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

Overflow tests on Dutch levees

Foto: Vilda-Yves Adams

Adaptation to climate change

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Overflow tests on Dutch 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 flood 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.

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1 Introduction

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

Within the Polder2C's project, 27 overflow tests on 11 Belgian and 11 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	Reference
-	B-OF02 Short Grass + Artif. Anom	Alternative vegetation + Slope anomaly
-	B-OF03 High Discharge	High Discharge
-	B-OF04 Tree	Tree
-	B-OF05 Erosion 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 Reference	Reference
-	B-OF09 High Discharge	High Discharge
-	B-OF10 High Discharge	High Discharge
-	B-OF11 Tree	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	Damage repair
-	N-OF05C RTM	RTM
-	N-OF06 RTM	RTM
-	N-OF07 RTM	RTM
-	N-OF08 Grass sods	RTM
-	N-OF09 Burrow protection	Burrow protection
-	N-OF10 Reed vegetation	Alternative vegetation
-	N-OF11 Reed vegetation	Alternative vegetation

Herein, the tests performed on the Dutch part of the levee are reported (dotted box above).

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2 Test overview

2.1 Situation

On the Dutch part of the levee in Hedwige-Prosper polder, 11 overflow tests have been conducted. The location of these 11 tests is depicted below (Figure 1) and the coordinates of the crest location shown in

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Table 1. All tests have been conducted in the direction of the polder (i.e. southwestward). 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 Dutch part of the HPP Living Lab. The background image (PDOK aerial photo) is from 2021 (showing the sites with reinforced turf mats).

In general, the levee has an absolute crest elevation of ca. 11.8 to 12 m (Belgian TAW reference) and a toe elevation on the polder side of +/- 4 m. The marsh in front of the levee on the river side is higher (5 to 6 m). The crest is typically 10 m wide and has a landward side slope of 10/4 or ca. 21-22°. At the far end of the toe, a ditch is present.

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Table 1 - Overflow test coordinates of crest position.

Test ID	X (m L72)[1]	Y (m L72)[1]	Lon (°E WGS84)	Lon (°N WGS84)
N-OF01	140265.3	226526.2	4.22904	51.34843
N-OF02	140306.4	226474.1	4.22963	51.34796
N-OF03	140313.0	226465.6	4.22973	51.34789
N-OF04	140431.5	226316.5	4.23143	51.34655
N-OF05(+B/C)	140257.8	226535.6	4.22893	51.34852
N-OF06	140262.0	226530.5	4.22899	51.34847
N-OF07	140275.0	226513.9	4.22918	51.34832
N-OF08	140285.8	226500.3	4.22934	51.34820
N-OF09	140295.8	226487.5	4.22948	51.34808
N-OF010	140454.1	226288.3	4.23176	51.34630
N-OF011	140451.4	226291.7	4.23172	51.34633

Figure 2 - View on a test setup consisting of side boarding, camera portals and other equipment.

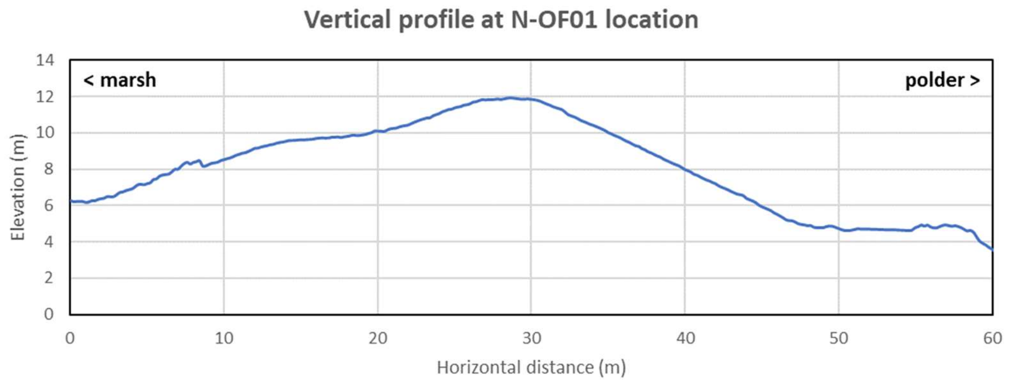

Figure 3 - Elevation profile over the levee at test site B-OF01.

2.2 Test series goals

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

N-OF01 Reference 160: The first test conducted on a 'test section with a good visual condition' on a Dutch levee, serves as a first reference section.

N-OF02 Reference / clay erosion: The test started out as a normal overflow test. On the last day, an artificial anomaly was created for a clay erosion test.

N-OF03 Reference ~300: A reference test during which additional hydraulic measurements were conducted. An artificial burrow was made at the end of the test.

N-OF04 Reference: A reference test during which additional hydraulic measurements were conducted. Small burrows were also detected.

N-OF05 Burrow: A large animal burrow entrance was present mid-slope of the section. The impact of overflow on such a large anomaly was tested.

[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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N-OF05 B+C Damage repair (clay infill (B) and RTM (C)): The overflow test on N-OF05 led to significant damage, which was repaired with a clay infill covered with a reinforced turf mat and retested at a later moment.

N-OF06 RTM: A test section from which the vegetation cover was removed and protected by a reinforced turf mat (i.e. a type of geogrid with vegetation growing *through*). The section was then tested with overflow.

N-OF07 RTM: A test section from which the vegetation cover was removed and protected by a reinforced turf mat (i.e. a type of geogrid with vegetation growing *through*). The section was then tested with overflow.

N-OF08 RTM: A test section from which the vegetation cover was removed and protected by a reinforced turf mat (i.e. a replaced grass turf from a different location). Detailed results are discussed outside this report because this section served as a test site for a PhD research (Van den hoven, 2022).

N-OF09 Burrow protection test: A test section on which a mole burrow system was discovered, was tested with a protection measure applied (covering plates), whilst performing ERT measurements.

N-OF10 Reed (vegetation anomaly): A wet and soft area (the cause of this is debated) on the levee slope near the landward toe gave rise to a reed overgrowth because the patch could not be mowed. The impact on levee strength is tested through overflow.

N-OF11 Reed (vegetation anomaly):: A replicate of test N-OF10.

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, 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.

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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, the 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 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:

[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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- 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 Test conditions summary

The general test conditions of all tests performed on Dutch levees are summarized in Table 2. The *discharge range* is the minimum resp. maximum average applied during a test block. If no discharge measurement is available, a nominal discharge is shown in brackets. A *block* refers to a period of typically 1 or 2 hours during which overflow is occurring. In between blocks, a pause is present to assess damage, make photographs, etc. The total duration refers to the accumulated overflow duration.

Table 2 - Test conditions

Test	Date	Specific discharge ($l.s^{-1}.m^{-1}$)	# blocks	Total duration
N-OF01	24-27/11/2020	175	29	30h30
N-OF02	1-3/12/2021	550	12	10h30
N-OF03	6-8/12/2021	330	11	14h30
N-OF04	15-20/12/2021	330	18	25h00
N-OF05 + B/C	23/11/2020 (B: 17/11/2021; C: 17+18/11/2021)	90 (375 and 150 for 5B and 5C)	10 (B: 4; C: 7)	1h19 (B: 1h15, C: 4h30),
N-OF06	22/11/2021	100	2	2h00
N-OF07	23/11/2021	200	1	0h30
N-OF08	24/11/2021	200	8	2h00
N-OF09	25-30/11/2021	500	11	10h00
N-OF10	13/12/2021	200	1	1h00
N-OF11	13/12/2021	200	1	0h31

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 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).

2.5 Available data

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

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

A: Field sketches of damage made during test breaks.

B: Vegetation counts in small patches.

2.6 General levee properties

Granulometric analysis performed by Flanders Hydraulics Research on samples from the top soil layer near N-OF01 indicate a silty grain size of the top layer (71.4% silt, 8.4% clay, 18.4% fine sand, 1.8% medium sand). A Jet Erosion Test sample of the top soil (jet test sample VI-E6) showed a multilinear behaviour, with an initial critical stress of 97 Pa (Kd = 1.1 cm^3/Ns) followed by a higher critical stress of 130 Pa (Kd = 57 cm^3/Ns). More information on the JET tests can be found in Davion, et al., 2021.

Electrical Resistivity Tomography (ERT) and other geophysical surveys have been executed in order to image the subsurface structure. The data of these surveys is available in separate reports (CEREMA, in preparation; Fugro, 2019). The Fugro ERT data shows a thin top layer with medium resistivity covering a (sand) core with high resistivity, above the low resistivity substratum. The CEREMA data has a cross-profile (id: TRE23S6NORD) about 15 m northwards, and a long profile over the levee crest corresponding to the profile of the Fugro 2019 survey (Profile id in CEREMA report: TREL2S6NORD).

