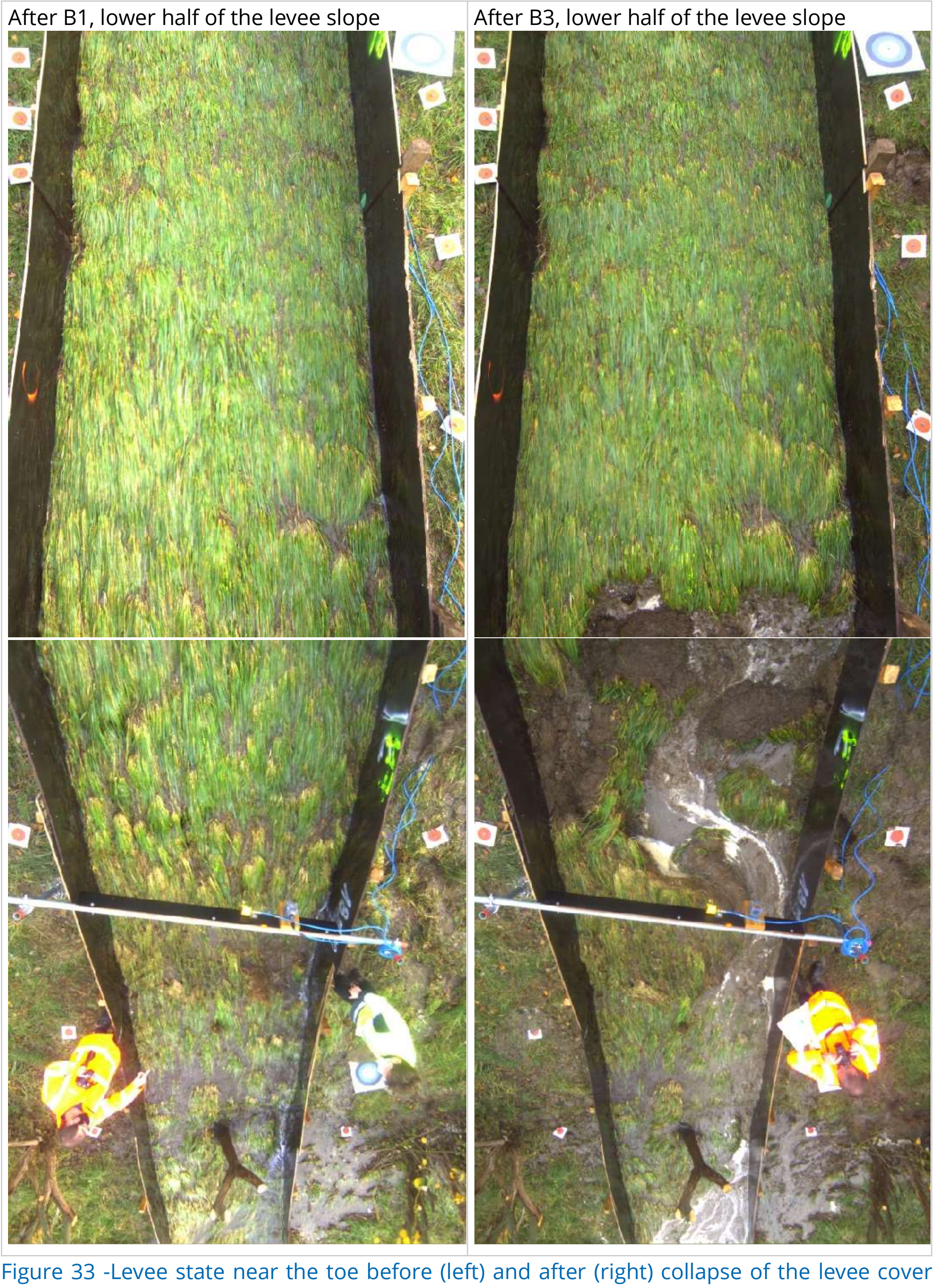

Figure 33 -Levee state near the toe before (left) and after (right) collapse of the levee cover layer. The upper part of the images is lookup upwards towards the crest of the levee, and the lower part is looking towards the toe (with the tree in view).

6.4.3 Monitoring timeseries

Discharge was only measured during the last (short block), indicating a discharge of 327 l.s^{-1}.

Mean water heights were recorded as:

- Water height CREST 16.4 cm
- Water height UPPER slope 5.6 cm
- Water height MIDDLE slope (MOBILE-) 12.5 cm
- Water height LOWER slope 18.1 cm

Mean velocities (note that velocities are considered less reliable) were:

- Velocity UPPER slope 2.26 m/s
- Velocity MIDDLE slope (MOBILE) 4.16 m/s
- Velocity LOWER slope 2.40 m/s

Note that the block numbering is incorrect: B20 is actually the first block; presumably numbering from a previous test was continued.

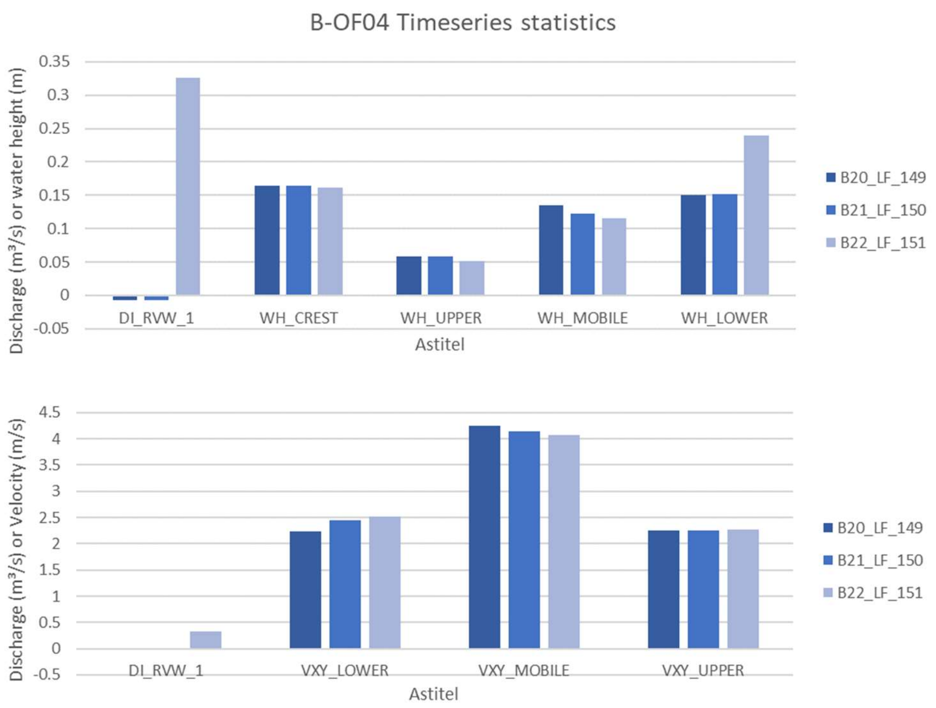

Figure 34 - Timeseries statistics per overflow block.

It is noted that the water height at the lower location in the last block is 8-9 cm higher than in the preceding two blocks. This is not a measurement error, but due to ground subsidence under the sensor (indicating imminent/approaching failure). Due to the impending collapse of the cover layer (see the description and interpretation above), the distance to the sensor had increased already (this was also visually observed).

A detailed presentation of each block is presented in the Annex document.

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6.4.4 Other data

3D laser scans before and after the experiment are available, and yield insight in the magnitude of the resulting damage.

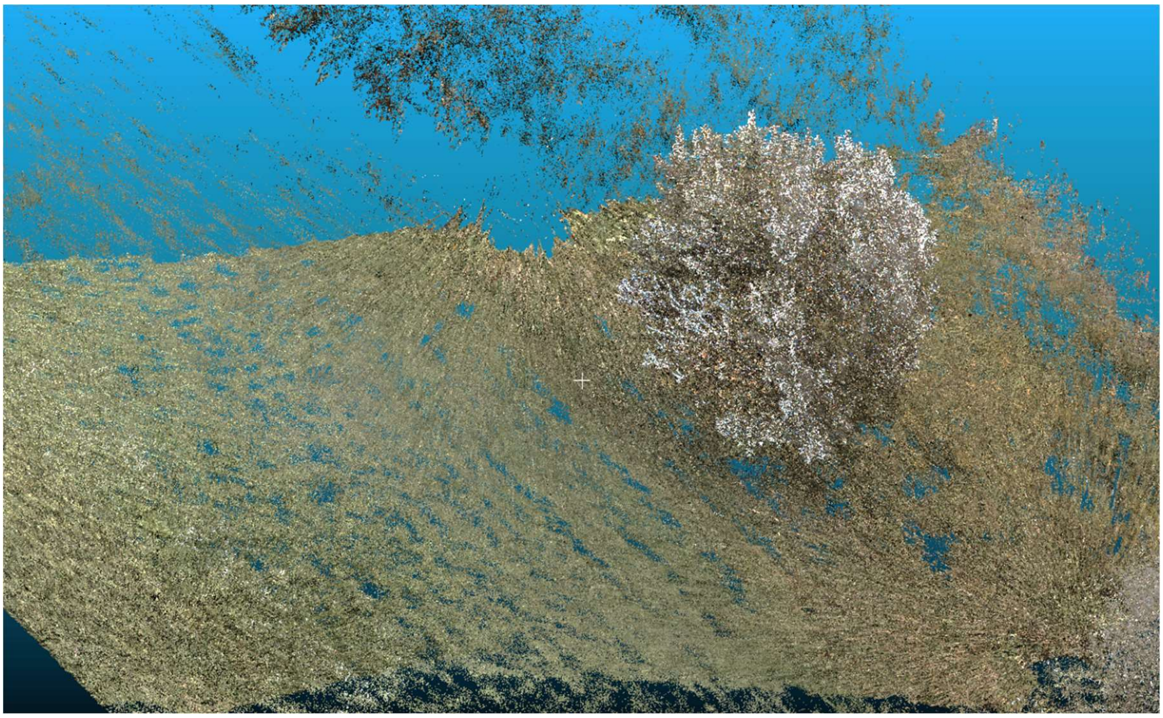

Figure 35 - Screenshot of the B-OF04 site before the experiment, including tree.

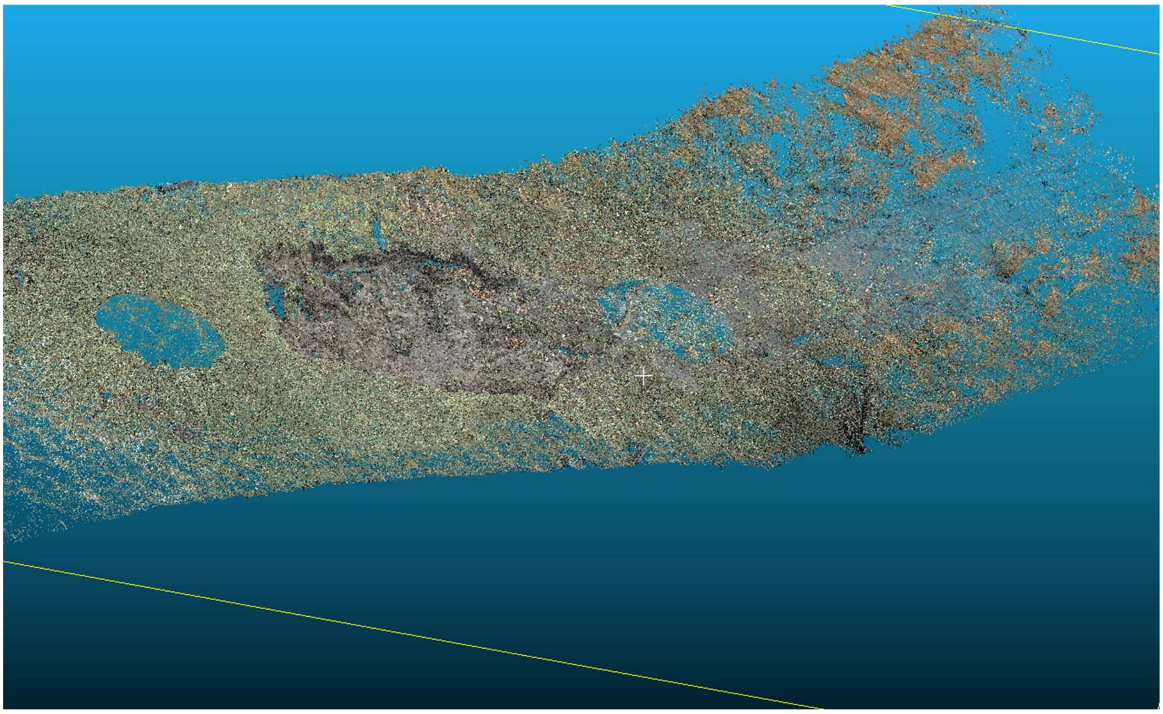

Figure 36 - Screenshot of the 3DLS scan of the damage.

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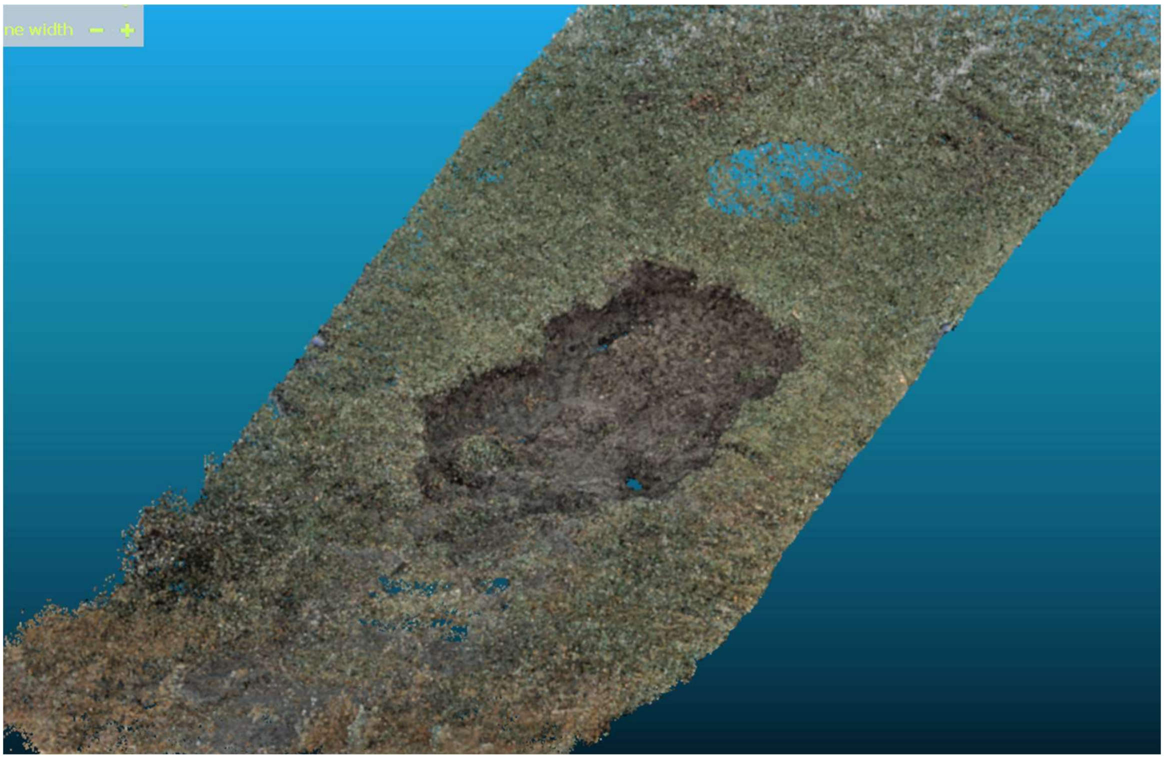

Figure 37 - Screenshot of the 3DLS scan of the damage.

6.5 First insights

Based on the test results described above, first insights and conclusions can be formulated:

- The presence of a tree and surface root system enhances erosion of the soil around the tree. However progress was slow without quickly escalating to any (critical) damage.
- The small cliff on the lower part of the slope a couple meters in front of the tree, created by sheep did not give rise to direct damage.
- The presence of burrows (mice, mole) is believed to have provoked the flow of water under the clay cover, through the inner sand core. This fairly quickly led to outflow of sediment near the toe of the levee (notable adjacent to the test section). The resulting mass deficit lead to ground subsidence and finally a collapse of the top layer into the created void.
- Dewatering of the upwind sediments was observed during which collapse of the sand and tearing of the overlying clay cover occurred, effectively resulting in upward moving head-cut erosion.

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7 B-OF05 Cliff (slope anomaly)

7.1 Goal

In order to test the impact of an cliff structure near the toe of the levee, this location was selected as B-OF05 overflow test. The nature of the cliff is a sudden steepening of the levee slope. The origin of this feature is presumably the presence of animals (sheep) that have a sleeping spot near and under several trees that occur in this area. Due to the animal's activity, cliff formation near the toe has occurred and shaped it into a fairly steep, 1 m high cliff structure. It is thought this feature will destabilize the levee and/or promote instability at the toe area.

7.2 Setup

The B-OF05 Erosion Cliff overflow test has been executed on the landward side of a Belgian levee in the Hedwige-Prosper Polder (X=140862.9 m; Y = 225811.9 m). The elevation of the crest is 11.2 m TAW, while the landward toe is situated at +/- 4 m TAW. The slope angle is 19° halfway the levee slope (which equals to a "11/4 slope"). At the far end of the toe, a trench is present.

The levee slope is characterized by a local, steep cliff of more than 1 meter high near the levee toe (Figure 39). This cliff probably originates from grazing and sleeping of animals (sheep).