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

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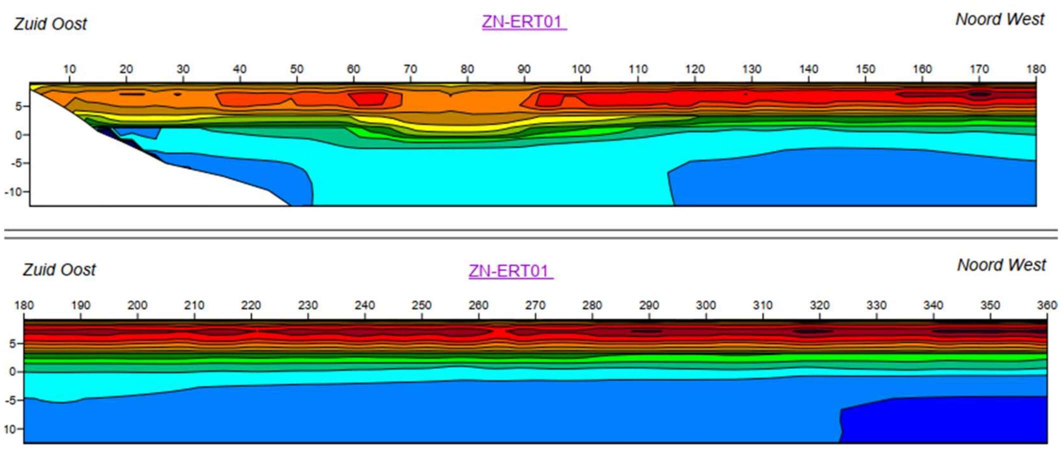

Figure 4: Extract of the Fugro 2019 ERT survey in HPP sector VI illustrating the layered structure of the subsurface. Blue colors indicate low resistivity; red colors high resistivity. See Fugro (2019 for more information).

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 tests and investigation within Work Package 1 of the Polder2C's project, are given in the reference list.

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3 N-OF01 Reference 160

3.1 Goal

The main goal of the N-OF01 Reference test, was to set a reference case for the Dutch style levee in the Hedwige-Prosper Polder. This test was therefore conducted on a section without visual anomalies and subject to the normal Dutch style maintenance method. On the practical side, adaptations to the setup for the test were required due to small differences in levee geometry between the Dutch and the Belgian levees in the area.

3.2 Test setup

The N-OF01 Reference test has been executed on the landward side of a Dutch levee in the Hedwige-Prosper Polder (Belgian Lambert coordinates: X=140265.3 m; Y = 226526.2 m or WGS84: 4°22904E, 51°34843N). The elevation of the crest is 11.9 m TAW[4] or 9.55 m NAP, while the landward toe is situated at +/- 4.5 m TAW. The slope angle is 22° halfway the levee slope (which equals to a "10/4 slope"). The vertical profile over the levee section is shown in Figure 5. At the far end of the toe, a gully is present. Note that the marsh elevation is higher than the polder elevation.

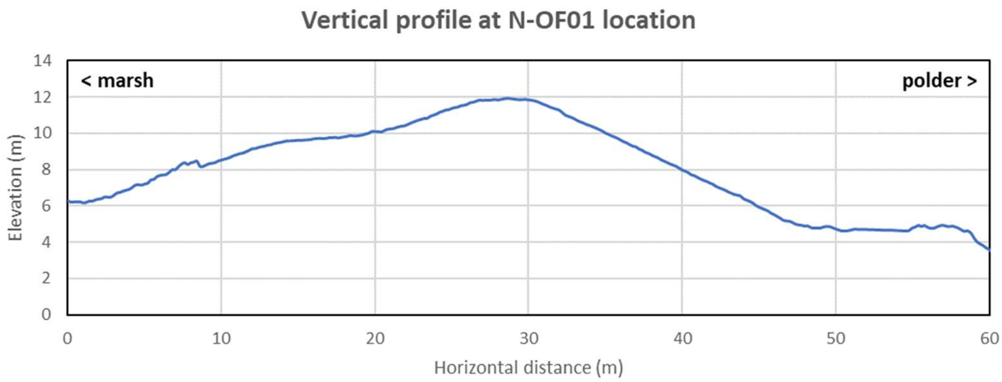

Figure 5 - Topographical profile at the N-OF01 test location.

The test section is 2 m wide, sided by wooden boarding, and the surface is considered to be in a good condition without any visible anomalies (such as burrows, objects or other damage) on the slope. At the toe, there are some crane track marks (visible in Figure 6), but its influence on the overflow process – especially on the slope – was deemed negligible.

The vegetation state is considered in a good state, with grass lengths of ca. 10 to 20 cm and the result of normal Dutch maintenance methods. A detailed vegetation survey has been performed on Belgian and Dutch levee stretches, reported in Vandevoorde & Lierop (2022). Granulometry analysis indicates a silty top layer, which is typically 80 cm thick. The sand core below the top layer consists of medium sand. An asphalt road is present at the toe of the levee.

The monitoring setup has been applied and is described (and validated) in Vercruysse et al. (2022). The monitoring setup includes discharge monitoring, water height monitoring at different locations (levee crest, upper, middle and lower slope) and velocity monitoring (upper,

[4] *TAW = "Tweede Algemene Waterpassing", the Belgian vertical reference. The reference plane is situated 2.35 m lower than the Dutch reference plane ('NAP' = 'Normaal Amsterdams Peil').*

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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.

Due to a GPS survey data loss (hardware malfunction), there is no exact map of sensor positions. However, the default setup is applicable (Figure 6; Vercruysse et al, 2022).

Figure 6 - View on test section N-OF01 (25/11/2020 08:41).

The pump employed to generate the discharge was a twin parallel Hidrostal F10K-HD submerged pump system. The theoretical capacity of a single F10K-HD is 970 m³/h or 270 l/s. Taking into account head differences of more than 10 m and conduit length, the practical maximum discharge appeared not to surpass +/- 1500 m³/h or 416 l/s, and effectively average and maintained discharges peaked around 350 l/s.Execution

The overflow test is performed in blocks: these are periods during which the overflow takes place continuously. Blocks are separated by breaks of 10 to 20 minutes to record and assess the state of the levee, perform adaptations to the setup, etc.

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In total, 29 blocks of overflow have been executed (note that numbering runs through 30, because block number 28 being skipped), on 24 and 25/11/2021 for a total duration of 30.5 hours (Table 3).

Table 3 - Execution summary

Date	# Blocks	Runtime	Specific discharge	Remarks
24/11/2020	2	2h	~ 160 $l.s^{-1}.m^{-1}$	/
25/11/2020	8	8h 10'	~ 160 $l.s^{-1}.m^{-1}$	/
26/11/2020	9	8h	~ 160 $l.s^{-1}.m^{-1}$	Logbook missing.
27/11/2020	7	8h	~ 160 $l.s^{-1}.m^{-1}$	Logbook missing.
28/11/2020	3	4h 20'	~ 160 $l.s^{-1}.m^{-1}$	Logbook missing.
total	29	30h 30'	~ 160 $l.s^{-1}.m^{-1}$	Logbook missing.

Due to the failure of the RTK GPS measurement, the coordinates of the reference points are not known. Therefore it is not possible to process the images and consequently to process the PTV measurements.

3.3 Test results

3.3.1 Visual observations

The start on November 24, 2020 in the afternoon, was followed by 5 days of testing with a nominal pump discharge of ca. 320 to 350 l/s (or 160 - 175 $Ls^{-1}.m^{-1}$). Here, a river water level of +/- 15 to 20 cm (there is some variation over the crest due to irregularity of the profile) above the crest was imitated.

During the more than 30 hours of overflow, no noteworthy damage occurred. During the test, it was observed that soil eroded slowly and exposed grass roots, without creation of any significant damage that would lead to imminent failure of the levee slope. Near the levee toe edge, a drainage layer became exposed and some of the gravel that was part of that drainage layer, got washed away (visible on Figure 6). However, this did not lead to any critical damage. As already indicated above, the levee toe was not in a 'pristine' state due to crane and truck tracks.

3.3.2 Video and photo imagery

Surface state

Levee slope surface images have been recorded during breaks in between overflow blocks in order to visualize the surface state evolution. Examples are shown on the following pages (Figure 7, Figure 8).

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T0 state on 24/11/2020 (14:00) T24 state on 27/11/2020 (16:15)

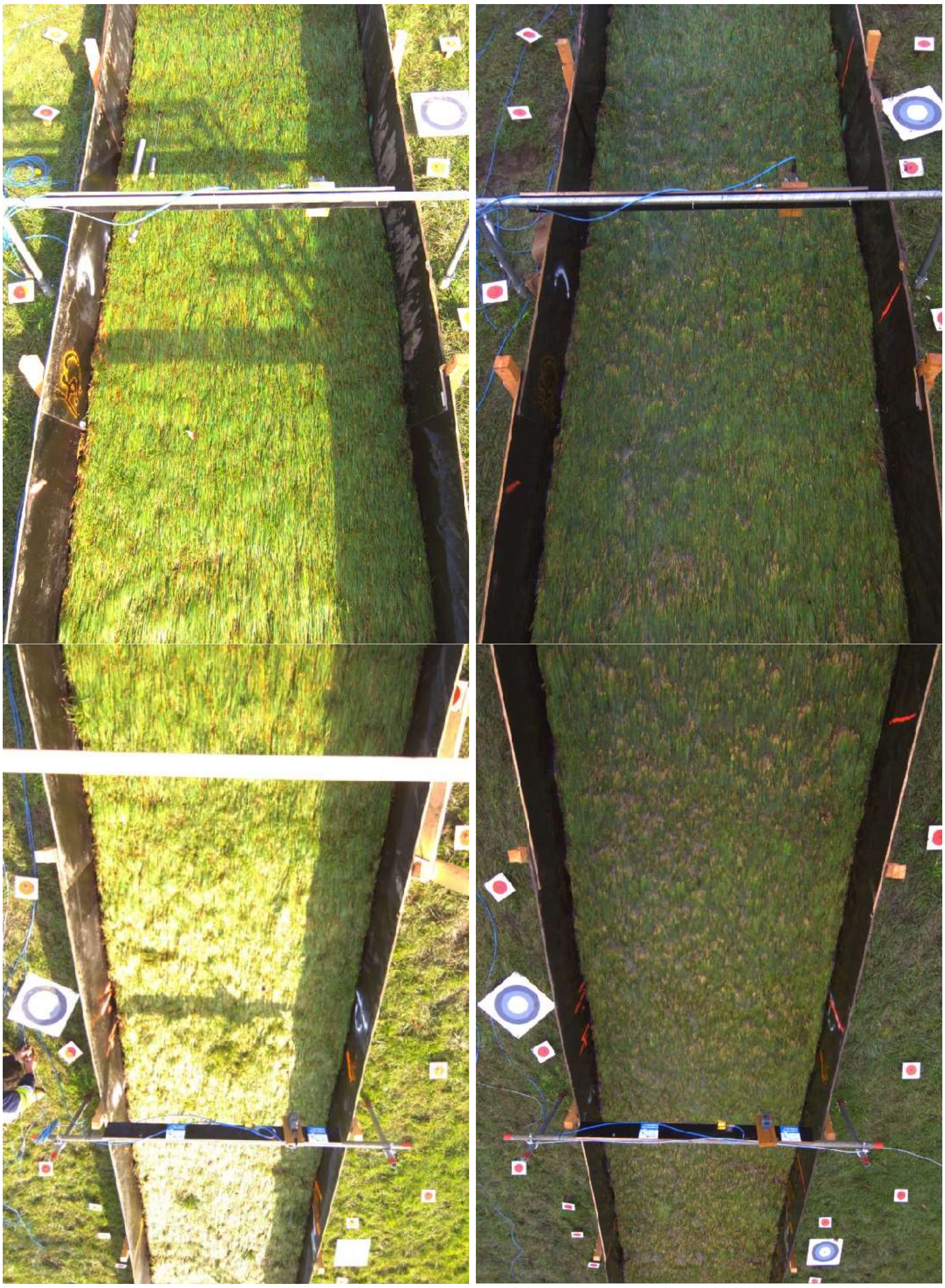

Figure 7 – Images from the upper portal at N-OF01 block B0 and block B24.

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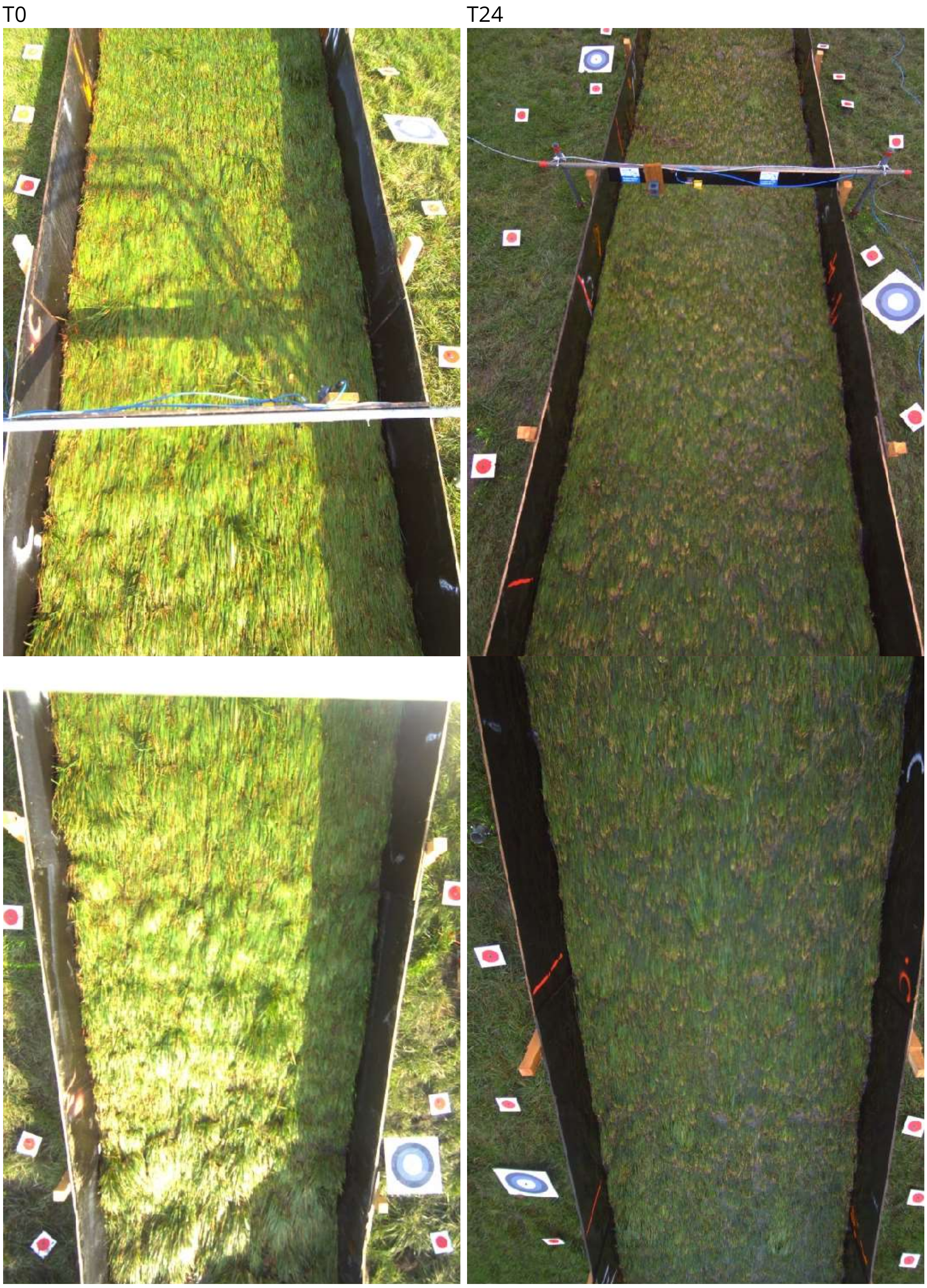

Figure 8 – Images from the lower portal at N-OF01 block B0 and block B24.

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Overflow surface current patterns

During the overflow, images have been created at different intervals to image the surface current. The images below give an impression of the aeration of the flow in the test section.