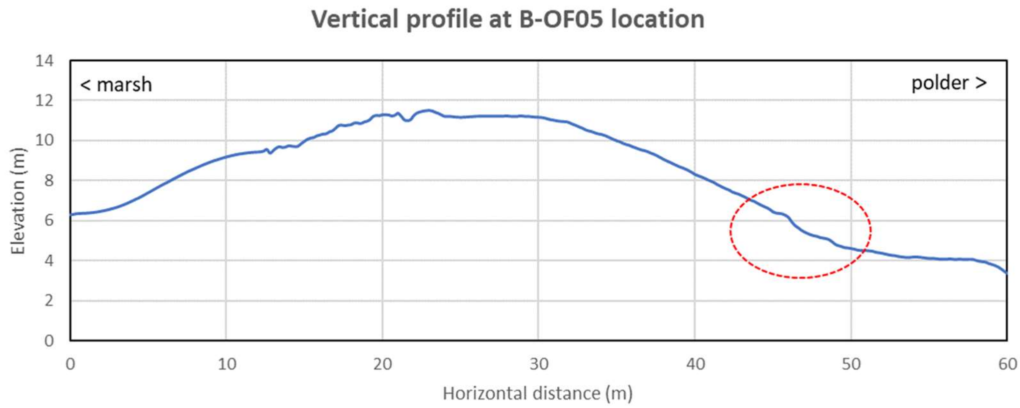

Figure 38 - B-OF05 topographic profile (erosion cliff noted in red circle).

The test section is 2 m wide, sided by plywood boarding, and considered to be in a good condition without any visible anomalies, except from the cliff itself, where the vegetation cover is somewhat interrupted. The vegetation state is considered in a state after normal maintenance, with grass lengths of ca. 20 to 40 cm. Note that the grass may have suffered from the extended dry period from April to September '20. Detailed vegetation survey has been performed on Belgian and Dutch levee stretches, reported in Vandevoorde & Lierop (2022). The granulometry analysis (see the integration report in Depreiter et al., 2022) indicates a silty top layer, which is typically 40 to 50 cm thick. The sand core below the top layer consists of medium sand. An asphalt road is present on the levee crest.

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Figure 39 - Slope damage at the toe transition due to cattle activity in an area with trees.

Figure 40 - Slope damage in the test section.

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The default monitoring setup has been applied and is described in Vercruysse et al. (2022): discharge monitoring, water height monitoring at different locations (levee crest, upper, middle and lower slope) and velocity monitoring (upper, middle and lower slope). Camera frames allow to make images of the surface to assess damage evolution, and movies to visualize current patterns. Drawings of the damage have been made, as well as regular photographs by the test operators. There is no map of sensor positions, due to GPS data loss (hardware error). The lower sensors have been place 4 m upward from the cliff edge; usually this is 4 m upward from the levee toe.

7.3 Execution

The execution of the B-OF05 Sheep Cliff overflow test took place on 13 – 15/11/2020. In total, 17 blocks of overflow activity were held, for a total of 17 hours and 4 minutes.

The discharge that was close to 320 $l.s^{-1}$ corresponding to a specific discharge of 160 $l.s^{-1}.m^{-1}$.

On 15/11 the section failed after sunset. Within a limited time, the damage that had occurred had developed into a large slope failure as described further.

Figure 41 - End state of the B-05 test during cleanup.

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7.4 Results

7.4.1 Visual observations

The test at the cliff was proceeding without any notable observations and events, other than that grass sods were becoming increasingly exposed at the root area, as observed in other tests.

The occurrence of the slope failure has not been observed visually, as the team was preparing to shut down the experiment for the day. The failure occurred after sunset and was detected because one of the sensors on the computer display suddenly acted abnormally.

7.4.2 Video and photo imagery

The video portals that are installed overhead the test section have been used to produce 2 types of pictures: 1) the surface state of the test section in between blocks of overflow action in order to assess and record the vegetation and surface state and damage occurred; 2) images of the flowing water in order to visualize current patterns.

Damage pictures are available at block B1 (initial state) and blocks B10, 11, 12, 13, 14, 15, 16,17, 18 and 19 (the latter 2 depict the final damage state recorded on the morning following the damage). The original and end state are shown in the image below. Note that due to loss of GPS measurement data it was not possible to rectify the images.

7.4.3 Monitoring timeseries

The sensor data of the B-OF05 overflow test is summarized in Figure 43 and Figure 44.

The discharge of the experiment has been kept at a constant value of 320 $l.s^{-1}$ corresponding to a specific discharge of 160 $l.s^{-1}.m^{-1}$ This discharge has yielded a water level at the crest of 9.6 cm, although there is some variation in the data.

Other water height sensors have a more consistent data distribution, with averages:

- Water height CREST 9.6 cm
- Water height UPPER slope 8.9 cm
- Water height MIDDLE slope (MOBILE) 9.9 cm
- Water height LOWER slope 13.4 cm

The measured velocities are internally consistent however considered less reliable in general:

- Velocity UPPER slope 2.49 m/s
- Velocity MOBILE sensor has been replaced during the test:
  - MIDDLE slope B1 → B9: 3.93 m/s
  - CREST B10 →B17 2.24 m/s
- VELOCITY LOWER slope 3.67 m/s

Details about the timeseries are also shown in the Annexes.

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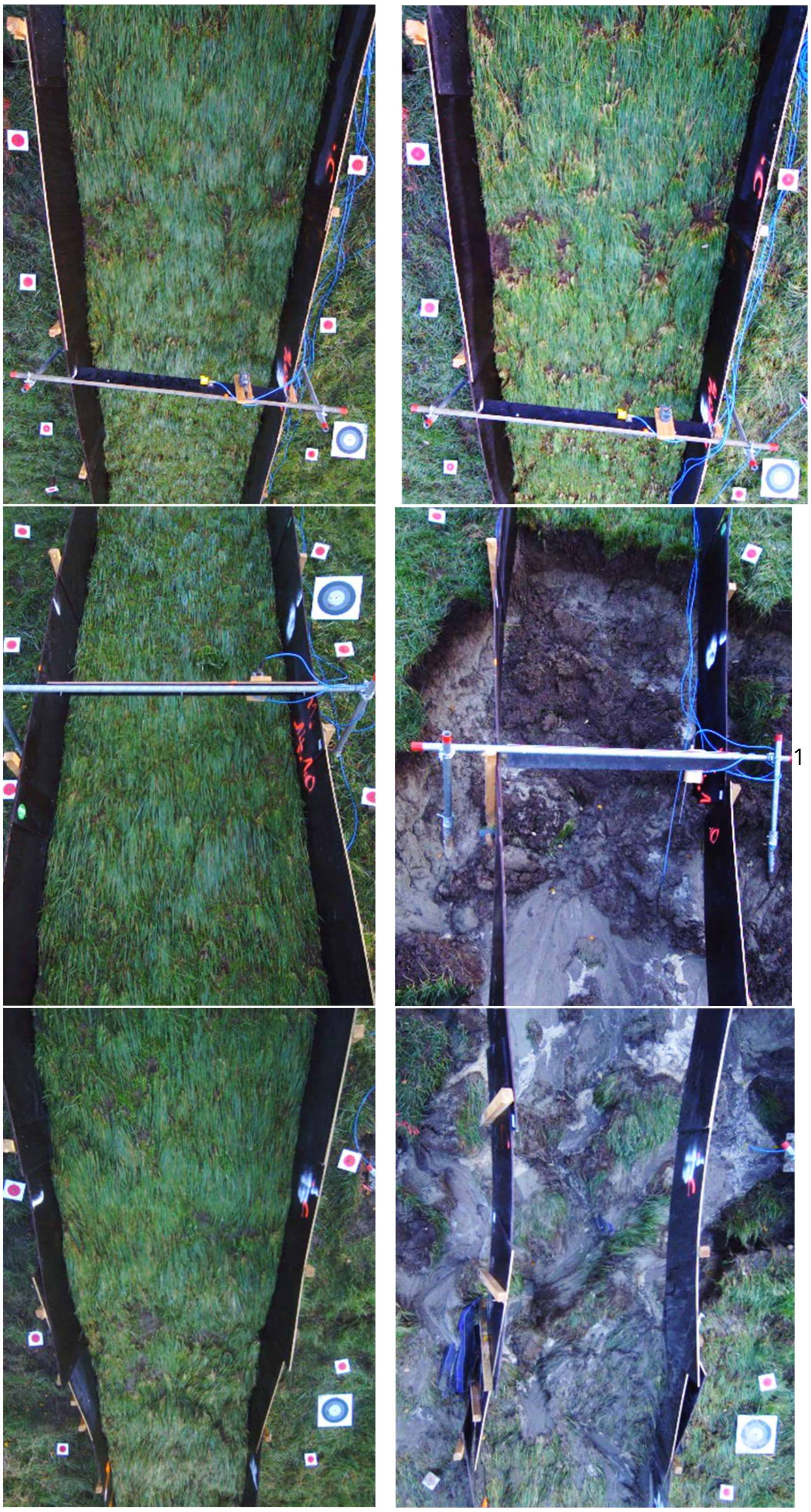

Figure 42 - Image composition of the test section state at the start (left) and the end (right) of the B-OF05 test.

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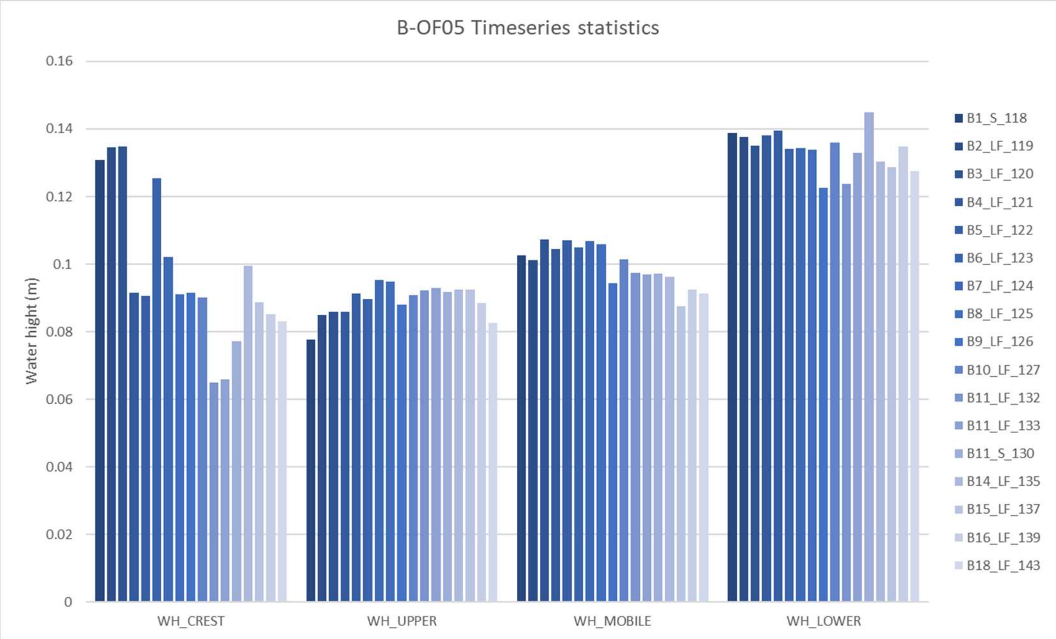

Figure 43 - Water height timeseries statistics per sensor and block.

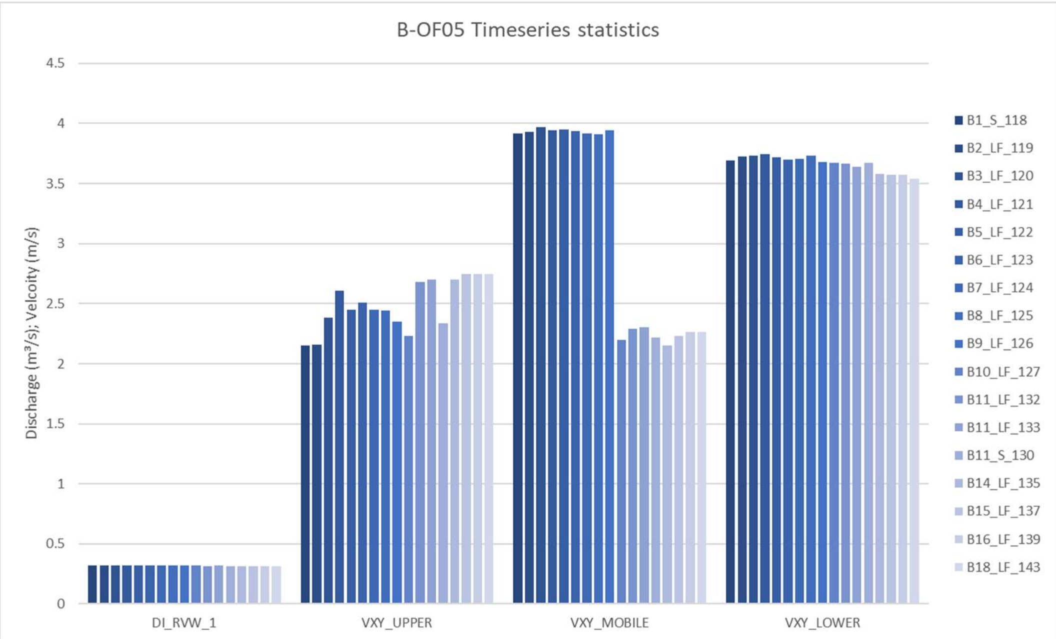

Figure 44 - Discharge and velocity timeseries statistics per sensor and block.

7.4.4 Other data

Based on the 3D-laser scanning data acquired before and after the experiment, it is possible to perform volume calculations of the damage. It appears that the cavity created has a volume of approx. 16.4 m³. A contour map of the height difference, and visualisation of the damage based on the LiDAR data are shown in Figure 45 and Figure 46..

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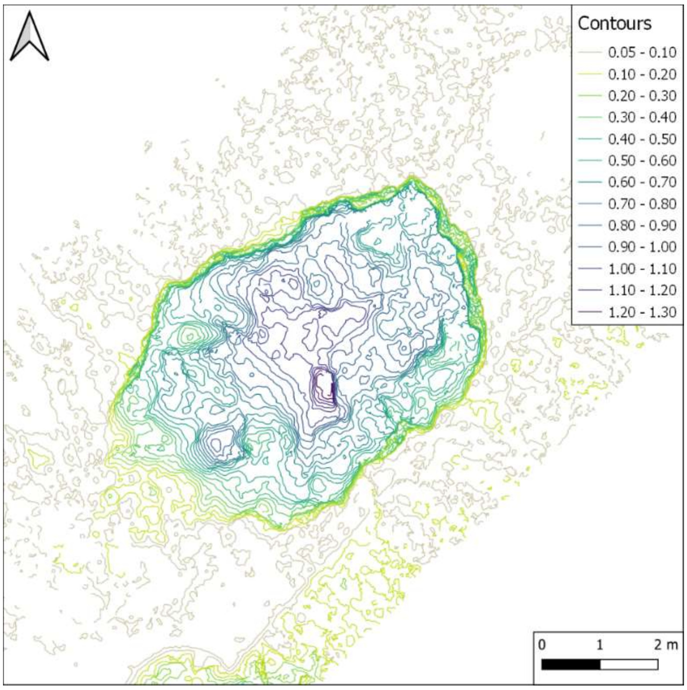

Figure 45 - Contour map of the T0-T1 vertical height difference .

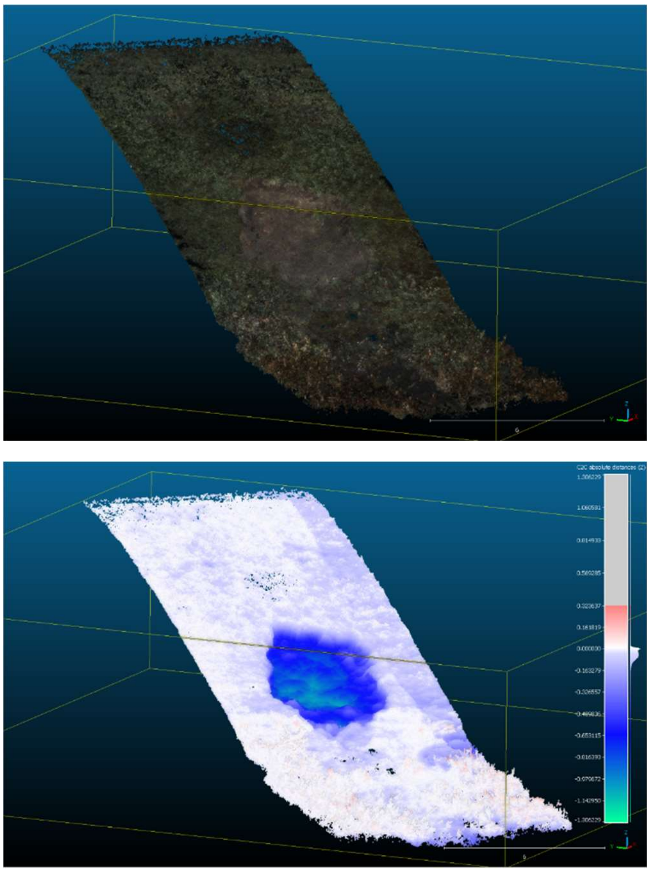

Figure 46 - Top: RGB coloured point cloud. Bottom: Difference between point cloud at initial state (not shown; T0) and the damaged section (T1)

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7.5 First insights

Based on the test results, first insights can be formulated:

- The section B-OF05 has developed into a slope instability after 17.1 hours of overflow. The process responsible for this is, however, not exactly known. It is assumed that gradually surface erosion of the cliff area, resulting in steepening of the slope and a cover layer getting thinner, suddenly gave rise to a connection with the sandy core, giving rise to an abrupt failure.
- Undermining of the cliff by erosion of the sandy core, similar to test section B-OF04, was not witnessed.
- The presence of animals and vegetation in the area may have promoted the presence of other animals (e.g. mole, rabbit, mice) that created small burrows in the area. Other experiments in Polder2C's learned that burrows may be a critical feature in levee cover safety.
- A levee slope may appear stable and in a good shape for an extended period of time. However, during in an overflow event, the evolution from minor to major (decametric) damage may develop within minutes. Saturation of the levee cover sands, which is thought to take several hours to accomplish, may play a role in this fast evolution.

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8 B-OF05B/C – Damage repair with EDPM and rock bags

The damage created during the B-OF05 test, was repaired with an infill of rock bags. Later, this area has been subject to further investigation. The description and discussion of design, emplacement and mechanical performance of this damage repair solution is outside the scope of this report. Overflow was performed and it was found that animal burrows facilitated the flow of water under the cover layer, into the rock filled void.

To better understand the role of burrows in this setting, several activities have been performed and have been separately reported in Hölscher et al. (2021). The main finding for the B-OF05(B) test site was that the entry point of water inflow into the levee was situated near the side of the road. The flowing of the water underground could be heard underneath the rock bags. At a later stage, the flow pathway was further investigated and was identified as a mole burrow which connects the surface to the sand core. Part of the burrow system was grouted and excavated.

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9 B-OF06 Erosion patches

The Erosion patch experiment comprises a test that was designed by KULeuven students A. Van Daele and A. Vandenbussche under supervision of Prof. P. Rauwoens, as part of their master's thesis called: "Erosiebestendigheid van de toplaag van grasdijken – vernieuwde inzichten uit overloopproeven op het binnentalud van de Scheldedijk in de Hedwige- en Prosperpolder" (Erosion resistance of the toplayer of grass levees – novel insights from overflow experiments on the inner slope of the Scheldt levee in the Hedwige- and Prosper polder". The thesis comprises multiple goals and analyses and we refer to their thesis document for a full report.

In the present document, only reporting of the hydraulic properties of the flow can be found.

9.1 Goal

The goal of the B-OF06 test was to execute overflow tests on patches from which the grass was removed (the root system still in place), in order to calibrate and evaluate the "Erosiegevoelige Plekken Model", developed for wave over*topping* tests on vegetated levees (Erosion-sensitive Patches Model; van den Bos, 2006) and compare results with other models.

9.2 Setup

The B-OF10 test section is executed at the landward side of the Belgian levee at coordinates X=140 994.60m; Y=225 673.50m (Lambert '72 coordinates) or 4.23953°E, 51.34078°N (WGS84).

The crest culminates at 11.2 m TAW (Belgian vertical reference), whereas the toe altitude is ca. 4 m TAW. Beyond the toe, a trench is present. The slope angle is 19° halfway the levee slope, which equals to a 11/4 slope.

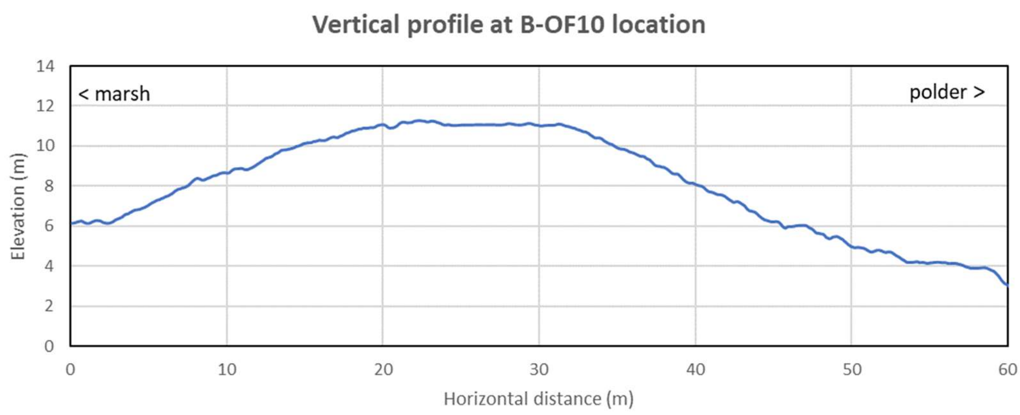

Figure 47 - Vertical profile at the B-OF10 site.

As stated in the goal, the test section width is reduced in width to 1 meter, so that higher specific discharges could be reached.

No anomalies have been reported for the section. Vegetation was in a normal condition, with vegetation lengths of ca 15 to 30 cm.

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The default monitoring setup has been applied and is described in Vercruysse et al. (2022): discharge monitoring, water height monitoring at different locations (levee crest, upper, middle and lower slope) and velocity monitoring (upper, middle and lower slope). Camera frames allow to make images of the surface to assess damage evolution, and movies to visualize current patterns. Drawings of the damage have been made, as well as regular photographs by the test operators.

The B-OF06 experiment was executed during the second episode of tests and thus involves a different (stronger) pump setup than in experiment B-OF01 to B-OF05.

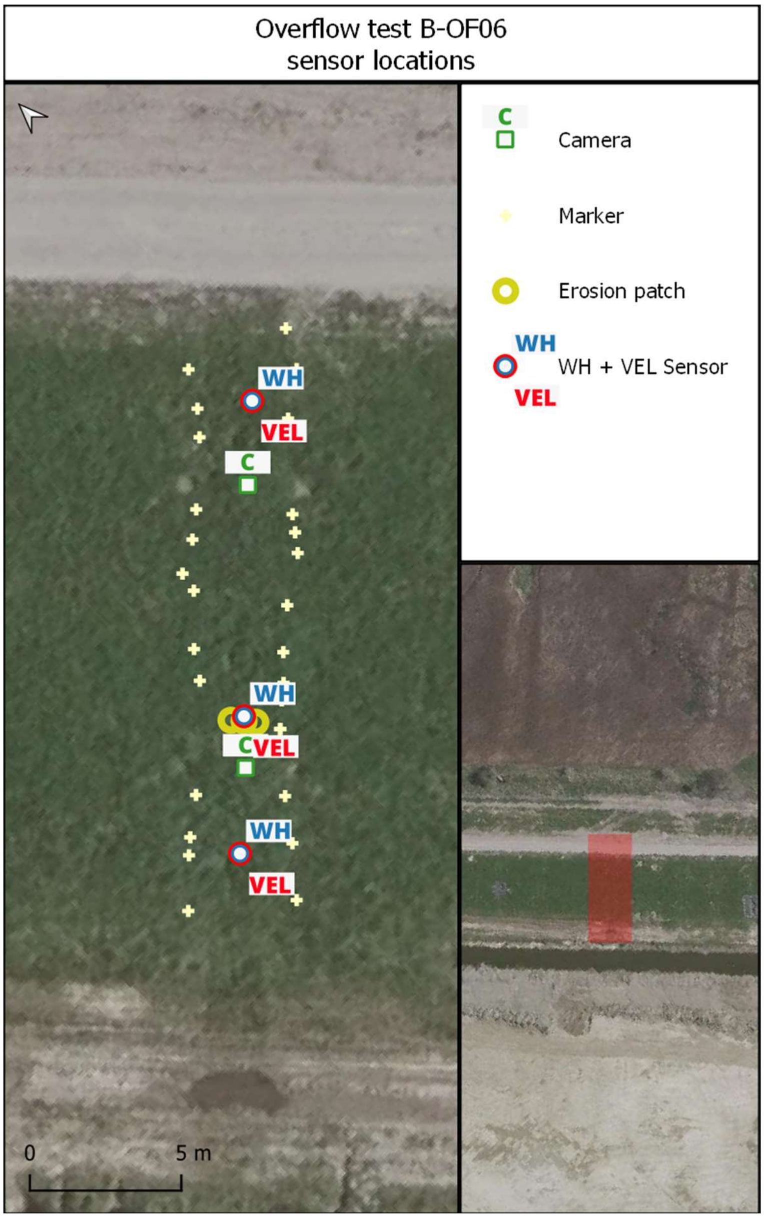

Figure 48 - Sensor location of the B-OF10. Aerial photograph background shows damage repair.

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Table 10 - Sensor locations (approximate) (Lambert '72 coordinates)

SENSOR	X	Y
WH CREST	140994.60	225673.55
WH + VEL UPPER	1409941.69	225670.71
WH + VEL MOBILE	140986.15	225665.39
WH + VEL LOWER	140980.82	225660.07
CAMERA UPPER	140989.44	225668.75
CAMERA LOWER	140982.79	225662.16

9.3 Execution

The test was executed in the spring of 2021, on 19/02 – 23/02/2021.

20 blocks of overflow testing have been executed for a total duration of 18 hours and 51 minutes. Especially on the second day, short blocks have been executed in order to observe surface erosion of the slope with time. The majority of the blocks was executed at a discharge of 250 $l.s^{-1}$ (or 125 $l.s^{-1}$ specific discharge).

9.4 Results

9.4.1 Monitoring timeseries

The overall averages of the monitoring timeseries are:

- Discharge 262 $l.s^{-1}$
- Water height CREST 18.7 cm
- Water height UPPER slope 20.4 cm
- Water height MIDDLE slope (MOBILE) 10.6 cm
- Water height LOWER slope 20.3 cm
- Velocity UPPER slope 2.65 m/s
- Velocity MIDDLE slope (MOBILE-) 2.37 m/s
- Velocity LOWER slope 1.10 m/s

The statistics per overflow block show that the measured discharges and water heights are fairly consistent. The velocities measurement however are less consistent and should be used (or interpreted) with care.

A full description of the timeseries is available in the Annex document.

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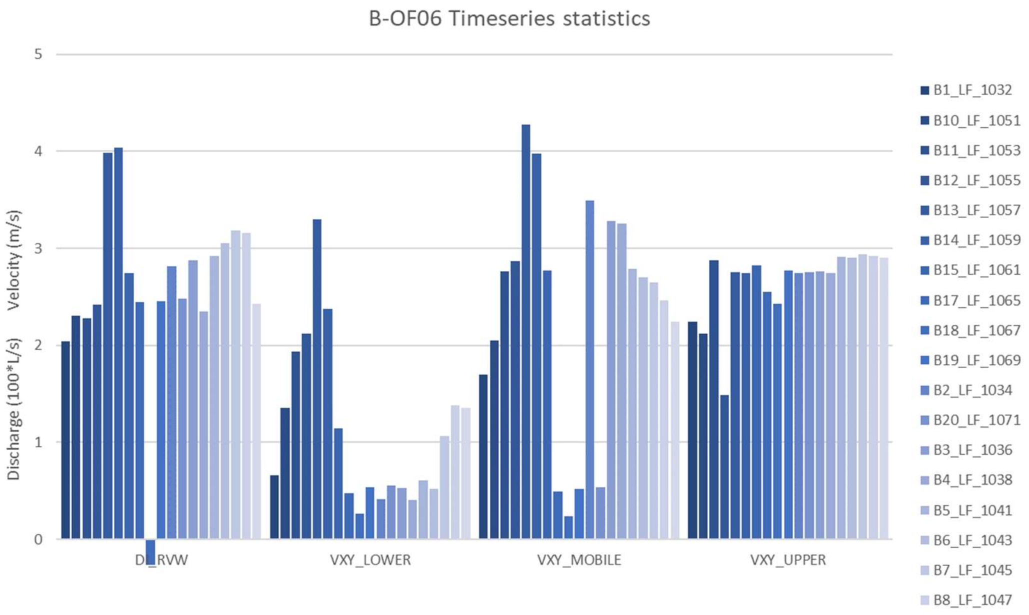

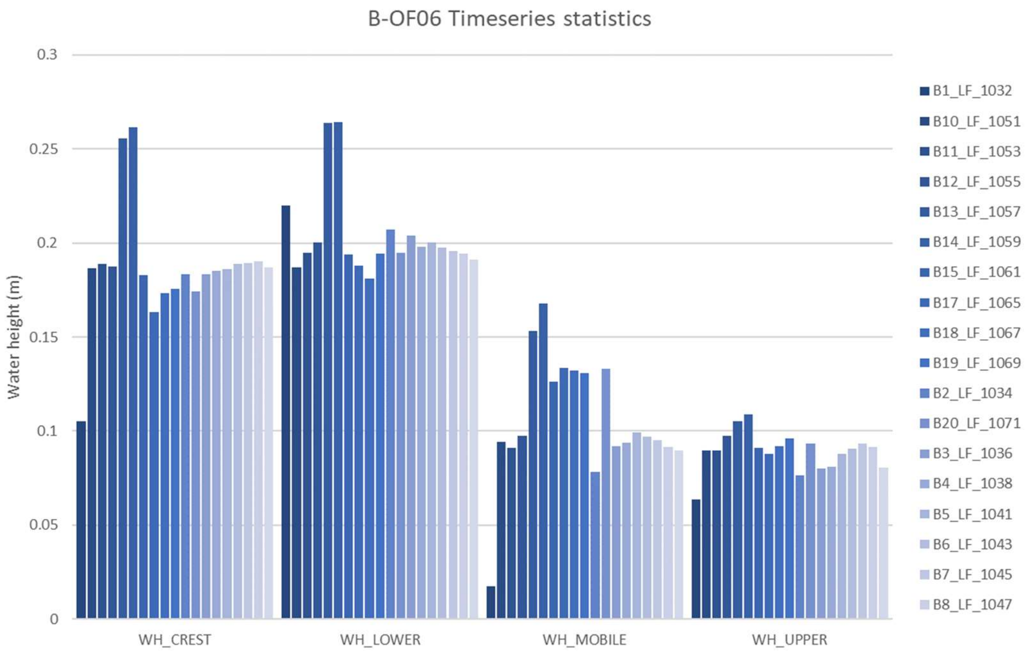

Figure 49 - Overview of timeseries statistics per block.

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9.4.2 Erosion patches

The results of this test relate to the erosion of patches on the levee slope and are discussed in Van Daele & Vandenbussche (2021). The erosion data and trends are reproduced here. Based on this data, a calibrated erosion curves relating maximum water velocity and duration was presented and compared with other data and models.

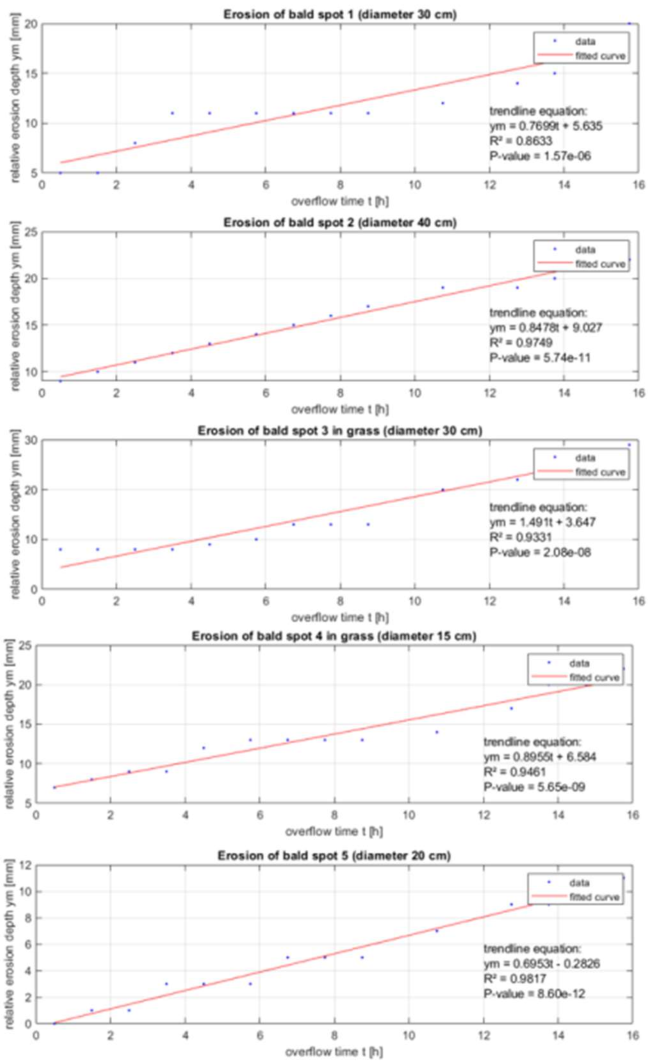

Figure 50 - Erosion measurements and trends of the different patches (from Van Daele & Vandenbussche, 2021).

9.5 First insights

Based on the field test and model investigation, it was concluded by Van Daele & Vandenbussche (2021) that the presence of vegetation and its root systems, have a strong influence on the result of existing soil erosion models that are often applied in levee investigation and design. Further outcomes concerning the performance of models and other test outcomes are discussed in Van Daele & Vandenbussche (2021).

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10 B-OF07 Levee Challenge

10.1 Test goal

Overflow test B-OF07 is a special kind of test. On this test section, the first Polder2C's Levee Challenge took place; a contest between two student teams who were asked to design a levee emergency repair strategy, and apply it to a damaged levee stretch. The goal of the test is to serve as an educational environment in which repair measures are tested.

10.2 Test setup

The B-OF07 Levee Challenge test has been executed on two adjacent test strips on the landward side of a Belgian levee in the Hedwige-Prosper Polder (X=140944.8 m; Y = 225726.5 m). The elevation of the crest is 11.2 m TAW, while the landward toe is situated at +/- 4 m TAW. The slope angle is 19° halfway the levee slope (which equals to a "11/4 slope").