B15 flow surface (26/11/2020)   ^ CREST

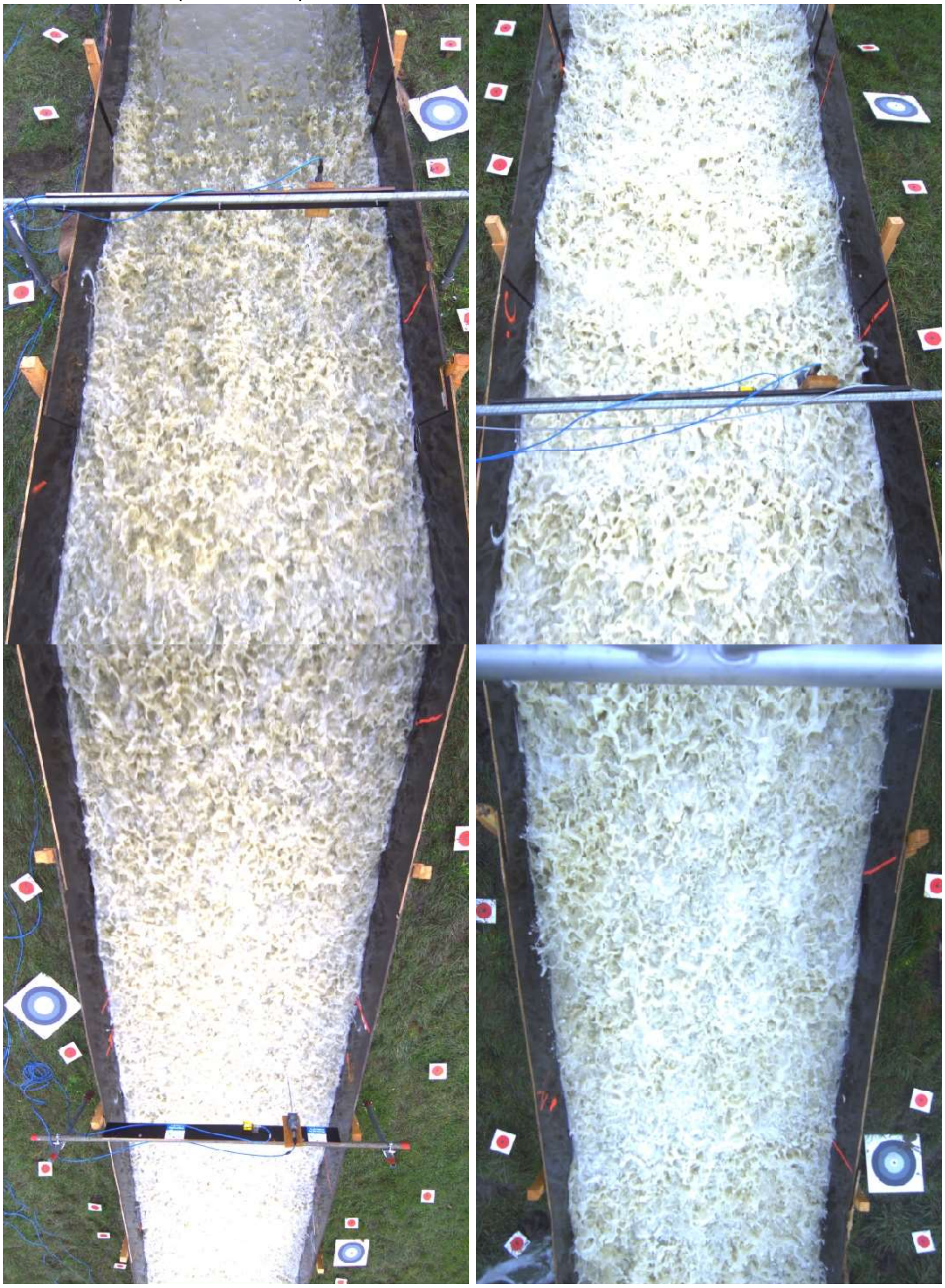

Figure 9 – Images during overflow section N-OF01 block B15. (left upper portal , right lower portal)

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PTV images

During block B2, B4, B5, B7 and B8, objects (tennis balls, pingpong balls) have been released at the crest. During these events, the camera acquisition was performed at high rate so that the object could be tracked. During block B8, PTV was performed at very low discharge (nominal discharge of 80 $l.s^{-1}$). This information could be used for surface velocity determination. Due to the lack of GPS position of the geo-referencing markers, the data has not been processed or analyzed.

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 N-OF01. The numers refer to file id's.

Block	Surface images	Flow images
0	175, 175v2 (T0, before flow)	
1	177	176
2	187	186
3	189-194 (test images)	188
4	203	195
5	214	204
6	216	215
7	226	217, 225
8	235	227, 234
9		236
10	239	238
11	241	240
12	243	242
13	245	244
14	247	246
15	249	248
16	251	250
17	253	252
18	255	254
19	257	256
20	259	258 (2x)
21		260
22	263	262
23		264
24	267	266
25		268
26		270
27 + 28		272 (2x)
29		274
30		275

3.3.3 Timeseries

During most of the N-OF01 overflow test, an average measured discharge of 330 $l.s^{-1}$ (specific discharge of 165 $l.s^{-1}.m^{-1}$) has been applied.

Figure 10 shows the average discharge and water heights for the blocks 1 to 30. For the first day of testing, some of the blocks were interrupted to perform PTV measurements (Blocks 2, 4, 5, 7 and 8). There, the timeseries are spread over multiple files. Only the main part of the file has been used to calculate the statistics.

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No discharge measurements are available for Block 0 and 1. For the WH_LOWER sensor, several blocks at the end of the test (Block 22 and afterwards) have no data.

The average observed water heights observed are:

- WH_CREST 13.2 cm
- WH_UPPER 8.1 cm
- WH_MOBILE 8.2 cm
- WH_LOWER 10.2 cm

Figure 10 - Water height and discharge timeseries statistics of the main overflow blocks.

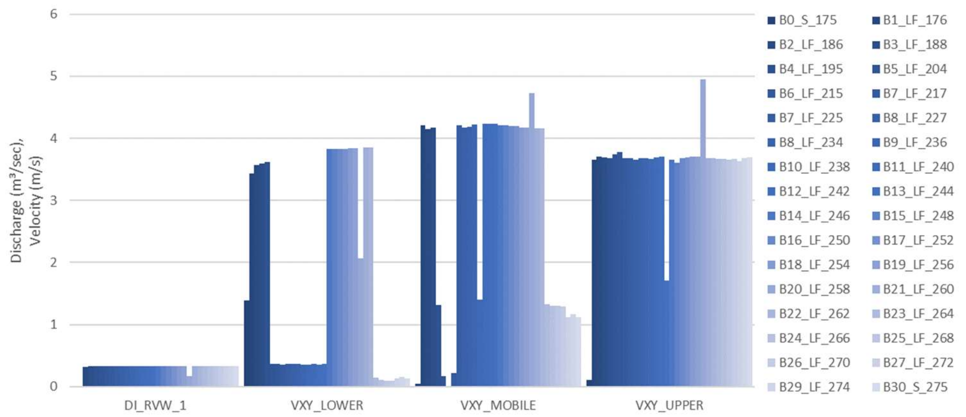

Figure 11 - Velocity and discharge timeseries statistics of the main overflow blocks.

Figure 11 shows the mean velocities (and discharge) of the 3 different sensors. As can be seen from the graphs, the mean velocities display a wide spread, which indicates that part of the measurements are unreliable. The validation of the monitoring setup (Vercruysse et al., 2022) indicated that the mobile and lower velocity measurements are considered unreliable, whereas for the upper slope position the data is more reliable because of the lesser aeration of the flow. Based on the information in Annex A of the Annex document (with the details of each block), an overall average can be determined:

- VXY_UPPER 3.76 m/s (on the basis of blocks 1-12, 14-27, 29, 30)
- VXY_MOBILE 4.11 m/s (not reliable; on the basis of blocks 1-4, 7-9, 11-22)
- VXY_LOWER 3.77 m/s (not reliable; on the basis of blocks 1, 3, 4, 14-22)

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Data files

The list of raw data files is shown below. Annex A of the annex document contains the processed data file details and plots. The full data file name format are explained in the introduction; here the identifying part is shown.

Table 5 - Overview of raw timeseries data files.

Block	Normal acquisition	Separate file during PTV
1	S_175 (B0); LF_176	
2	LF_186	PTV_178 -> PTV_185
3	LF_188	
4	LF_195	PTV_196 -> PTV_201
5	LF_204	PTV_205 -> PTV_213
6	LF_215	
7	LF_217, LF_225	PTV_218 -> PTV_224
8	LF_234	PTV_228 -> LF_233
9	LF_236	
10	LF_238	
11	LF_240	
12	LF_242	
13	LF_244	
14	LF_246	
15	LF_248	
16	LF_250	
17	LF_252	
18	LF_254	
19	LF_256	
20	LF_258 (2x)	
21	LF_260	
22	LF_262	
23	LF_264	
24	LF_266	
25	LF_268	
26	LF_270 (2x)	
27	LF_272	
28	-	
29	LF_274	
30	S_275	

3.4 First insights

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

- A well maintained, Dutch levee that is in a visually good condition without any significant anomalies (e.g. burrows) is able to withstand an overflow of ca. 330 $l.s^{-1}$ (or a specific discharge of 165 $l.s^{-1}.m^{-1}$) for at least 30.5 hours. Some erosion of soil and exposure of vegetation root systems occur, but this does not lead to significant or critical damage.

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4 N-OF02 Clay Erosion

4.1 Goal

Research is being conducted to relate the outcome of large-scale erosion tests such as the overflow tests, to small-scale tests. Jet erosion tests, for example, and that are part of the survey conducted prior to the overflow tests, are giving insight in the small-scale erosion process. In order to obtain data to relate both types of tests, Rijkswaterstaat (M. Vandamme) performed clay erosion measurements in a step-shaped anomaly created near the levee toe.