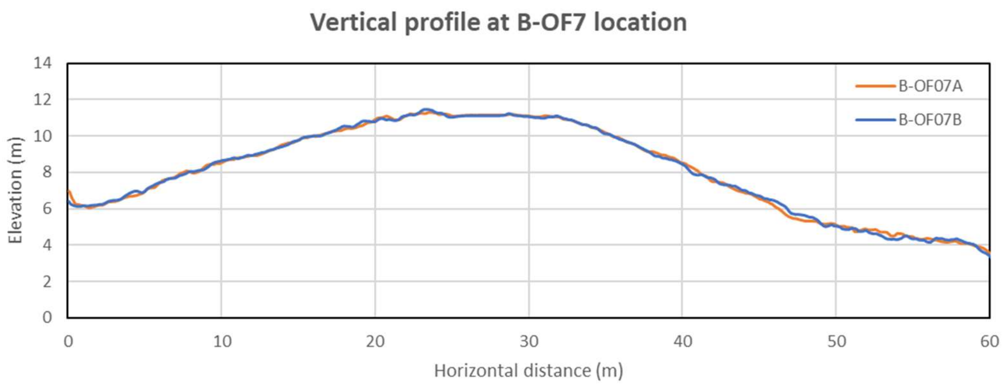

Figure 51 - Elevation profile over the B-OF01 Reference site. Data from drone based photogrammetry survey.

Both test sections are 2 m wide, sided by wooden boarding, and considered to be in a good condition without any visible anomalies. The original vegetation state is considered in a state after normal maintenance, with grass lengths of ca. 20 to 40 cm. The granulometry analysis indicates a silty top layer, which is typically 40 to 50 cm thick. The sand core below the top layer consists of medium sand. An asphalt road is present on the levee crest.

However, artificial damage has been done to the levee slope: 1/ the removal of a strip of vegetation at the upper slope, and 2/ the creation of a step-like anomaly at the lower slope. Consecutively, these damages have been protected by levee repair techniques. The damage and repair techniques are reported in detail by the reports of the 2 student teams (KULeuven: Team Brugse Diek (Barra et al., 2021) and TUDelft: Team Hansje Brinker (Buitelaar et al., 2021).

The monitoring setup has been adapted so that on both sections, one camera portal is present. The rest of the setup is comparable to that described in Vercruysse et al. (2022) but reduced in scope: discharge monitoring, a single water height and velocity monitoring location, upward from the damage at the lower slope end. Sensor positions are illustrated in Figure 54. GPS coordinates of the UPPER and CREST positions were not available and therefore not shown in the map.

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Figure 52 - The two parallel test sections for the Levee Challenge.

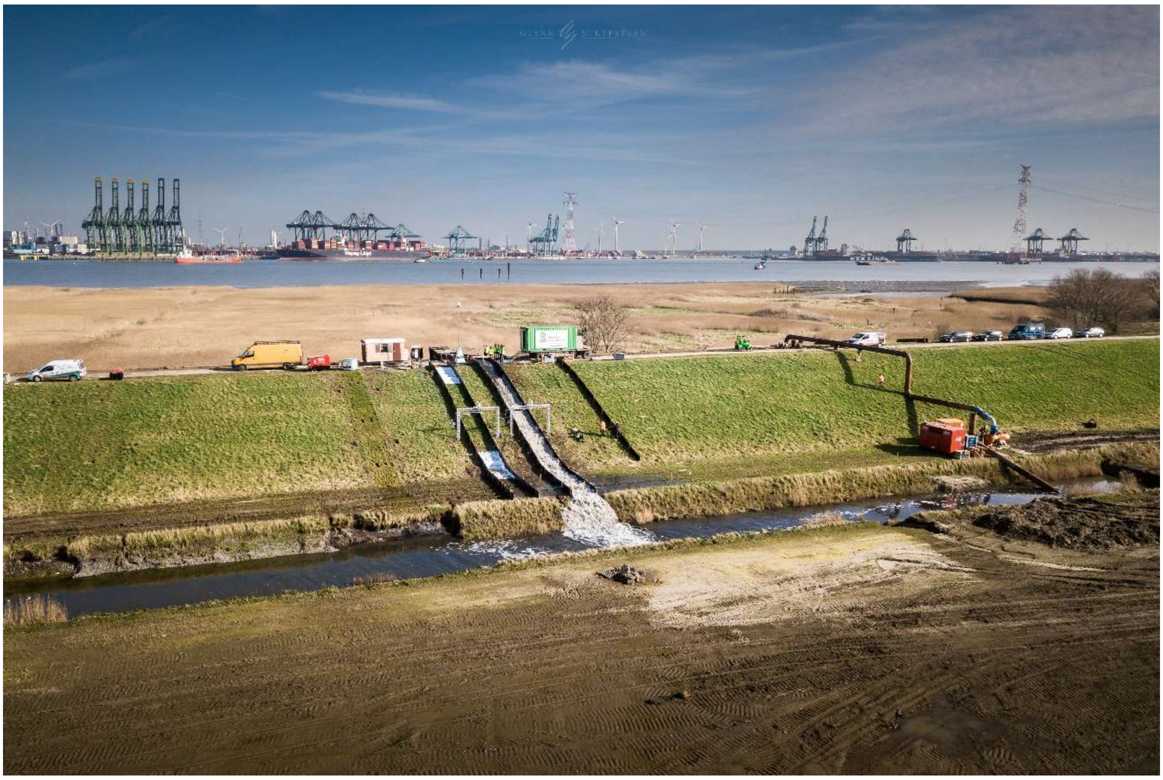

Figure 53 - Levee Challenge in Execution.

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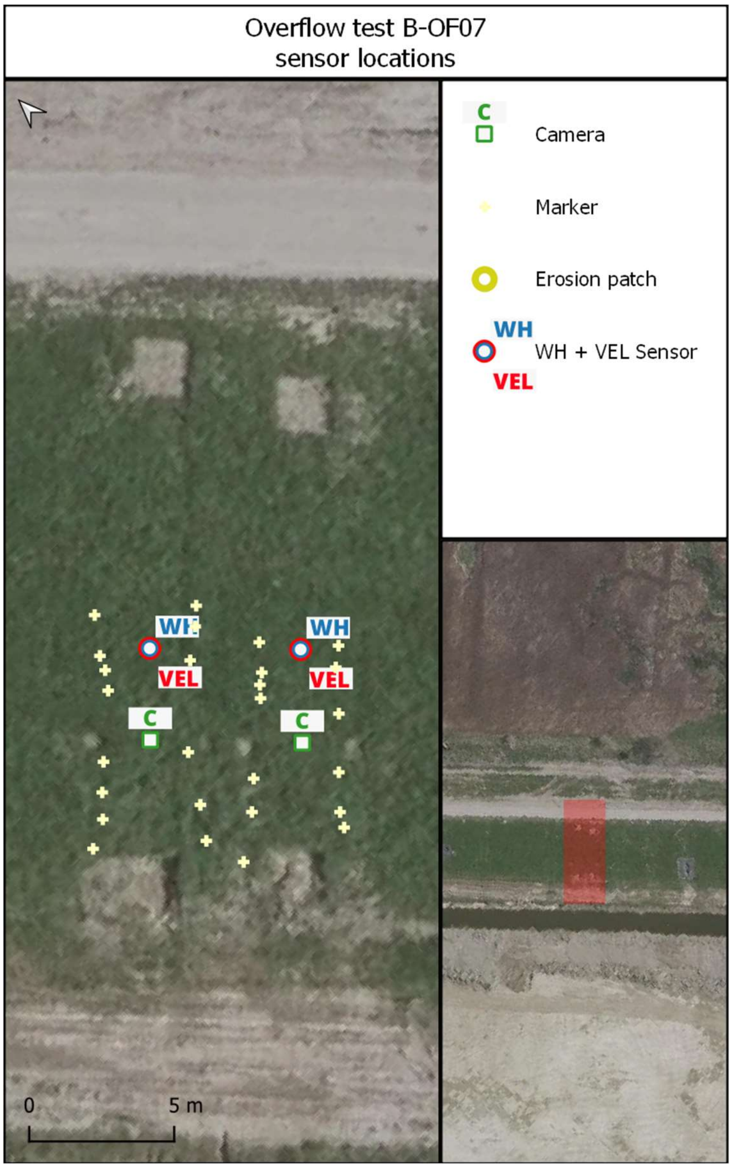

Figure 54: Sensor locations on B-OF07.

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10.3 Execution

The overflow experiment was executed in 'blocks' of typically 0.5 hour long. In between blocks, a short break was held to monitor damage evolution, assess the section and take photographs.

The first section was tested on 25/02/2021 in a total of 6 blocks, for a total overflow duration of 3 hours and 34 minutes. The second section was tested on 26/02/2021, with a similar time and duration.

10.4 Results

All results are described in the student reports (KULeuven: Team Brugse Diek, 2021 and TUDelft: Team Hansje Brinker, 2021). Here we only show the basic timeseries statistics.

First session averages:

- Total discharge 342 $l.s^{-1}$
- Water height Crest 36 cm
- Water height _UPPER 13 cm
- Water height LOWER 15 cm
- Velocity at upper portal 1,53 $m.s^{-1}$
- Velocity at lower portal 4.12 $m.s^{-1}$

Second session averages:

- Total discharge 497 $l.s^{-1}$
- Water height Crest_ 29 cm
- Water height Upper portal 12 cm
- Water height Lower portal (MOBILE) 15 cm
- Velocity at upper portal 0.79 m. s^{-1}
- Velocity at lower portal 3.47 m. s^{-1}

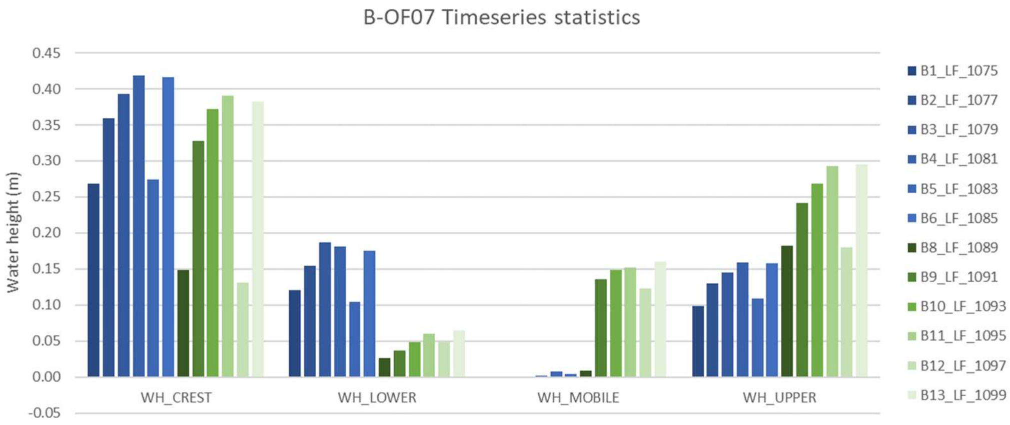

Figure 55 - Average statistic of the water height timeseries per block.

10.5 First insights

All conclusions are described in the student reports reports (KULeuven: Team Brugse Diek, 2021 and TUDelft: Team Hansje Brinker, 2021).

This project has received funding from the Interreg 2 Seas programme 2014-2020 co-funded by the European Regional Development Fund under subsidy contract No [2S07-023]

11 B-OF08 Reference

11.1 Goal

The goal of the B-OF08 Reference, is to perform an extra long overflow test on a test section that seems in a good shape, i.e. no anomalies present. The purpose of this is to validate grass performance curves (velocity-duration curves) (see e.g. chapter 8 of the International Levee Handbook, CIRIA, 2013) for overflow of a slope representative for the Flemish Scheldt estuary. During this test, several additional monitoring techniques were used in order to better characterize the hydraulic conditions of overflow.

At the end of the test, a constriction of 50% of the section width was placed to evaluate what the impact of an obstruction is.

11.2 Setup

The B-OF08 test has been executed on a section on the landward side of a Belgian levee in the Hedwige-Prosper Polder (X=140978.55 m; Y = 225691.39 m). The elevation of the crest is about 11.2 m TAW, while the landward toe is situated at +/- 4 m TAW. The slope angle is 19° halfway the levee slope (which equals to a "11/4 slope"). The profile of the centre line is shown in Figure 56.

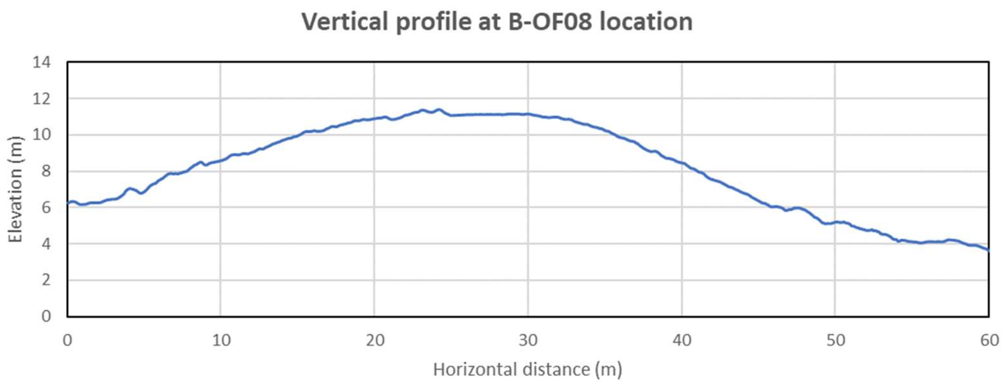

Figure 56 - Profile along the B-OF08 test section.

The test section is 2 m wide, sided by wooden boarding, and considered to be in a good condition without any visible anomalies. The vegetation state is considered in a state after normal maintenance, with grass lengths of ca. 20 to 40 cm. Detailed vegetation survey has been performed on Belgian and Dutch levee stretches, reported in Vandevoorde & Lierop (2022). The granulometry analysis indicates a silty top layer, which is typically 40 to 50 cm thick. The sand core below the top layer consists of medium sand. An asphalt road is present on the levee crest.

The monitoring setup has been applied and is described in Vercruysse et al. (2022): discharge monitoring, water height monitoring at different locations (levee crest, upper, middle and lower slope) and velocity monitoring (upper, middle and lower slope). Camera frames allow to make images of the surface to assess damage evolution, and movies to visualize current patterns. The locations of the sensors is indicated in Figure 57 and Table 11. In addition to this monitoring, PTV and LSPIV (using high speed cameras) have been executed. These data sources have been used in Vercruysse et al. (2022) for validation of the default monitoring strategy.

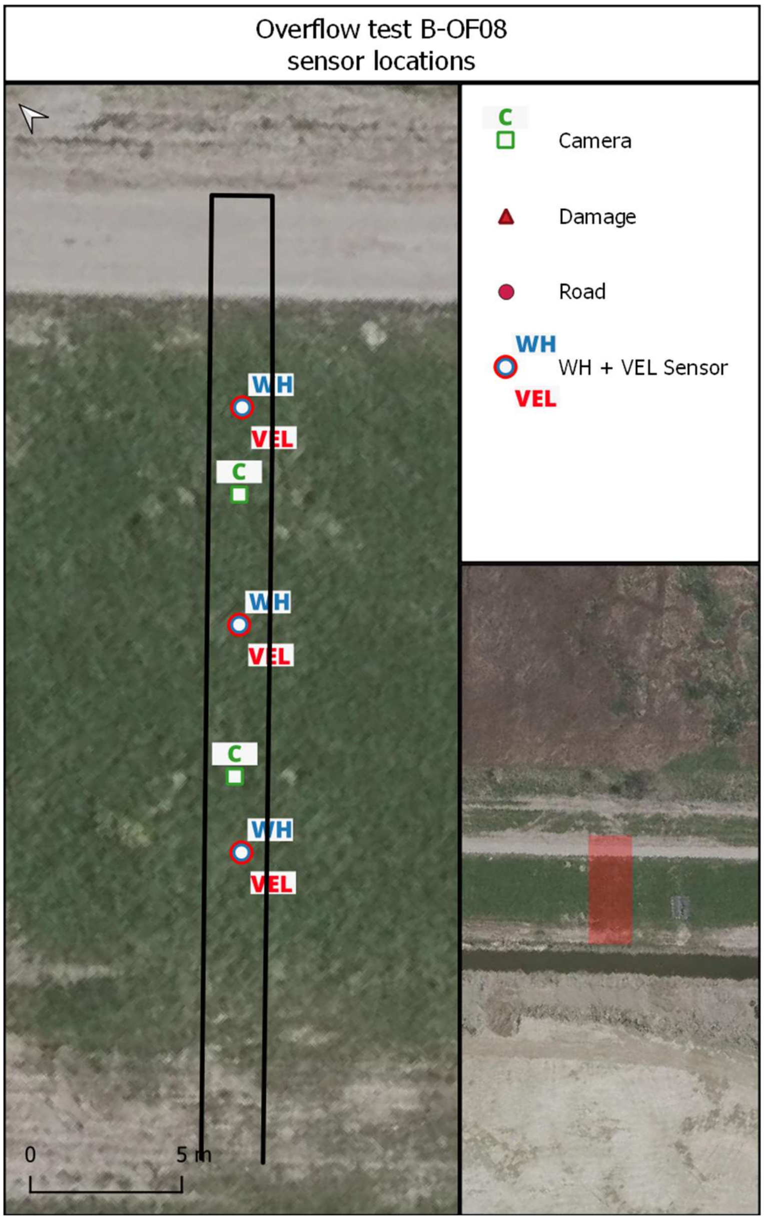

Figure 57 - Positioning of the sensors at the B-OF08 position.

Table 11 - Sensor locations (approximate) (Lambert '72 coordinates) (WH_CREST location not available)

SENSOR	X	Y
WH + VEL UPPER	140974.92	225687.87
WH + VEL MOBILE	140969.77	225682.85
WH + VEL LOWER	140964.49	225677.47
CAMERA UPPER	140972.81	225685.90
CAMERA LOWER	140966.11	225679.41

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11.3 Execution

The overflow experiment was executed in 'blocks' of 1 to 2 hours. In between blocks, a short break was held to monitor damage evolution, repair the section and take photographs.