The experiment started off as a "standard" section; the erosion test was performed on the last day of the experiment. The results of this test are reported in a separate document that discusses clay erosion in more detail (van Damme et al., 2022).

4.2 Setup

The N-OF02 Clay Erosion overflow test has been executed on the landward side of a Dutch levee in the Hedwige-Prosper Polder (X = 140306.5 m, Y = 226474.1 m, or 4.22963°E, 51.34796°N). The elevation of the crest is 12.1 m TAW (= 9.75 m NAP) while the landward toe is situated at 4 to 4.5 m TAW. The slope angle is 21.5° halfway the levee slope. At the far end of the toe, a gully is present which was used for recirculation of water.

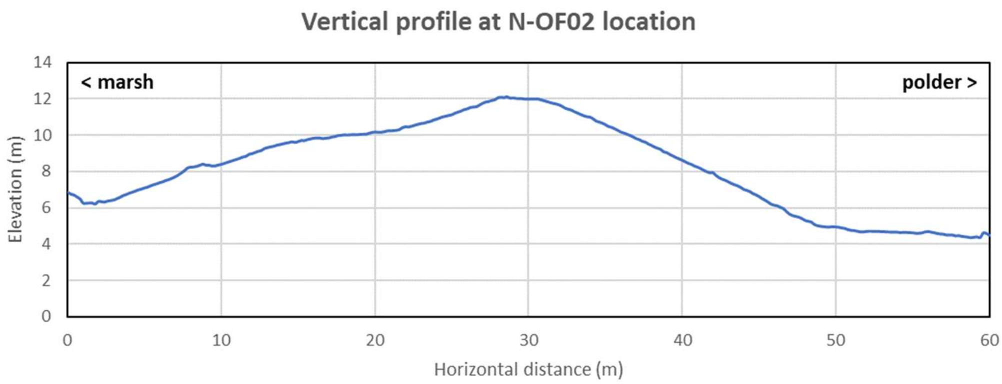

Figure 12 - Vertical profile of the B-OF02 overflow test section.

The test section is 2 m wide, sided by wooden boarding, and the surface is considered to be in a good condition without any visible anomalies (such as burrows, objects or other damage) on the slope. At the toe, there are some crane track marks, but the distance to the slope is sufficient to expect no influence from this. The vegetation state is considered in a state after normal maintenance, with grass lengths of ca. 10 to 20 cm and subject to normal Dutch maintenance methods. Note that the grass may have suffered from the extended dry period from April to September '20. A detailed vegetation survey has been performed on Belgian and Dutch levee stretches, reported in Vandevoorde & Lierop (2022). Granulometry analysis indicates a silty top layer, which is typically 80 cm thick. The sand core below the top layer consists of medium sand. An asphalt road is present at the toe of the levee.

The monitoring setup has been applied and is described (and validated) in Vercruysse et al. (2022). The monitoring setup includes 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

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damage evolution, and movies to visualize current patterns. Drawings of the damage have been made, as well as regular photographs by the test operators.

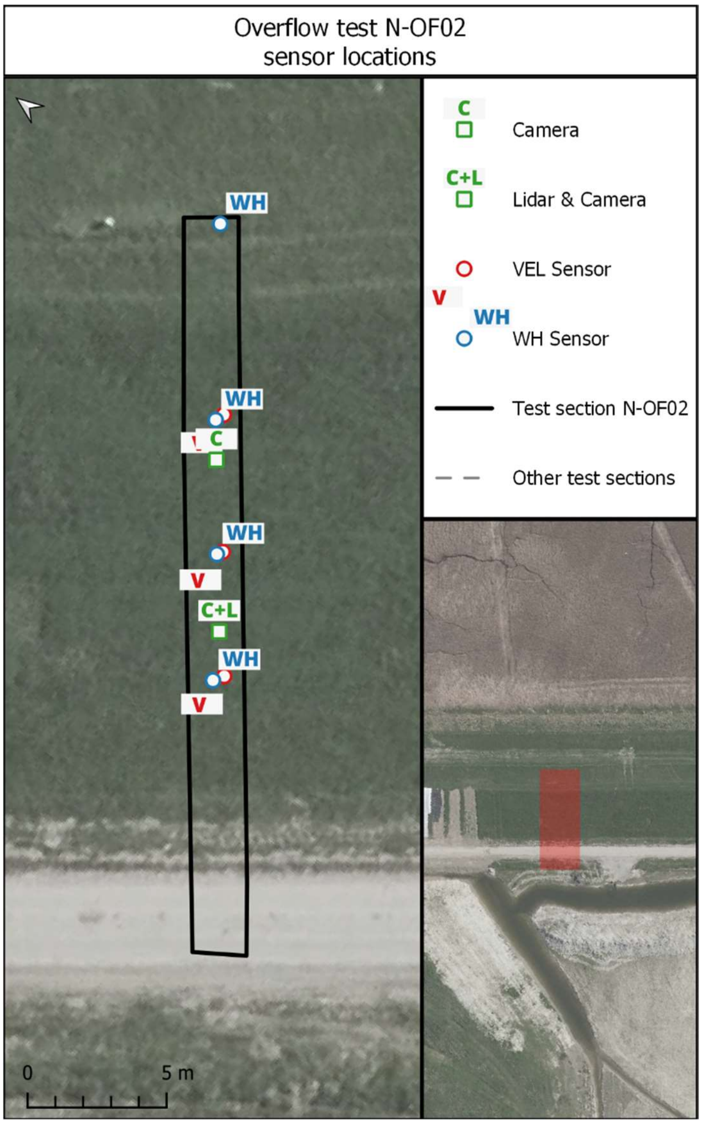

Figure 13 - Sensor location on N-OF02.

Table 6 - Sensor coordinates (Lambert '72) on N-OF02.

Sensor	X	Y
WH_CREST	140306.75	226474.21
WH_UPPER	140301.06	226470.06
WH_MOBILE	140297.27	226467.09
WH_LOWER	140293.59	226464.45
VEL_UPPER	140301.39	226469.94
VEL_MOBILE	140297.46	226466.97
VEL_LOWER	140293.95	226464.22
CAM_UPPER	140299.94	226469.17
CAM_LOWER	140295.12	226465.33

The overflow was generated by the setup provided by Waterschap Brabantse Delta, using two pumps (BA300 and BA500) which allow to vary discharge, and reach discharges till approx.

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1100 $l.s^{-1}$ when both pumps ran simultaneously. The discharge was regulated by adjusting the pump's RPM's and direct discharge measurement was not always successful.

The setup of the clay erosion measurement is discussed in van Damme et al. (2022). The step created was early morning of 3/12/2021 and is about 15 to 20 cm high. During the breaks, the erosion in the step was measured.

Figure 14 - Setup and execution of the clay erosion experiment. Red arrow: lidar scanner.

Additionally, 2D LiDAR profiles were captured using a Sick LMS 511 LiDAR scanner (visible on the lower camera portal, red arrow, in the figure above, further details and a validation described in Vercruysse et al. (2022)). The lidar records a line profile in the longitudinal direction of the test section. Records have been made at different time intervals (13x in total, with and without streaming water).

4.3 Execution

The N-OF02 experiment has been executed on 1-3/12/2021 and consisted of 11 blocks of overflow for a total duration of 10 hours and 35 minutes. The erosion experiment was conducted during block B9, 10 and 11 for a total duration of 3.5 hours. Short breaks were held to measure the erosion (every 5 to 15 minutes). Discharges were varied as well. The details are listed in Table 7 and in the timeseries annex B (separate document).

Table 7 - Execution summary

Date	**Blocks**	**Runtime**	**Specific discharge**	**Remarks**
1/12/2021	3	3h	~ 40 - 160 $l.s^{-1}.m^{-1}$	
2/12/2021	5	5h	~ 160 $l.s^{-1}.m^{-1}$	Logbook failure.
3/12/2021	3	3h 34'	40 – 560 $l.s^{-1}.m^{-1}$	Frequent stops to measure erosion. See van Damme et al., 2022.

4.4 Results

4.4.1 Visual observations

During the first two days of overflow, no visual observations are different than what could be expected in comparison to the N-OF01 reference: slight soil erosion and exposure of vegetation roots.

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The observations made with regard to the erosion experiment are detailed in van Damme et al. 2022.

4.4.2 Video and photo imagery

Surface state

Levee slope surface images have been recorded during breaks in between overflow blocks in order to visualize the surface state evolution. The original data has been acquired at different lighting conditions and therefore has been recorded with different exposure settings. As part of the preprocessing, under- or overexposed images have been removed. For each picture, duplicates or triplicates were made. For the sake of data reduction, only one file has been retained during processing. Examples are shown in Figure 15 and Figure 16.

Surface flow

Similar to the surface pictures, images have been made of the overflowing water. A general remark for all the tests executed with the pumping installation of Waterschap Brabantse Delta (that fed water into the overflow generator from the top, compared to through a dissipation box in the base), is that the outflow of the generator is aerated and contains high velocity cores.

Data

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

Table 8 - Overview of imagery data availble per block in N-OF01. The numers refer to file id's.

Block	Surface images	Flow images
0	1291	1291
1	1293 (2x), 1294	1292
2	1296	1295
3	1298 (2x), 1299	1297
4	1302	1300
5	1304	1301
6	1306	1303
7	1308	1305
8	1310, 1311, 1312, 1313	1307
9	1315	1314
10	1317	1316
11	1319	1318

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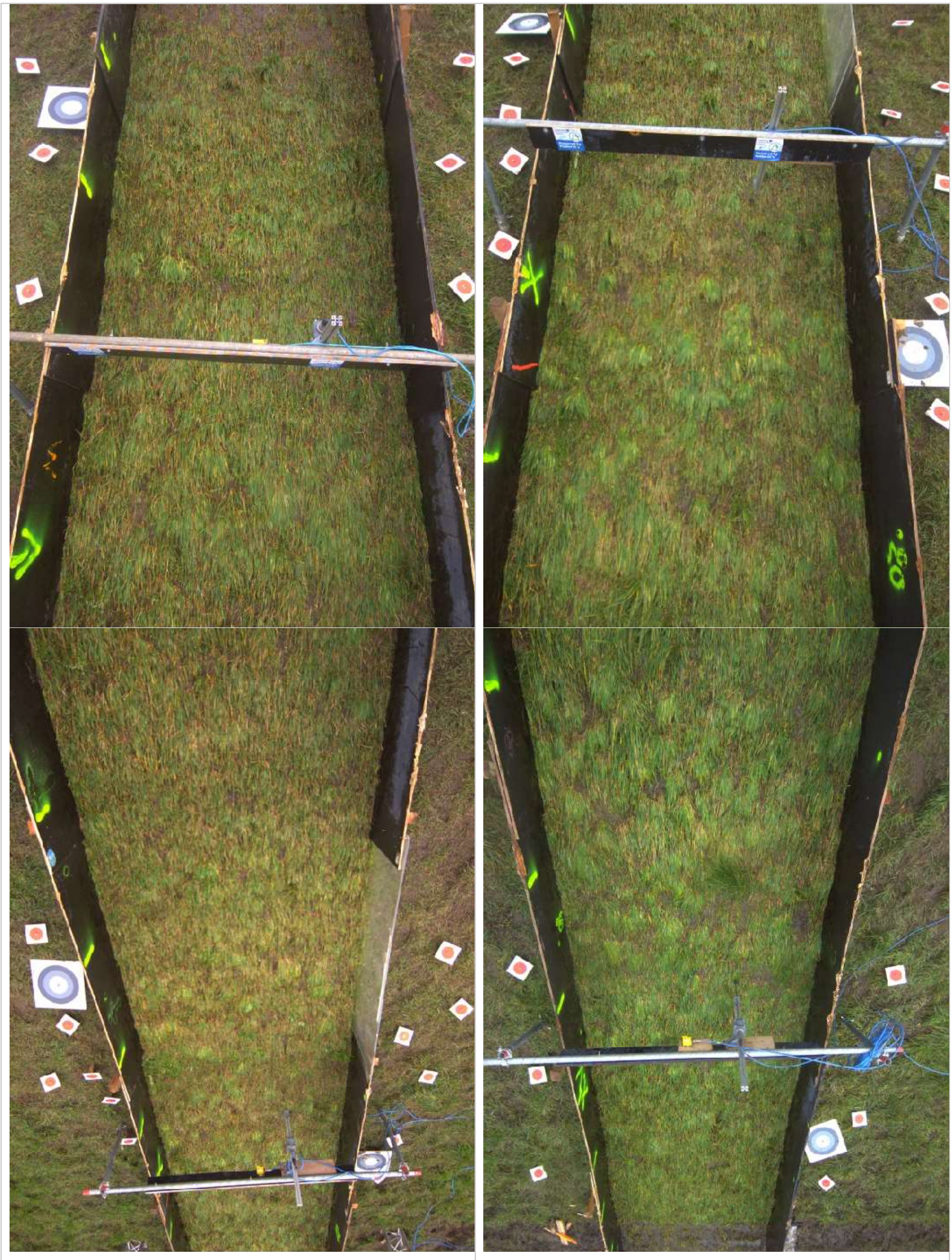

Figure 15 – Levee state in block B01. Left are camera 1 and 2. Right are camera 3 and 4. levee crest is in the upward direction, levee toe is in the downward direction.

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Figure 16 – Levee state in block B10. Left are camera 1 and 2. Right are camera 3 and 4. levee crest is in the upward direction, levee toe is in the downward direction. The erosion experiment is visible in the image of camera 4.

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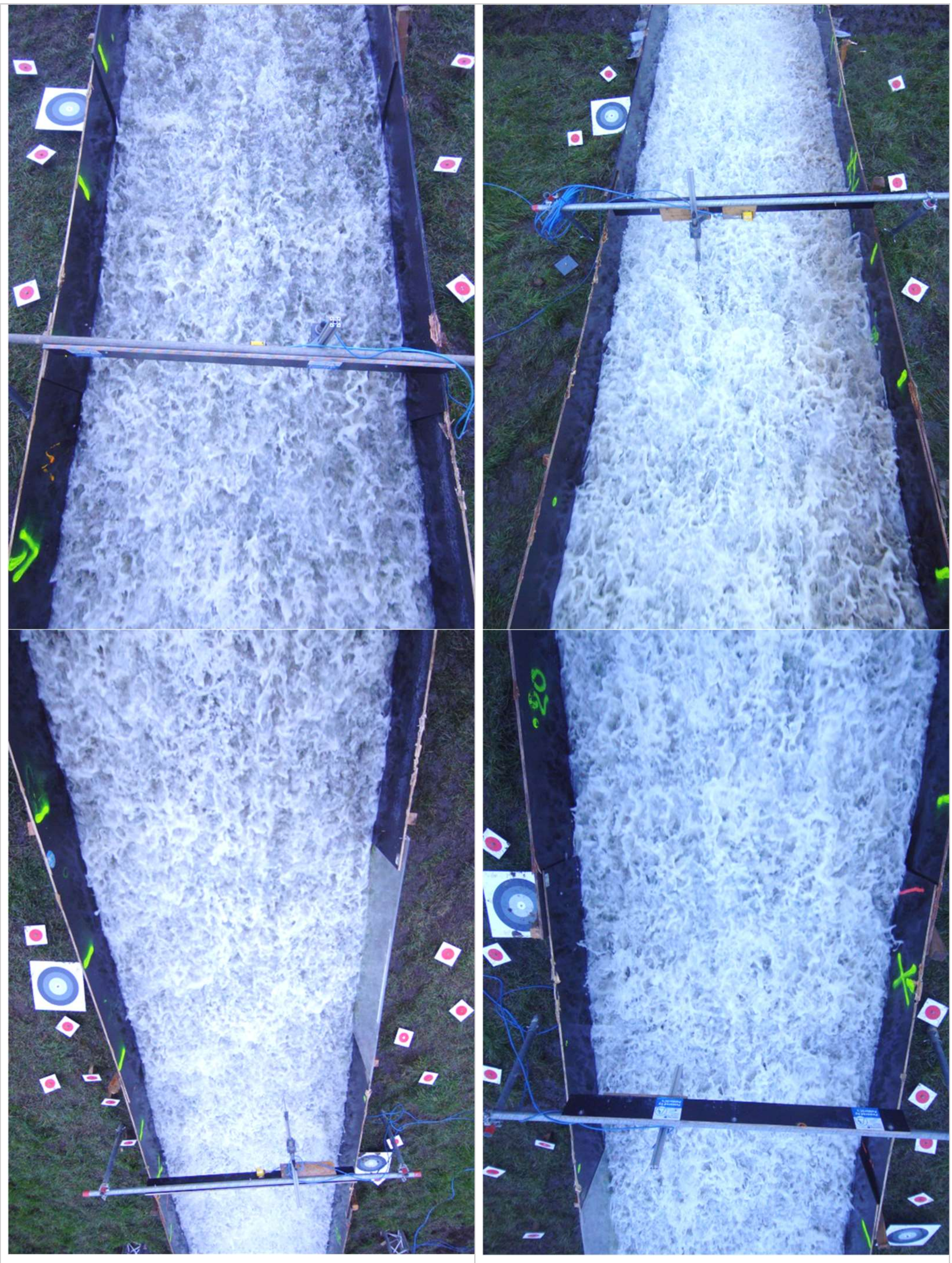

Figure 17 – Levee state during overflow in block B2.