At the B-OF08 test site, 15 blocks were executed on 1, 2, 3 and 4/03/2021. The nominal pump discharge was around 500 $l.s^{-1}$, while discharge variations were applied in different blocks. These are reported in detail the Annex document.

11.4 Results

11.4.1 Visual observations

The start on March 1, 2020 in the afternoon, was followed by 3 days of testing with a total pump discharge of ~500 $l.s^{-1}$ (or ~250 $l.s^{-1}.m^{-1}$). Here, a river water level of ~35-40 cm above the crest was imitated.

In total, water was flowing over the levee slope for 22 hours during which very little damage occurred. On the levee slope, the typical erosion of soil in between grass sods, and exposure of part of the grass roots, developed (Figure 58 - Vegetation state after 22 hours of overflow on B-OF08.). However, this did not lead to undercutting or loosening of the sods. This indicates that the grass cover layer – as a whole – was retaining its integrity.

At the levee toe however, more erosion and exposure of soil was evident. This is however limited to the transition from the slope to the flat surface, where increased impact load is evident (Figure 59 - Vegetation state on the lower slope and at the toe transition after 22 hours of overflow.). Even with this damage, no failure or critical events were signalled.

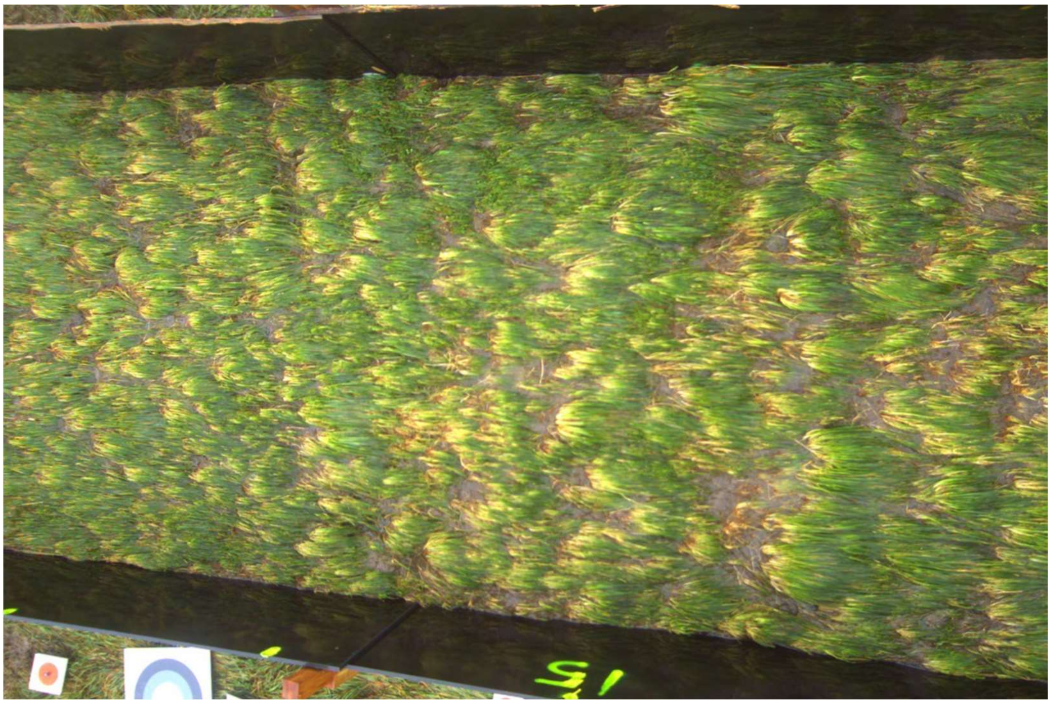

Figure 58 - Vegetation state after 22 hours of overflow on B-OF08.

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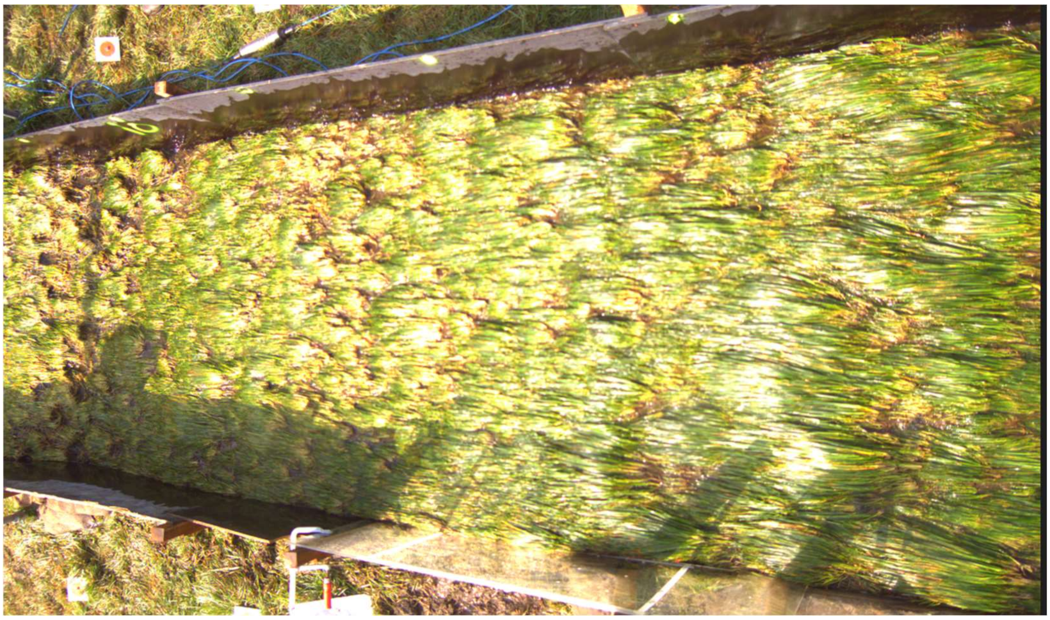

Figure 59 - Vegetation state on the lower slope and at the toe transition after 22 hours of overflow.

After 22 hours an abrupt narrowing of the section width was appliedFigure 52. Water was flowing through this narrowed section for 3 hours. The experiment was stopped before this could evolve into severe damage, however, increased removal of grass strands and increased exposure and erosion of soil is observed next to the obstructed area (Figure 60).

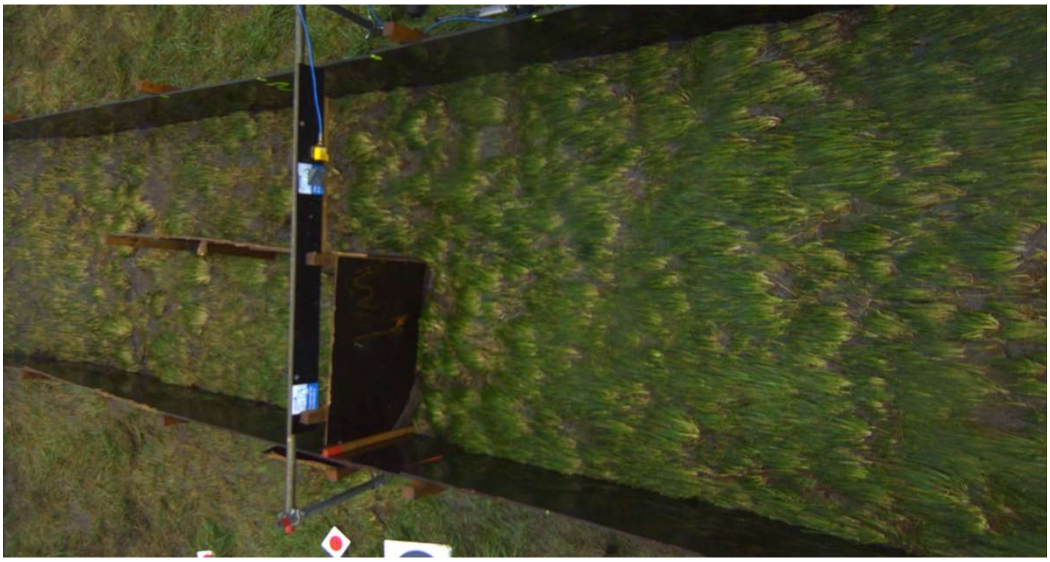

Figure 60 - End state of the obstructed area near the toe, after 24 hours of overflow.

11.4.2 Video and photo imagery

During the overflow runs, images are taken at different intervals in order to capture the flow patterns. In between the runs, images of the surface are made in order to have a record of the evolution of this surface. An example of such an image is shown in Figure 60.

Data files

The complete list of blocks for which imagery is available is shown in Table 12.

Table 12 - Overview of imagery data availble per block in B-OF08. The numers refer to file id's.

Block	Surface images	Flow images
0	1102	
1	1104	1103
2	1106;1107	1105
3	1109	1108
4	1111	1110
5	1113	1112
6	1115; 1116	1114
7	1118	1117;1135
8	1125	1119
9		1126
10	1136;1137	1135
11	1139	1138
12	1160	1140
13	1161;1163	1162
14	11615	1162
15		1166

11.4.3 Monitoring timeseries

The total discharge has been kept at a high level during all of the overflow blocks, mostly varying between 400 $l.s^{-1}$ and slightly over 500 $l.s^{-1}$.

The statistics per overflow block show that the measured discharges and water heights are fairly consistent (Figure 61). The velocities measurements however are less consistent and should be used or interpreted with care.

The timeseries averages are as follows:

- Total Discharge — 477 $l.s^{-1}$ (or a specific discharge of 238 $l.s^{-1}.m^{-1}$)
- Water height crest — 15.2 cm
- Water height upper slope — 8.4 cm
- Water height middle slope (MOBILE) — 14.0 cm
- Water height lower slope — Strongly variable, not reliable
- Velocity upper slope — 3.16 m/s
- Velocity CREST (mobile) — 2.23 m/s
- Velocity lower slope — Strongly variable, not reliable

For a detailed view of the timeseries, we refer to the Annex document.

During block 12 of this test, discharge variations over a large range were executed. From this, it was possible to derive trends in water levels and velocities. From this, it appears that the water levels increase fairly linearly with increasing discharge, except for the WH_MOBILE sensor which has a uncorrelated (and unexplained) behavior. The velocities on the other hand increase linear up to a discharge of about 400 to 450 $l.s^{-1}$ to become rather constant at higher discharges.

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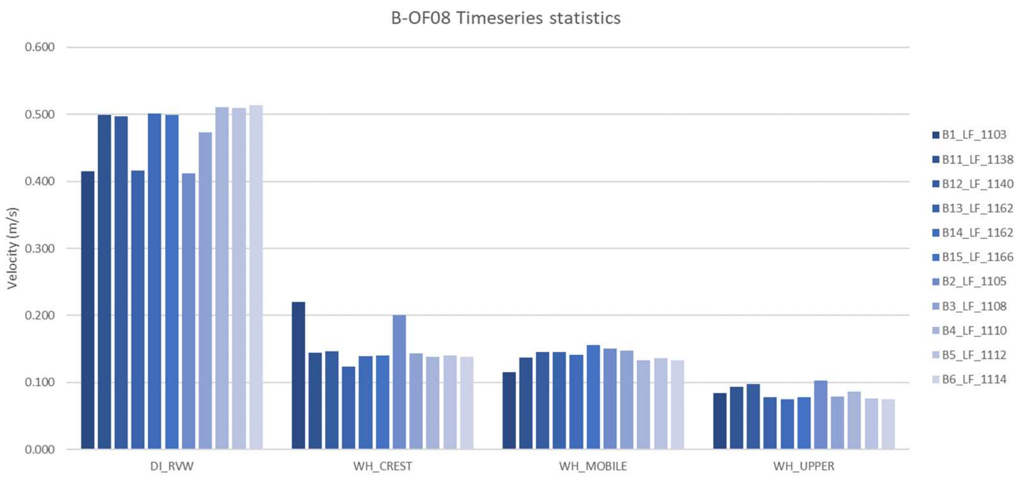
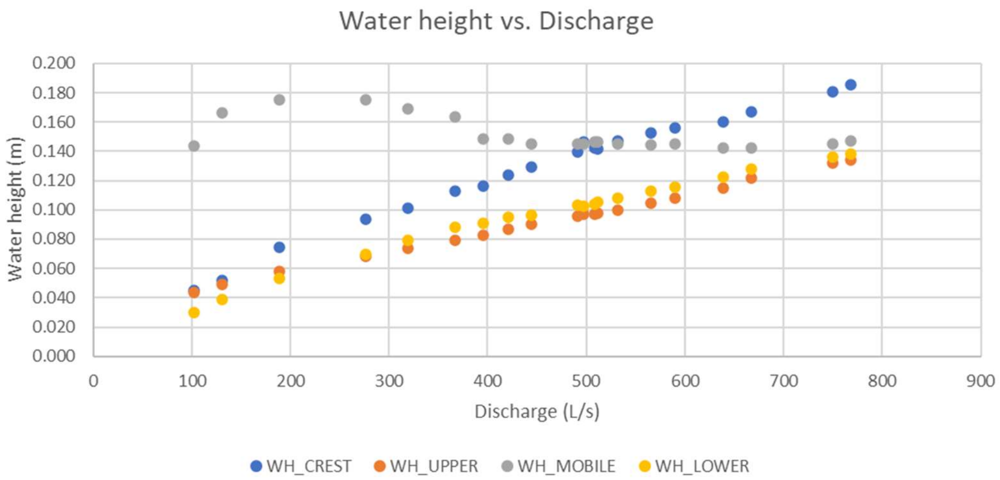


Figure 61 - Average discharge and water levels per block.



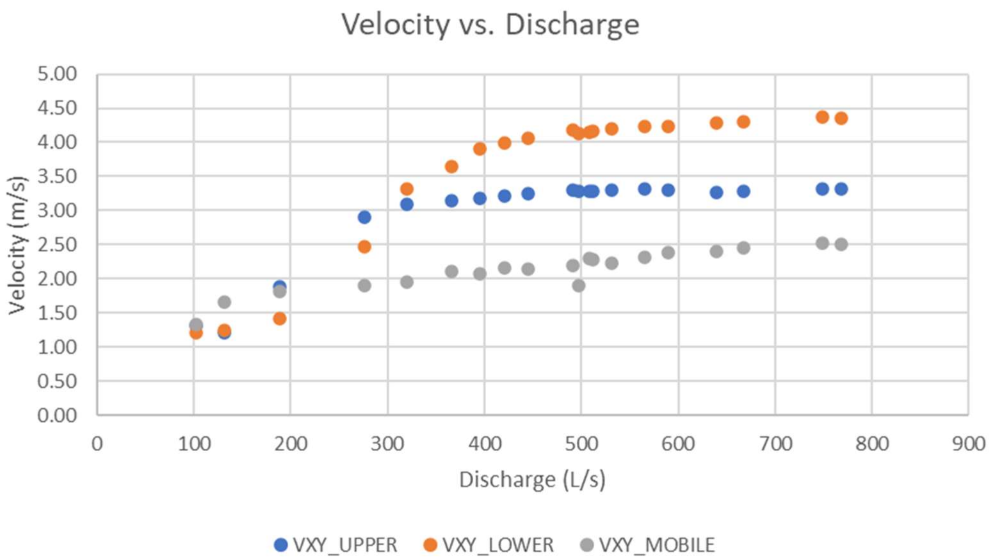


Figure 62 - Average water heights (upper) and velocities (lower) vs. discharge.

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Data files

Table 13 - Overview of raw timeseries data file numbers for block B-01.

Block	Timeseries	PTV	Block	Timeseries	PTV
0			*11*	*1138*	
1	1103		*12*	*1140*	*1142-1159*
2	*1105*		13	1162	
3	1108		14	1162	
4	1110		15	1166	
5	1112				
6	1114				
7	1117				
8	1119	1120-1134			
9	1126				
10	1135				

11.4.4 Other data

As part of the monitoring validation, LSPIV and PTV data have been analysed and presented in Vercruysse et al. (2022). The file ID's for the PTV are also shown in Table 13.

11.5 First insights

The main conclusion of the B-OF08 test is that a vegetated cover layer in visually good condition with normally maintained vegetation ('according to the Flemish method'), is able to withstand overflow at an average specific discharge of 250 $l.s^{-1}$ per m for more than 24 hours accumulated, without leading to failure of the cover layer.

This contrasts strongly with the tests that lead to failure after 1 or a few hours (e.g. B-OF04, B-OF10). From what we see, it appears that the presence of animal activity (burrowing, directly or as a consequence of the presence of e.g. trees, cattle areas, …) strongly diminishes the effective strength of the levee cover and, as a consequence, the levee as a whole.

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12 B-OF09 Mid high Discharge

12.1 Goal

The goal of B-OF09 was to perform an additional test under severe load (high discharge), but implemented over a width of 2 m. In contrast, the B-OF03 High Discharge test (and the following B-OF10 High Discharge test) were executed over a width of 1 m.

12.2 Setup

The B-OF09 test has been executed on a section on the landward side of a Belgian levee in the Hedwige-Prosper Polder (X=140994.60 m; Y = 225673.50 m). The elevation of the crest is about 11.2 m TAW, while the landward toe is situated at +/- 4 m TAW. The slope angle is 19° halfway the levee slope (which equals to a "11/4 slope"). The profile of the centre line is shown in Figure 63.