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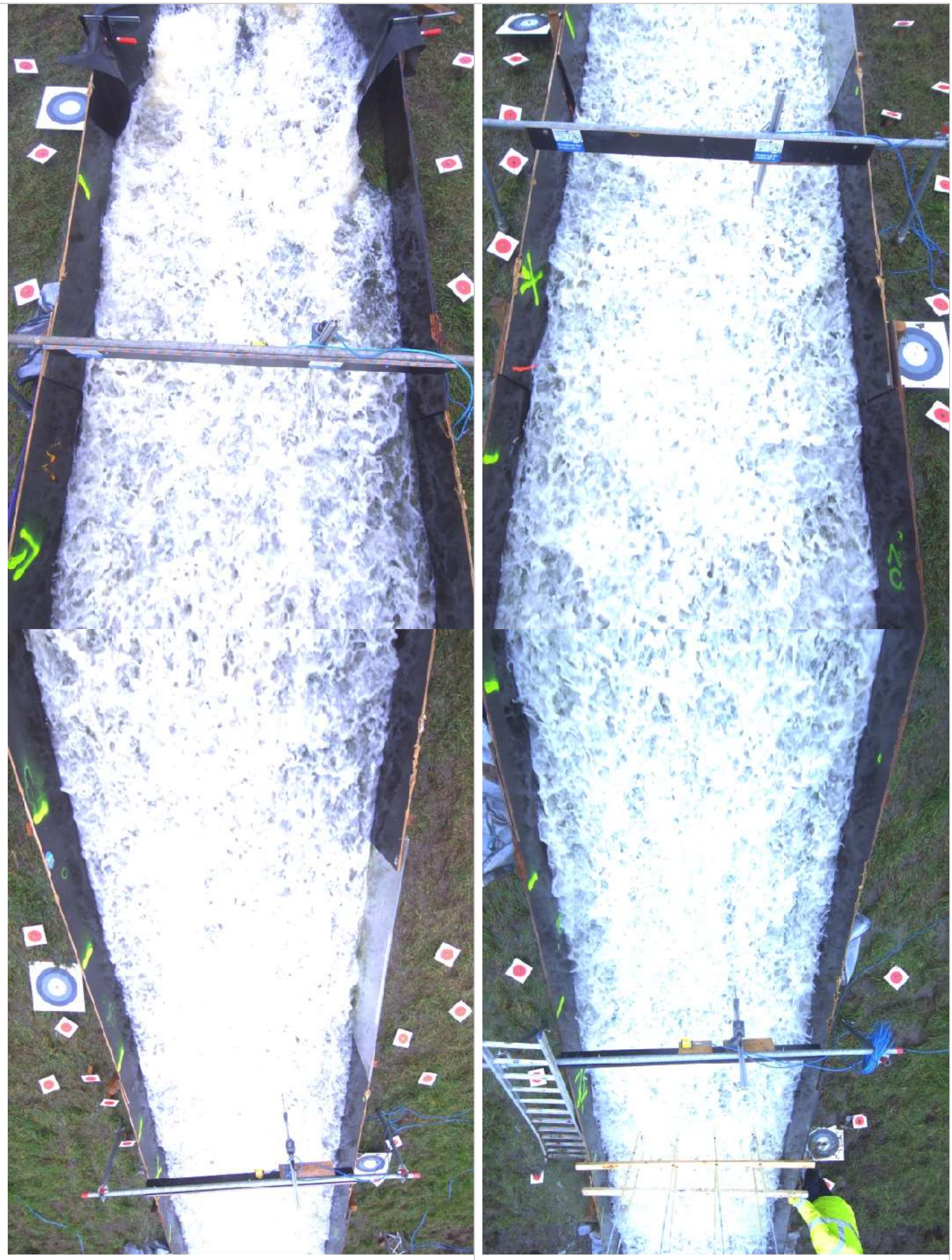

Figure 18 – Levee state during overflow in block B10 (discharge 165 $l.s^{-1}.m^{-1}$).

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4.4.3 Monitoring timeseries

The timeseries have been processed per datafile. The average water heights and velocities are shown below. Due to malfunctioning of the WH_CREST sensor, this sensor is omitted. More data is shown however in the annex B of the Annex document.

The average water heights per sensor vary with the discharge. The blocks measured on the first day (B1->3) used a (measured) discharge of up to ca. 480 to 500 $l.s^{-1}$. On the second day (B4->8), a much higher discharge was applied, of approx. 900 $l.s^{-1}$. On day 3 (during the erosion experiments) no detailed discharge data was available. The pump powers are recorded in the logbook and a pump-power – discharge relation is available in this report.

The water heights vary from 3 cm for the lower discharges at the upper sensor, to nearly 18 cm for the higher discharges in the same locations.

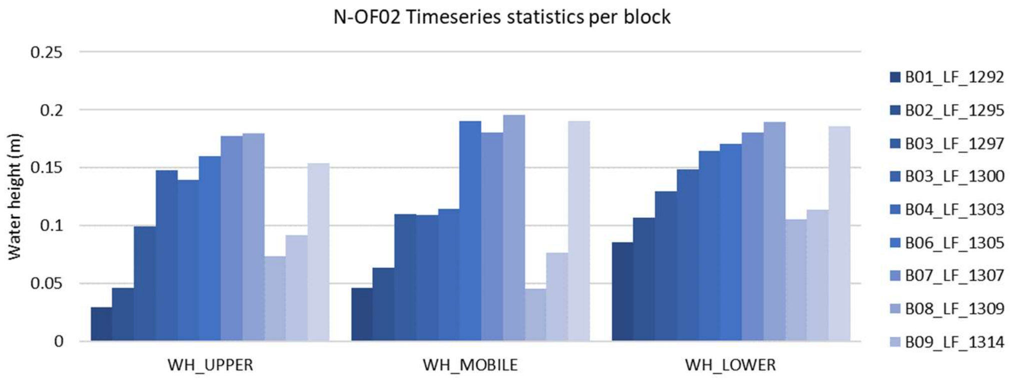

Figure 19 - Average water height in Upper, Mobile and Lower sensor position.

The average velocities display a similar trend as the water heights. However, due to foam, bubble occurrence and strong turbulence, the quality of the velocity measurements is less certain than that of the water heights.

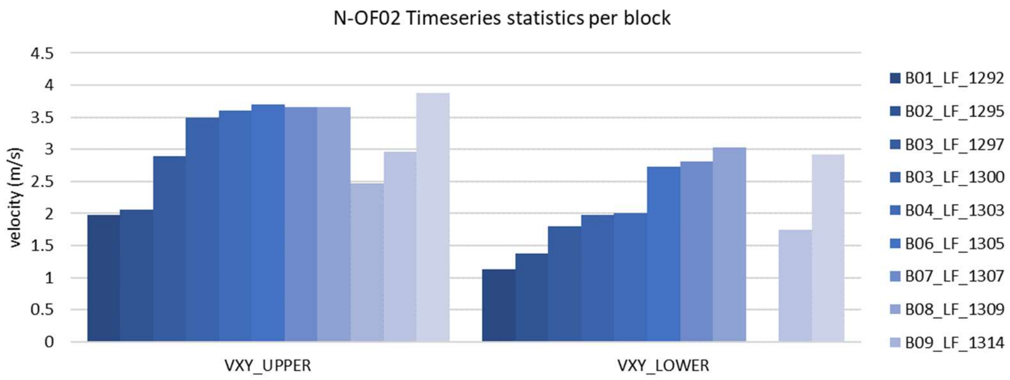

Figure 20 - Average current velocity in Upper and Lower sensor position.

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Data files

The list of raw data files is shown below. Annex B of the annex document contains the processed data file details and plots. The full data file name format are explained in the introduction; here the identifying part is shown.

Table 9 - Overview of raw timeseries data files.

Block	Normal acquisition
1	LF_1292
2	*LF_1295*
3	*LF_1297*
4	*LF_1300*
5	*LF_1303*
6	*LF_1305*
7	*LF_1307*
8	*LF_1309*
9	*LF_1314*
10	*LF_1316*
11	*LF_1318*

4.5 First insights

The evolution of the vegetated levee under normal overflow conditions corresponds to the observations for the reference section N-OF01, albeit for a shorter time span: 8 hours after 2 days of testing lead to no significant damage to the levee.

For insights and conclusions concerning the erosion tests (where they are put in relation to other large and small scale tests), reference is made to van Damme et al. (2022).

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5 N-OF03 Reference

5.1 Goal

Overflow test N-OF03 is a reference test, which means that it is executed at a selected location which is void of any anomaly or obstacle. Moreover, the test has been used to perform additional hydraulic measurements on top of the standard monitoring. In order to induce damage, on the last half day, several holes had been drilled through the cover layer on the lower part of the levee slope.