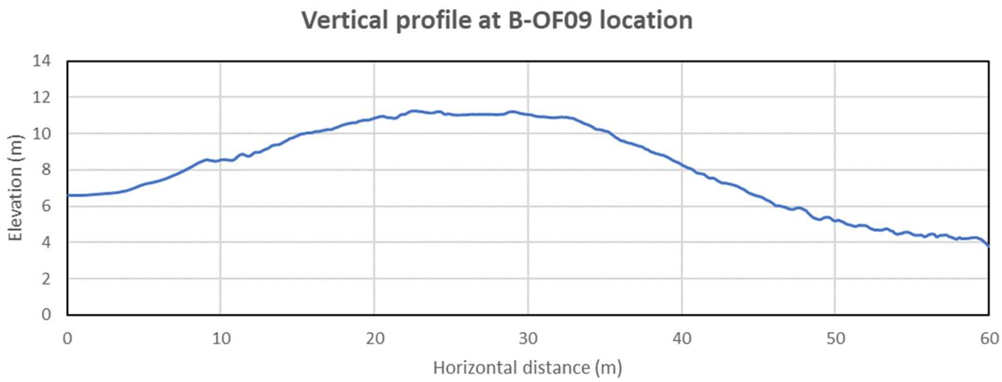

Figure 63 - Profile along the B-OF09 test section.

The test section is 2 m wide, sided by wooden boarding, and considered to be in a good condition without any visible anomalies. The vegetation state is considered in a state after normal maintenance, with grass lengths of ca. 20 to 40 cm. Detailed vegetation survey has been performed on Belgian and Dutch levee stretches, reported in Vandevoorde & Lierop (2022). The granulometry analysis indicates a silty top layer, which is typically 40 to 50 cm thick. The sand core below the top layer consists of medium sand. An asphalt road is present on the levee crest.

The default monitoring setup has been applied and is described in Vercruysse et al. (2022): discharge monitoring, water height monitoring at different locations (levee crest, upper, middle and lower slope) and velocity monitoring (upper, middle and lower slope). Camera frames allow to make images of the surface to assess damage evolution, and movies to visualize current patterns.

In addition, ground water tension sensors (Watermarks) are installed in the upper and middle part of the slope in and below the top layer of the levee in order to assess the infiltration of water into the subsurface during the overflow tests. The sensors had been installed well in advance so that long-term variations or fluctuations would be measured.

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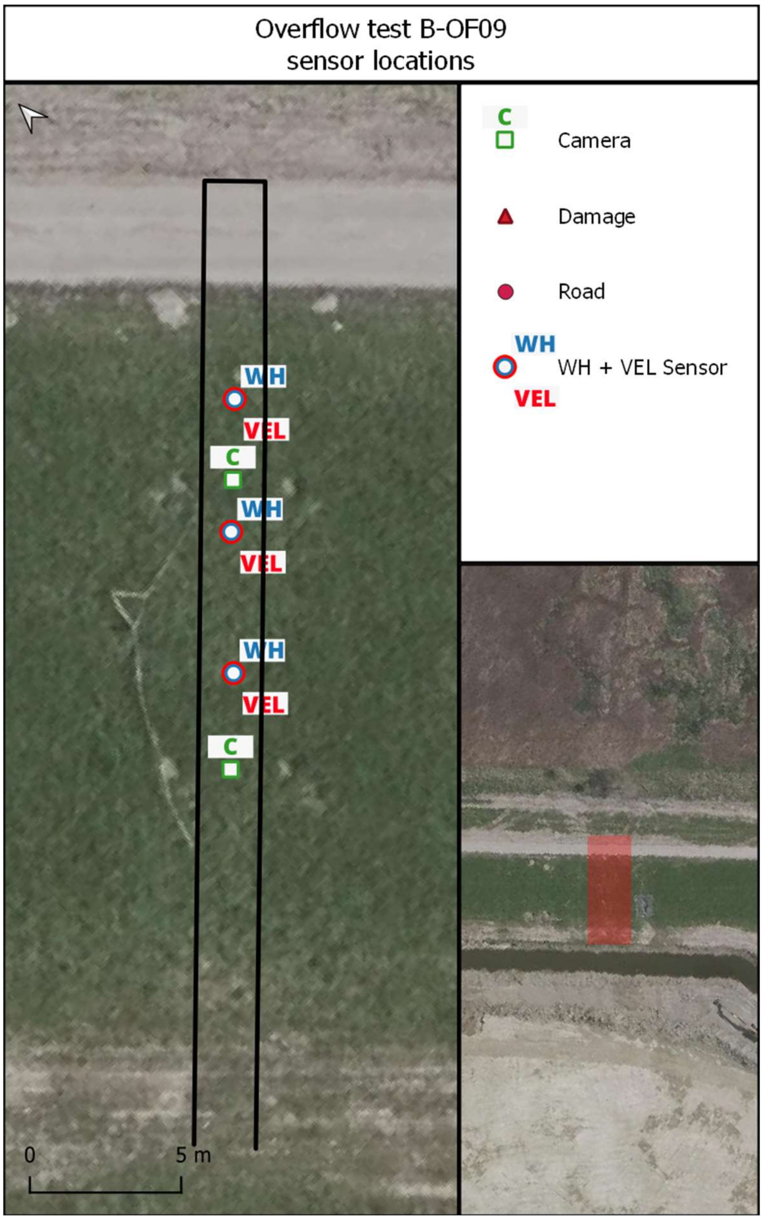

Figure 64 - Positioning of the sensors at the B-OF09 position.

Table 14 - Sensor locations (approximate) (Lambert '72 coordinates) (WH_CREST location not available)

SENSOR	X	Y
WH + VEL UPPER	140983.13	225679.21
WH + VEL MOBILE	140979.95	225676.19
WH + VEL LOWER	140976.70	225672.84
CAMERA UPPER	140981.20	225677.37
CAMERA LOWER	140966.11	225679.41

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12.3 Execution

The overflow experiment was conducted on 6-8/03/2021 and generally executed in 'blocks' of 1 or 2 hours. In total, 12 blocks were ran, with a total overflow time of 18.13 hours. In between blocks, a short break was held to monitor damage evolution, repair the section and take photographs. The nominal discharge was 750 $l.s^{-1}$, or a specific discharge of 375 $l.s^{-1}.m^{-1}$. Manual measurements indicated a water height on the crest of 20 cm.

On top of that, an artificial burrow was added to the section on the last day (see further).

12.4 Results

12.4.1 Visual observations

During the first 13 hours of overflow, the focus of the experiment was to perform high-discharge tests for extended time. This went without any significant damage to the levee. The observations included slight erosion of soil so that the vegetation roots became increasingly exposed. This also gave rise to some patches that looked bare. An overview image of this evolution is shown in §12.4.2.

Figure 65 - View of the state of the levee cover after 13 hours of overflow at 700 $l.s^{-1}$.

During the last day in the morning, it was decided to introduce an artificial burrow. The burrow was drilled vertically, in between the lower sensor and camera portals, and to a depth of more than 50 cm so that a contact with the sand core of the levee was made. The overflow was continued and during the breaks, it was observed that water was standing in the hole.

In order to test the hypothesis of outflow of water through a lower burrow entrance, a second burrow was drilled at 13h00, after 4 hours of additional overflow. This second drillhole was horizontal and departing from the toe area into the sand core as well. Note that both drillholes were not connected.

In between the 3 subsequent blocks (of 1 hour) of overflow, it was observed that water was flowing out of the lower burrow, but without significant sediment entrainment. Also, the outpour did not continue after the overflow stopped, but stopped after just a few minutes.

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At about 15h00 it was also noticed that some brown coloured water was flowing out of small burrows outside the test section. However, this also did not lead to important sediment entrainment. Failure of the levee slope could not be achieved before the end of the experiment.

Figure 66 - Drillhole at the toe (left: initial state, block B10; right; modest outflow of water and some sediment at the end of an overflow block, block 11).

12.4.2 Video and photo imagery

Images made during the experiment by use of the overhead camera portals are summarized in Table 15.

Data files

Table 15 - Overview of imagery data availble per block in B-OF01. The numers refer to file id's.

Block	Surface images	Flow images
0	1168	
1	1170	1171
2	1172	1173
3	1174	1175
4	1176;1178;1180	
5		
6		
7	1184	1183
8	1186	1185
9	1188	1187
10	1190	1189
11	1192	1191
12	1194	1193

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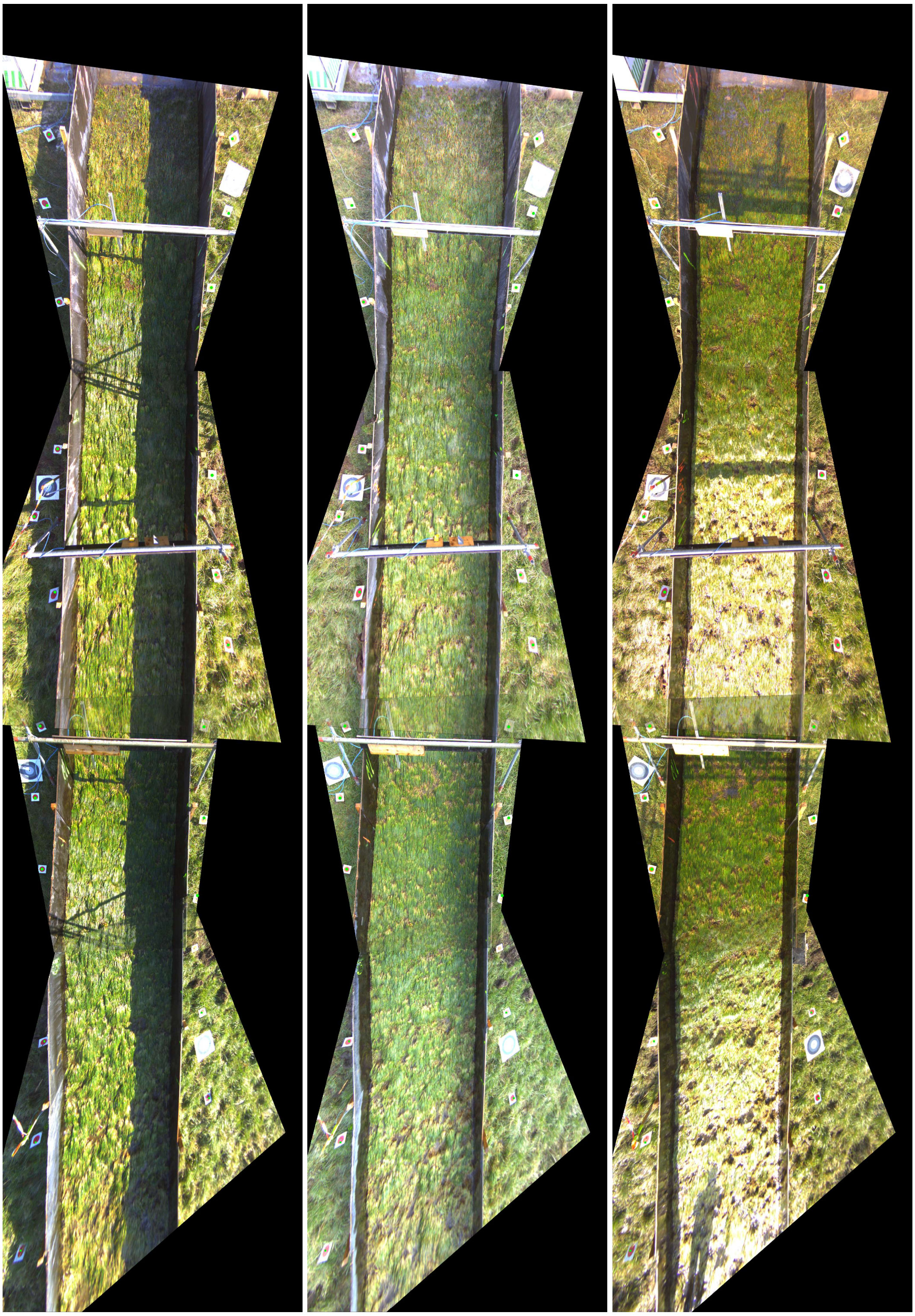

Figure 67 - Evolution of surface during experiment B-OF09 after block 1, 4 and 12.

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Data files

The complete list of blocks for which imagery is available is shown in Table 16.

Table 16 - Overview of imagery data availble per block in B-OF01. The numers refer to file id's.

Block	Surface images	Flow images
0	1168	
1	1170	
2	1172	1171
3	1174	1173
4	1176;1178;1180	1175
5		
6	11844	
7	1186	1183
8	1188	1185
9	1190	1187
10	1192	1189
11	1194	1191
12		1193

12.4.3 Monitoring timeseries

The discharge has been kept at a high level, without any variation throughout the B-OF09 experiment. The timeseries averages are:

- Total Discharge 744.96 $l.s^{-1}$ (equivalent to a specific discharge of 372.48 $l.s^{-1}.m^{-1}$)
- Water height Crest 17.9 cm (note: manual measurements indicated 20 cm)
- Water height Upper slope 12.5 cm
- Water height Middle slope 20.3 cm
- Water height Lower slope 18.6 cm
- Velocity Upper slope 2.16 m/s
- Velocity Middle slope 2.17 m/s
- Velocity Lower slope 3.84 m/s

Details concerning the timeseries are shown in the Annex document.

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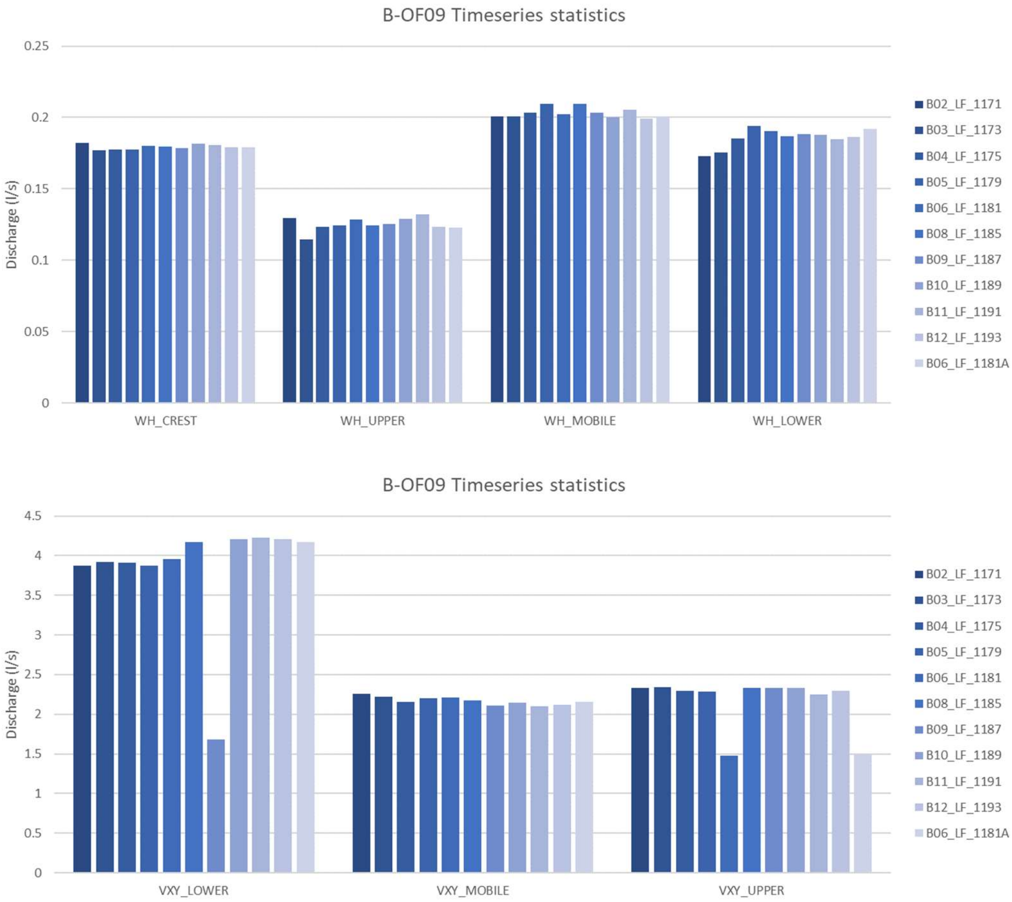

Figure 68 - Timeseries averages of water heights and velocities, per block.

Data files

Table 17 - Overview of raw timeseries data file numbers for block B-09.

Block	Timeseries
0	
1	1169
2	*1171*
3	1173
4	1175;1177;1178
5	1179
6	1181
7	1184
8	1185
9	1187
10	1189
11	*1191*
12	*1193*

12.4.4 Other data

Soil moisture data has been recorded on the B-OF09 location, just outside the test section. On the upper slope, close to the WH_UPPER position, 3 sensors have been installed at 15 and 30 cm depth (BLTShall, BLTMid) and 60 cm deep into the sand (BLTSand). Close to the toe, a sensor has been placed at 30 cm in the cover layer, and a second one also 60 cm deep into the sand (BToeTop, BToeSand). Similarly, two sensors were place halfway the slope (BTalTop and BTalSand).

The moisture data consists of water tension measurements taken with the Watermark sensors. The data, represented in kPa, are shown in Figure 70 and represent a high suction tension (capped at 250 kPa, and correspond to very dry conditions), or a low suction tension (0 kPa is totally saturated).

The data shows the variations and the presence of long drought periods in april-june 2021. Further analysis of this data is out of scope of this report.

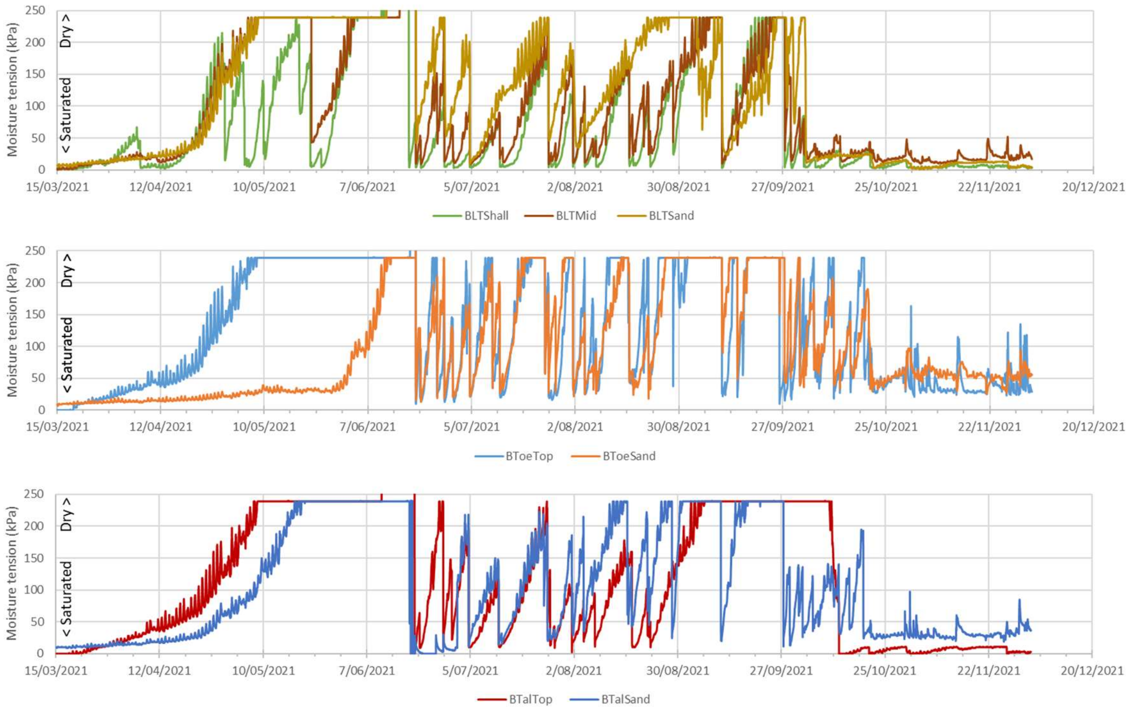

Figure 69 - Moisture tension monitoring at B-OF09 location.

12.5 First insights

From the observations, a number of first insights can be derived:

- A levee that is in a good state (i.e. without any significant, visible anomalies) is able to withstand overflow by a water height of 20 cm on the crest (or 350 $l.s^{-1}.m^{-1}$) for more than 18 hours.
- The creation of a "artificial burrow" entry and exit without any connection in between are not sufficient to provoke any significant flow of water through the levee core. Sediment entrainment is therefore very limited and insufficient to lead to major mass deficit under the levee top layer and ultimately to slope failure. This may indicate that a longer, continuous burrow may be advantageous for the flow and the sediment entrainment before such damage process develops. From the grouted and excavated burrows (see Hölscher et al., 2021) it is also known that these burrows are sinuous and irregular as well, potentially increasing points of attack.

13 B-OF10 High Discharge

13.1 Goal

Overflow test B-OF10 is conducted as a **high discharge** experiment by narrowing the section width to 1 meter (instead of 2 m). This way, the pump discharge was distributed over a narrower section, and would lead to a higher water level at the crest.

The purpose of the higher discharge test is to evaluate whether this factor influences the erosion resistance of the levee cover layer.

13.2 Setup

The B-OF10 test section is executed at the landward side of the Belgian levee at coordinates X=140 994.60m; Y=225 673.50m (Lambert '72 coordinates) or 4.23953°E, 51.34078°N (WGS84).

The crest culminates at 11.2 m TAW (Belgian vertical reference), whereas the toe altitude is ca. 4 m TAW. Beyond the toe, a small channel is present. The slope angle is 19° halfway the levee slope, which equals to a 11/4 slope.

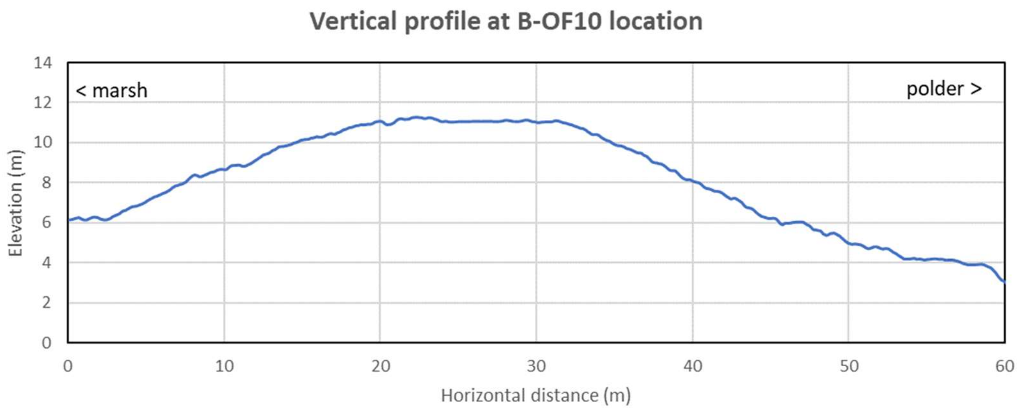

Figure 70 - Vertical profile at the B-OF10 site.

As stated in the goal, the test section width is reduced in width to 1 meter in order to generate higher specific discharges.

No anomalies have been reported for the section. Vegetation was in a normal condition, with vegetation lengths of 15 to 30 cm.

The default monitoring setup has been applied and is described in Vercruysse et al. (2022): discharge monitoring, water height monitoring at different locations (levee crest, upper, middle and lower slope) and velocity monitoring (upper, middle and lower slope). Camera frames allow to make images of the surface to assess damage evolution, and movies to visualize current patterns. Drawings of the damage have been made, as well as regular photographs by the test operators.

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the European Regional Development Fund under subsidy contract No [2S07-023]

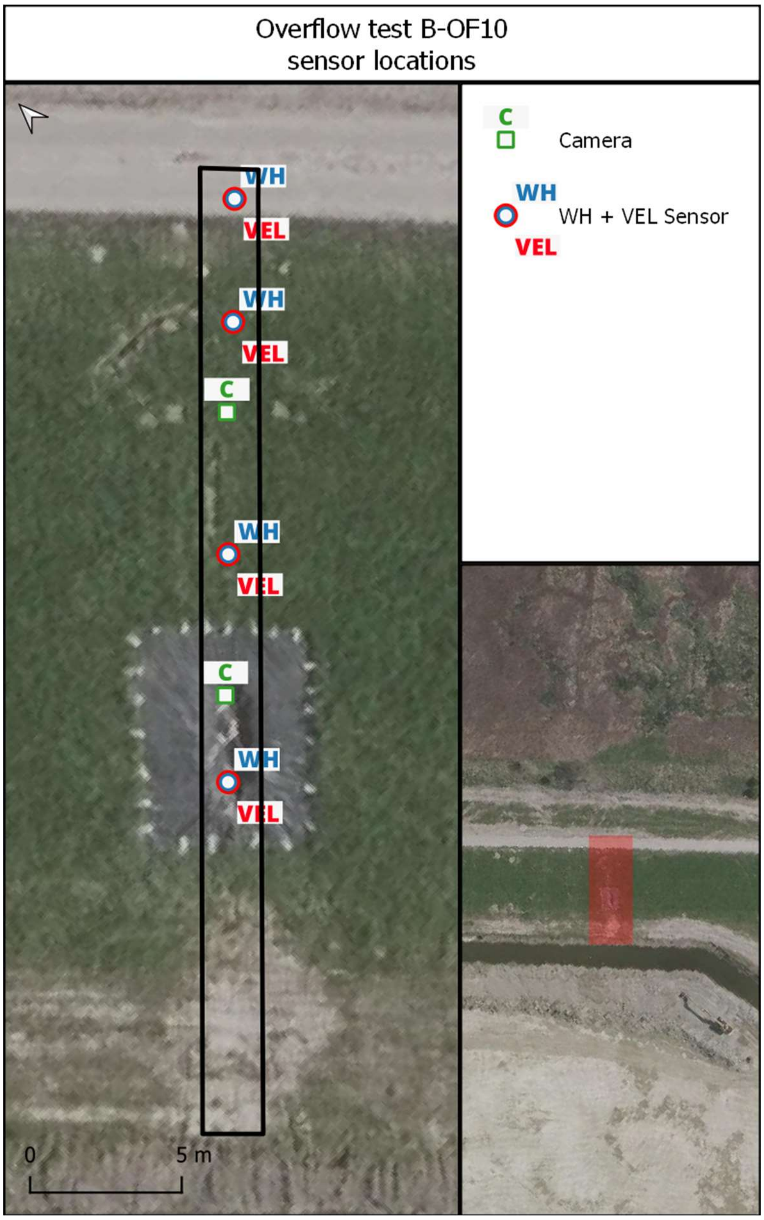

Figure 71 - Sensor location of the B-OF10. Aerial photograph background shows damage repair.

Table 18 - Sensor locations (approximate) (Lambert '72 coordinates)

SENSOR	X	Y
WH CREST	140994.60	225673.55
WH + VEL UPPER	1409941.69	225670.71
WH + VEL MOBILE	140986.15	225665.39
WH + VEL LOWER	140980.82	225660.07
CAMERA UPPER	140989.44	225668.75
CAMERA LOWER	140982.79	225662.16

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13.3 Execution

The test was the last experiment of the second test episode, in the spring of 2021, on 09/03-10/03/2021. This was also the last test performed on a Belgian levee within the framework of the Polder2C's overflow tests.

11 blocks of overflow testing have been executed for a total duration of 6 hours and 40 minutes. Especially on the second day, short blocks have been executed in order to observe the evolution of a slope damage (cliff formation) that evolved. The majority of the blocks was executed at a discharge of 550 $l.s^{-1}$ (or 550 $l.s^{-1}.m^{-1}$ specific discharge), the highest discharge of all tests executed so far.

13.4 Results

13.4.1 Visual observations

During the B-OF10 test, a normal progression of top layer and vegetation erosion was visible. With increasing duration grass roots became increasingly exposed and parts of soil became visible. However, during the first 4 hours of this very high discharge load (550 $l.s^{-1}.m^{-1}$) the cover layer itself stayed intact along the entire slope.

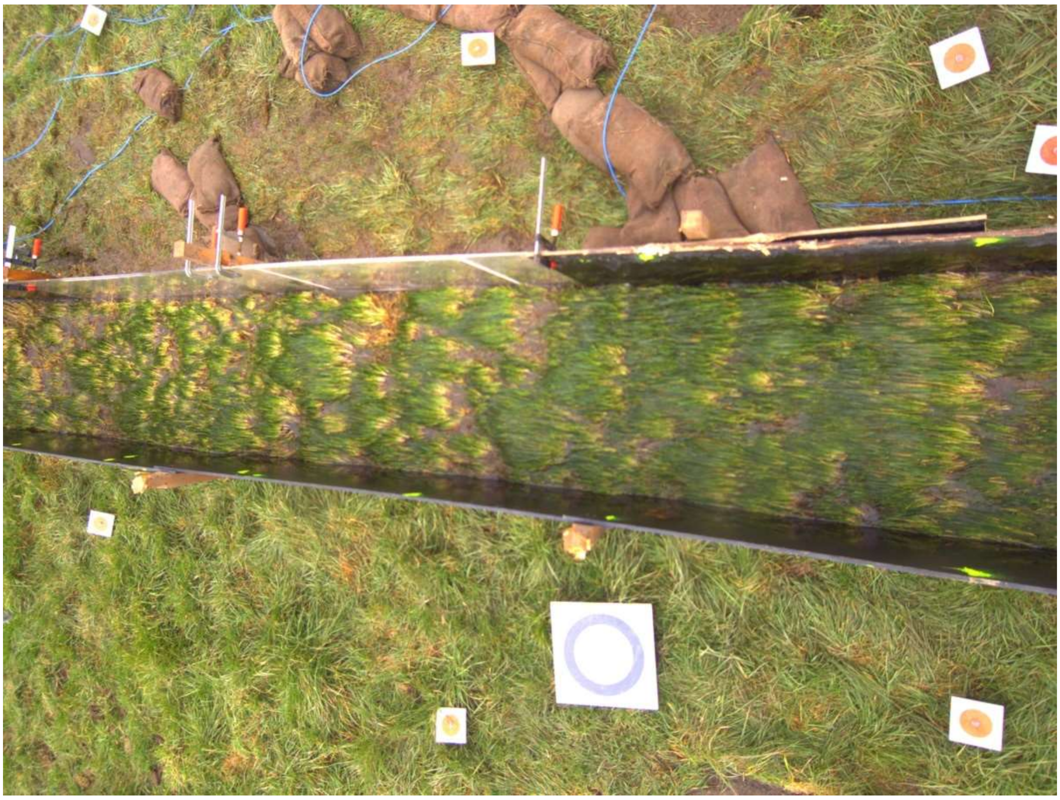

Figure 72 - Example of vegetation and top layer state after block B08.

Gradually, near the toe area, more bare patches and erosion became visible.

After 4 hours, about 2 meter above the toe, a scour erosion occurred along the wood side boarding. The nature of this erosion is so that it might be caused by the presence of the wood boarding which penetrates the top layer, and thus creates a possible weak spot. After 5 hours of overflow, the damage became significant and the blocks were reduced to short episodes (5 – 10 minutes) in order to prevent excessive damage.

The evolution of the damage was very fast between block B08 and B10: in a duration of approximately 15 minutes of overflow, a small erosion hole suddenly gave rise to a much larger depression. After block 10, it was decided not to continue this experiment in order not to provoke any further damage.

On the images below, it can also be observed that in the slope-toe transition (upper part of the images), there is a very strong erosion and ripping-off of vegetation ongoing.

Figure 73 - Damage evolution during the last minutes of test B-OF10 (after block B08, B09 and B10). (looking downward)

After block B10, a diversion of the flow has been constructed so that, after the test, a discharge variation could still be executed.

Although not known at the time of execution, the adjacent area was also identified as having an extensive system of small burrows that were interconnected and penetrated through the top layer into the sand core. (See chapters 6 and 7 in Tsimopoulou and Koelewijn, 2022). These burrows may have had an influence on the experiment but it is unknown whether this was the case, and if so, to what extent.

13.4.2 Video and photo imagery

After each of the blocks, images of the surface have been acquired (examples are shown in Figure 73).

Images during the overflow were made only during blocks B04, B05, B07, B08 and B10.

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Data files

The complete list of blocks for which imagery is available is shown in Table 19.

Table 19 - Overview of imagery data availble per block in B-OF10. The numers refer to file id's.

Block	Surface images	Flow images
0	1195	
1	1197	
2	1199	
3	1201	
4	1203	1202
5	1205	1204
6	1207	
7	1209	1208
8	1211	1210
9	1213	
10	1215	1214
11	1217	

13.4.3 Monitoring timeseries

The statistics of the hydraulic timeseries have been determined on the basis of blocks B01, B02 and B03. Block B02 and B03 are most representative for the test, and can be summarized as follows:

- Total Discharge 544 $l.s^{-1}$ (specific discharge also 544 $l.s^{-1}.m^{-1}$)
- Water height at crest 42,0 cm
- Water height at upper slope 21.8 cm
- Water height at middle slope 16.7 cm
- Water height at lower slope 23.7 cm
- Velocity at upper slope 2.83 m/s
- Velocity at lower slope 3.80 m/s

The details of all timeseries is given in Annex K (separate document).

The last block of the test, B11, was used to perform discharge variations. These could be performed between 80 and 260 $l.s^{-1}$. Due to dismantling of the lower sensors during the slope instability, the _LOWER sensors were not active. The velocity measurements also were unsuccessful. Based on the data, it is possible to derive relationships between the nominal discharge (which corresponds very well to the measured discharge) and the water heights at the CREST, UPPER and MOBILE position.

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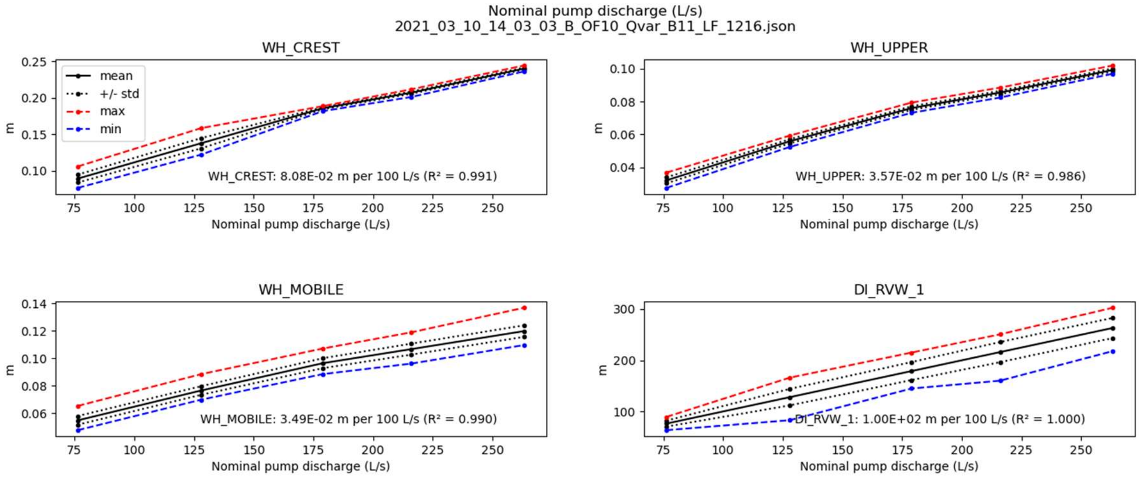

Figure 74 - Relations between timeseries (Water height at CREST, UPPER (= Upper slope) and MOBILE (= middle slope) and measured discharge (DI_RVW_1) in function of nominal discharge (= as per frequency regulator).

Data files

Table 20 - Overview of raw timeseries data file numbers for block B-10. A numbering occurred during this test, leading to the apparant (but not actual) gaps in the data.

Block	Timeseries
1	1196;1997
2	1198;1199
3	1200;1201
4	1202;1203
5	1204;1205
6	1206;1207
7	1208;1209
8	1210;1211
9	1212;1213
10	1214;1215
11	*1216;1217*

13.5 First insights

Based on the observations made during the high discharge test B-OF10, a number of insights are gained:

1. Narrow test sections (1 m wide) may lead to increased susceptibility to erosion, especially under high discharge and is therefore not recommended as setup.
2. Even under high discharge loads, the vegetated cover layer withstands over most of the levee slope.
3. Close to the toe, stronger erosion of soil and vegetation is observed, which may indicate stronger forces impacting at the slope-toe transition. However, the lack of vegetation counts prevents to make a quantitative assessment of this observation.

Later investigation (Tsimopoulou & Koelewijn, 2022) adjacent to this section also indicated the presence of small burrows in this area, that were also in contact with the sand core. An influence of these is not known, but cannot be excluded.

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14 B-OF11 Tree bis

14.1 Goal

The goal of the test was **to evaluate the effect of the presence of a tree at the levee toe (similar to B-OF04)**. The idea behind this was that the presence of the tree object may provoke scour erosion around the tree and destabilize the lower part of the levee slope. Because the B-OF04 test from the preceding test episode – which involved a tree as well – resulted in slope damage unrelated to the presence of the tree, this objective was repeated.

14.2 Setup

The B-OF11 test section is situated on the polder facing slope of a Belgian levee at coordinates 4.238175°E, 51.34167°N (WGS84) or 140900 m easting, 225773 m northing in Lambert'72 coordinates. A vertical profile of the section is shown in Figure 75.

The main anomaly, and simultaneously the test objective of this test, is a large tree situated at the toe of the levee, as shown in Figure 76. Besides the tree, no major or significant anomalies were observed before the start of the experiment.

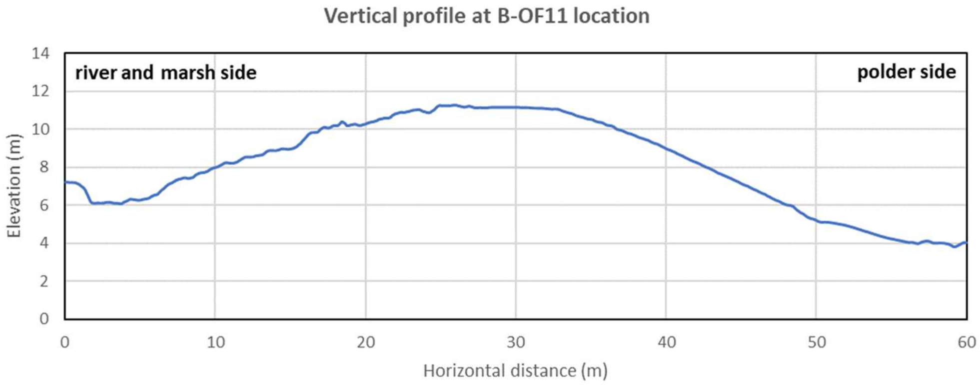

Figure 75 - Vertical profile through B-OF11.

Figure 76 – View on lower part of the B-OF11 section, with tree at the levee toe.

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The general setup of the levee section, follows the normal procedure: a 2 m wide section is bordered by wooden side boardings so that the water flow is directed straight down the levee slope. The overflow generator is situated at the top part of the river side slope, so that an overflowing water column is generated. Along the levee slope, a set of sensors is installed (the positions are illustrated on Figure 77.

The default monitoring setup has been applied and is described in Vercruysse et al. (2022): discharge monitoring, water height monitoring at different locations (levee crest, upper, middle and lower slope) and velocity monitoring (upper, middle and lower slope). Camera frames allow to make images of the surface to assess damage evolution, and movies to visualize current patterns.

Furthermore, Particle Tracking Velocimetry data acquisition has been executed by releasing objects into the overflowing current while filming the current.

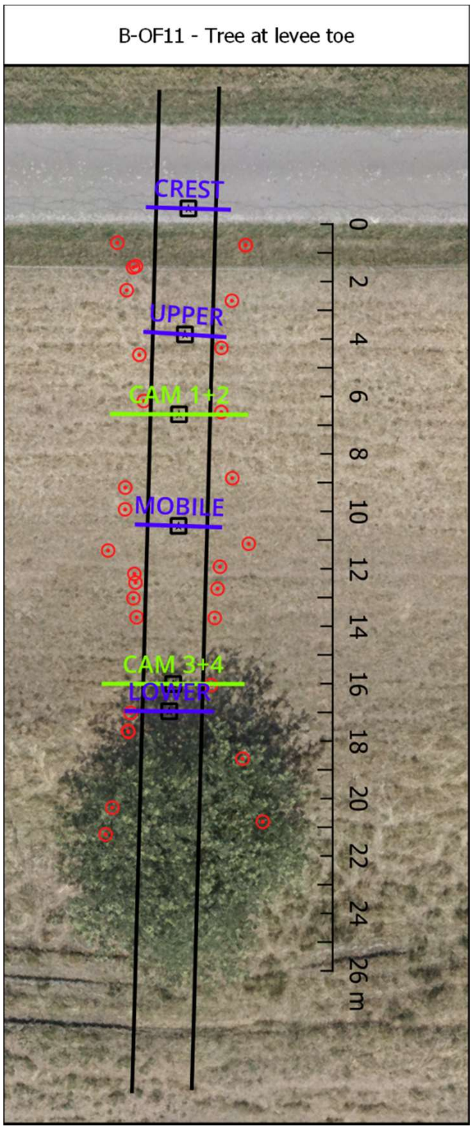

Figure 77 - Sensor locations on B-OF11 test section.

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Prior to the experiment, a 3D laser scan of the B-OF11 test area has been executed.

Figure 78 - 3D Laser Scan of the B-OF11 test section environment.

14.3 Execution

The experiment was performed on 17/02 and 18/02/2021. In total, 11 blocks of overflow have been executed for at total runtime of 13.05 hours.

The discharges applied, varied from 270 $l.s^{-1}$ to 500 $l.s^{-1}$ over a width of 2 m (therefore, the discharge per unit of width is half these values: 135 – 250 $l.s^{-1}.m^{-1}$).

14.4 Results

14.4.1 Visual observations

During the first day (17/02/2022) the experiment started with 2 blocks of 2 hours with a discharge of 270 $l.s^{-1}$ (135 $l.s^{-1}.m^{-1}$). During this time, no special observations were made with regard to erosion on the slope or around the tree, although the vegetation itself appeared to be 'thinning'. After 4 hours of overflow, the discharge was increased to ca. 375 $l.s^{-1}$ (187.5 $l.s^{-1}.m^{-1}$).

At the end of the first day, it was observed that little vegetation was left in the surrounding of the tree, but that the general condition of the levee top layer was still in good shape. At the surface, some near-surface tree roots became visible, which is indicative for some erosion, however it could not be described as a 'scour gully'. A (very small) step-like structure at the levee toe transition did not show any evolution. On the slope itself, the thinning of the grass cover was apparent, with some bold patches appearing. However, the clay-silty soil did not show any important erosion or other artefacts. More importantly, a 5 cm diameter animal burrow was discovered about 4 meter upward from the tree). No outflow of water (nor sediment) on another point was detected so far.

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Figure 79 - Levee toe area after 2 hours of overflow.

During the morning of 18/02/2022, 2 blocks of two hours were performed. Discharge was initially 400 $l.s^{-1}$ but then raised to about 500 $l.s^{-1}$ (200, resp. 250 $l.s^{-1}.m^{-1}$). The erosion at and beyond the levee toe was increasing, less so on the levee slope. The root system of the tree was becoming increasingly exposed. At the end of the second block of the morning, small sand boils outside the test section were observed.

The erosion around the tree was not seen as a real threat or risk. The overflow continued at 500 $l.s^{-1}$. Because of timing constraints (the experiment would have to be ended on this day) and the question whether burrows played a role in the levee slope destabilization, two burrows were dug: one vertical hole inside the levee test section, and one horizontal hole outside the levee section, so that an 'artificial burrow system' was created, because the two drillholes made contact. During the subsequent overflow block, it was observed how water flushed through the connected pipes, however not transporting any sediment. (It was thought that the length of the burrow under the cover layer was too short to significantly entrain sediments). After 30 minutes, the burrows were drilled a bit deeper, up to 70 cm and an additional hole from outside the section was drilled.

Figure 80 - Drilling a hole 70 cm deep, 40 cm from the "right bank" of the channel.

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During the subsequent block of 30' the same pattern of water outflow was observed without any significant sediment entrainment being noticed. However, at the toe of the levee, a sand patch was visible, indicating that sand had migrated from underneath the cover layer through a different pathway than the one we had artificially created. The exit point was located at the transition from levee slope to levee toe. Simultaneously, a depression of the surface was observed, indicating that the cover layer was collapsing (undermining), or at least not longer supported. Also, a crack of about 15 cm was observed, which indicated imminent collapse.

Figure 81 - Sand patch at the toe area, moments before the collapse of the levee.

The experiment was continued for another two minutes (still at a discharge of 500 $l.s^{-1}$ (250 $l.s^{-1}.m^{-1}$) before the cover layer collapsed and gave rise to a large slope failure.

The tree itself was still standing, although soil had eroded around it. The root system appeared to be strong enough to keep the tree structure in place.

After the experiment, it was discussed that the artificial burrow may have strengthened the inflow of water into the levee core (note that a natural burrow entrance had been found during day 1 of the test). The outflow through the artificial burrow did not displace sand, but the increased pressure may have accelerated the outflow of water and sand at the levee toe exit point that was observed just before the failure. In that sense, the artificial burrow may have accelerated the failure process, but probably not caused it by itself.

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Figure 82 - presumed exit point of the send, at the levee slope base (red arrow).

Figure 83 - Aftermath of the slope failure, with standing tree.

Figure 84 - Sand layer (up to 10 cm high) downstream the levee slope after the failure and after removal of the side boarding.

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Figure 85 - Aftermath of the slope failure.

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14.4.2 Video and photo imagery

A suite of pictures illustrates the progressive erosion of soil around the tree, exposing its root system.

Figure 86 - Soil erosion around the tree, after 0.5, 1 and 1.5 days.

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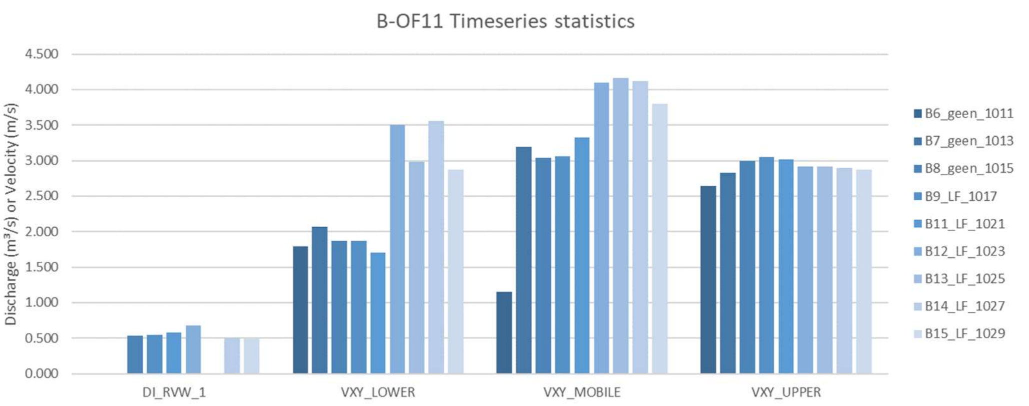
14.4.3 Monitoring timeseries

The discharge measurement is missing in a number of tests. A large number of tests have however been executed at a nominal discharge of approx. 500 $l.s^{-1}$(which is a specific discharge of 250 $l.s^{-1}.m^{-1}$). For these tests, the typical hydraulic conditions were:

- Discharge 554.0 $l.s^{-1}$(over a width of 2 m, so 178 $l.s^{-1}.m^{-1}$)
- Water height CREST 26.4 cm*
- Water height UPPER SLOPE 7.5 cm
- Water height MID SLOPE (MOBILE) 11.3 cm
- Water height LOWER SLOPE 16.8 cm
- Velocity UPPER SLOPE 2.90 m/s**
- Velocity MID SLOPE 3.33 m/s
- Velocity LOWER SLOPE 2.47 m/s

* Note that manual water height measurements on the crest have been performed and are significantly lower. It is likely that there are variations of the water height along the crest part of the test.

** There velocity measurements show (very) strong variations and care should be taken when using this data as it may be less reliable. Especially VXY_MOBILE and VXY_LOWER show strong variation in velocities reported per block. There is no clear explanation for this observation.



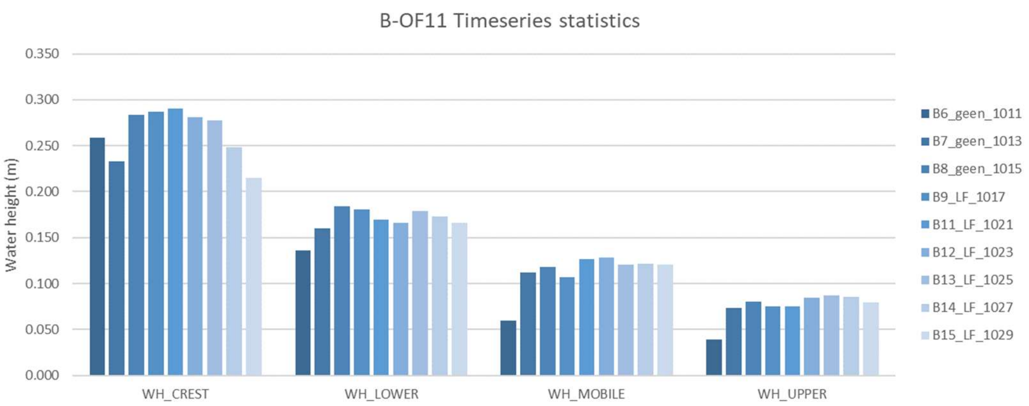


Figure 87 - Mean hydraulic parameters per test block.

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Data files

Table 21 - Overview of raw timeseries data file numbers for block B-11. A numbering occurred during this test, leading to the apparant (but not actual) gaps in the data.

Block	Timeseries	Block	Timeseries
0		*11*	1021
1		*12*	1023
2		13	1025
3		14	1027
4		15	1029
5	1009		
6	1011		
7	1013		
8	1015		
9	1017		
10	1019		

14.4.4 2D Line Lidar

In order to assess the water height at different positions, a 2D LiDAR scanner (Figure 89) has been used to measure the water level along the profile. The results of this are used and discussed in the validation part of the overflow generator design and application report (Vercruysse et al.,2022).

Figure 88 - Overhead cameras and 2D Line scanner mounted on the lower portal.

Figure 89 is an illustration of the actual levee slope and water profiles at different discharge conditions. It must be noted that there are uncertainties concerning the actual significance of the reflected surface.

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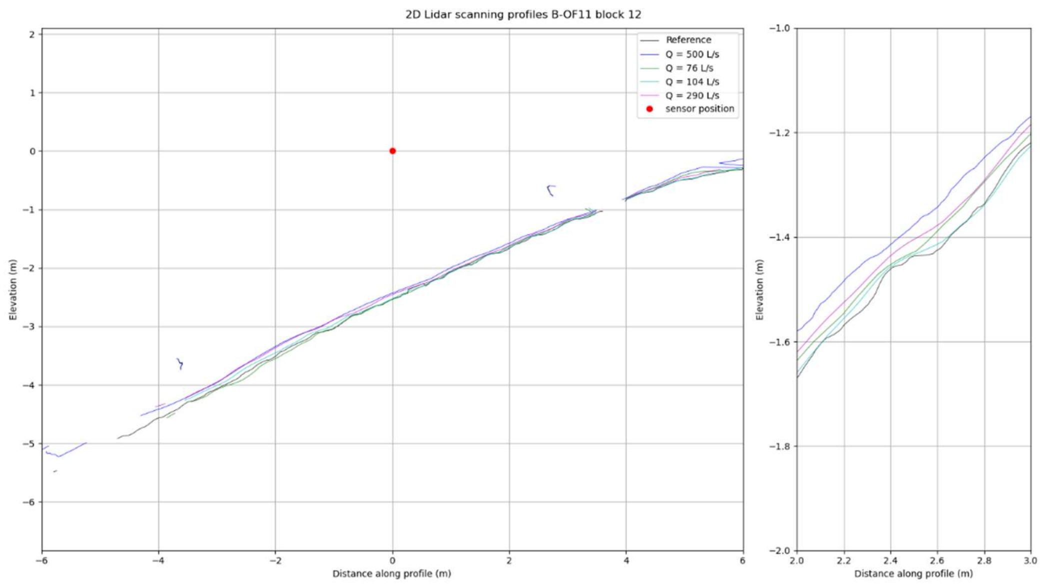

Figure 89 - 2D LiDAR scan of the ground and water surface at different discharge conditions.

14.5 First insights

Based on the test results, first insights and conclusions can be formulated. Further integration of test results are discussed in a summary report (Depreiter et al., in prep) and other future analysis reports.

- The presence of a tree at the levee toe, does create a small amount of erosion around the tree and exposure of the upper part of the root system
- The forementioned erosion does, however, not lead to destabilization or collapse of the tree or the surrounding areas , (no imminent danger)
- Besides hampering visual inspection of the levee cover, trees and scrub vegetation can enhance animal activity (burrows by rodents, tracks/cliff by sheep) which contributes to potential weak spots
- In this test, other anomalies (burrows, but also artificial burrowing) led to internal erosion of the levee core, which ended up in destabilization of the levee cover, and important slope failure.

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