5.2 Setup

The N-OF03 Reference overflow test has been executed on the landward side of a Dutch levee in the Hedwige-Prosper Polder (Belgian Lambert coordinates: X=140313.0 m; Y = 226465.6 m or WGS84: 4°22973E, 51°34789N). The elevation of the crest is 12.06 m TAW[5] or 9.71 m NAP, while the landward toe is situated at +/- 4.5 m TAW. The slope angle is 22° halfway the levee slope (which equals to a "10/4 slope"). The vertical profile over the levee section is shown inFigure 21. At the far end of the toe, a gully is present (not shown on the profile).

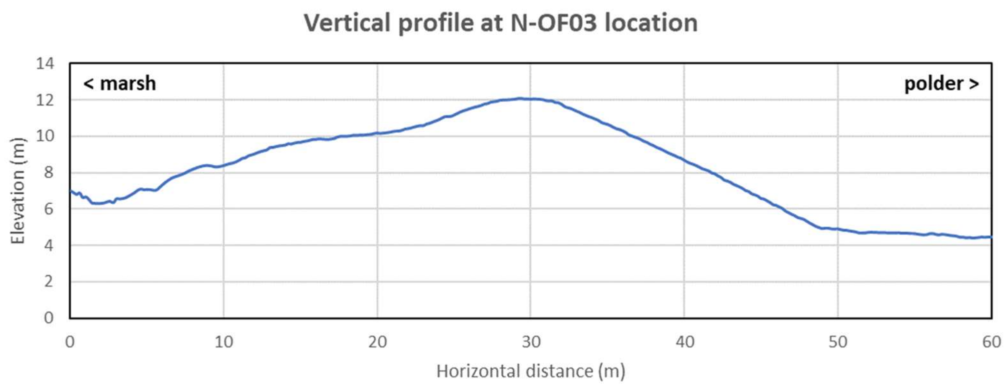

Figure 21 - Topographical profile at the N-OF03 test location.

The test section is 2 m wide, sided by wooden boarding, and the surface is considered to be in a good condition without any visible anomalies (such as burrows, objects or other damage) on the slope. At the toe, there are some crane track marks, but the distance to the slope is sufficient to expect no influence from this. The vegetation state is considered in a state after normal maintenance, with grass lengths of ca. 10 to 20 cm and subject to normal Dutch maintenance methods. A detailed vegetation survey has been performed on Belgian and Dutch levee stretches, reported in Vandevoorde & Lierop (2022). Granulometry analysis indicates a silty top layer, which is typically 80 cm thick. The sand core below the top layer consists of medium sand. An asphalt road is present at the toe of the levee.

The monitoring setup has been applied and is described (and validated) in Vercruysse et al. (2022). The monitoring setup includes 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

[5] TAW = "Tweede Algemene Waterpassing", the Belgian vertical reference. The reference plane is situated 2.35 m lower than the Dutch reference plane ('NAP' = 'Normaal Amsterdams Peil').

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damage evolution, and movies to visualize current patterns. Drawings of the damage have been made, as well as regular photographs by the test operators.

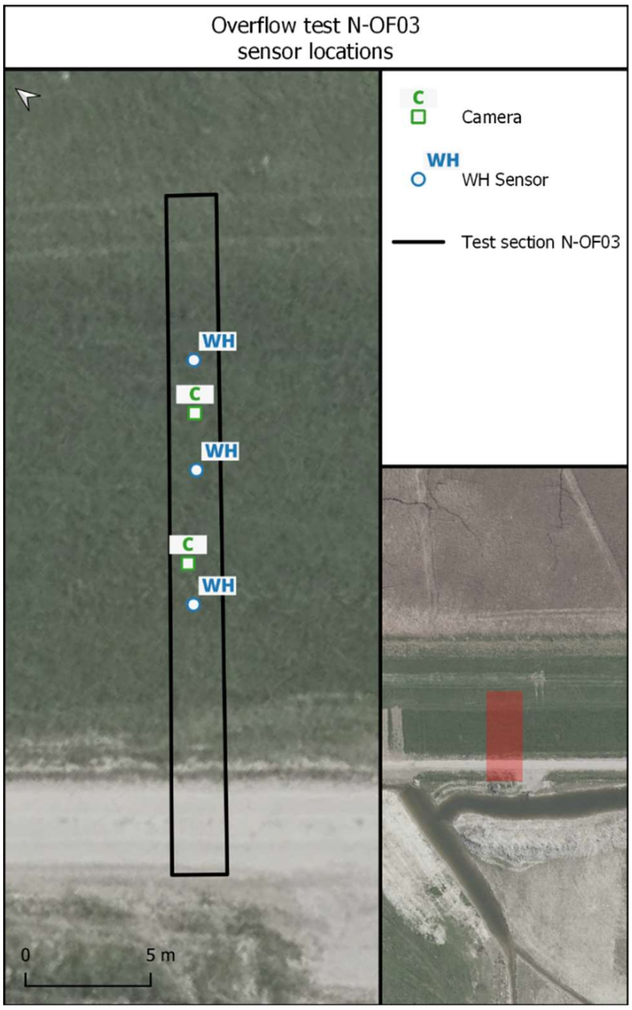

Figure 22 - Location of sensors at N-OF03.

Table 10 - Sensor coordinates (Lambert '72) on N-OF03.

Sensor	X	Y
WH_CREST	*Not measured*	
WH_UPPER	140308.22	226461.70
WH_MOBILE	140304.80	226458.93
WH_LOWER	140300.426	226455.72
VEL_UPPER	*Cfr WH_Upper*	
VEL_MOBILE	*Cfr WH_MOBILE*	
VEL_LOWER	*Cfr WH_LOWER*	
CAM_UPPER	140301.642	226456.92
CAM_LOWER	140306.57	226460.56

Additional hydraulic measurements have been executed, including Particle Tracing Velocimetry (PTV), LiDAR measurements of the water level and bottom,), LSPIV measurements of the watersurface and filming with a high-speed camera from the side through transparent boarding.

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The overflow was generated by the setup provided by Waterschap Brabantse Delta, using two pumps (BA300 and BA500) which allow to vary discharge, and reach discharges up to 1100 l/s. The setup was controlled by engine RPM's and direct discharge measurement was not always successful. However, pump power – discharge relations were created on test N-OF02 and N-OF04 (see Vercruysset et al., 2022).

Figure 23 - Start of the setup of the pumps by Waterschap Brabantse Delta.

5.3 Execution

The N-OF03 reference test was executed on 6-8/12/2021. 11 blocks of overflow were executed for a total runtime of 14 hours and 40 minutes. PTV measurements were executed on 6/12/2021 and Lidar, LSPIV and high-speed camera recordings on 7/12/2021.

Table 11 - Execution summary

Date	Blocks	Runtime	Total Discharge	Specific discharge	Remarks
6/12/2021	4	2h 50'	300 - ~ 650 l/s	150 - ~ 325 l/s.m	Variable RPM. See logbook. PTV measurements.
7/12/2021	5	6h 05'	300 - ~ 650 l/s	150 - ~ 325 l/s.m	
8/12/2021	3	5h 45'	300 - ~ 1000 l/s	150 - ~ 500 l/s.m	Afternoon: drillholes through cover layer

On 8/12/2021, the two pumps (BA300 + BA500) have been enabled, which gives an estimated maximum discharge of 1m³ per second. The lack of discharge measurements prevents the validation of this value.

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5.4 Results

5.4.1 Visual observations

The experiment starts with a levee slope that is visually in a good state. However, after a first occurrence of overflow, it is observed that on the lower part of the slope, some vegetation is quite 'thin', or missing. This is visible on Figure 24.

During the course of the experiment however, it is seen that the normal evolution as in other reference tests is ongoing: slight soil erosion and increasing exposure of vegetation root systems. However, there is no critical damage being created and the overall slope is holding.

During the last afternoon, holes were drilled to evaluate whether this would lead to damage, which appeared not to occur.

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5.4.2 Video and photo imagery

Surface state

Levee slope surface images have been recorded during breaks in between overflow blocks in order to visualize the surface state evolution. The original data has been acquired at different lighting conditions and therefore has been recorded with different exposure settings. As part of the preprocessing, under- or overexposed images have been removed. For each picture, duplicates or triplicates were made. For the sake of data reduction, only one file has been retained during processing. Examples are shown in Figure 15 and Figure 16.

Surface flow

Similar to the surface pictures, images have been made of the overflowing water. A general remark for all the tests executed with the pumping installation of Waterschap Brabantse Delta (that fed water into the overflow generator from the top, compared to through a diffuser at the base), is that the water surface on the crest is not stable as in the experiments with the other pumps.

Data

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

Table 12 - Overview of imagery data availble per block in N-OF03. The numers refer to file id's.

Block	Surface images	Flow images
0	1322, 1324	1323
1	1326	1325
2	1328	
3	1343, 1344	
4	1346	1345
5	1349	1347
6	1359	1351
7	1362	1361
8	1364, 1365	1363
9	1367	1366
10	1369	1368

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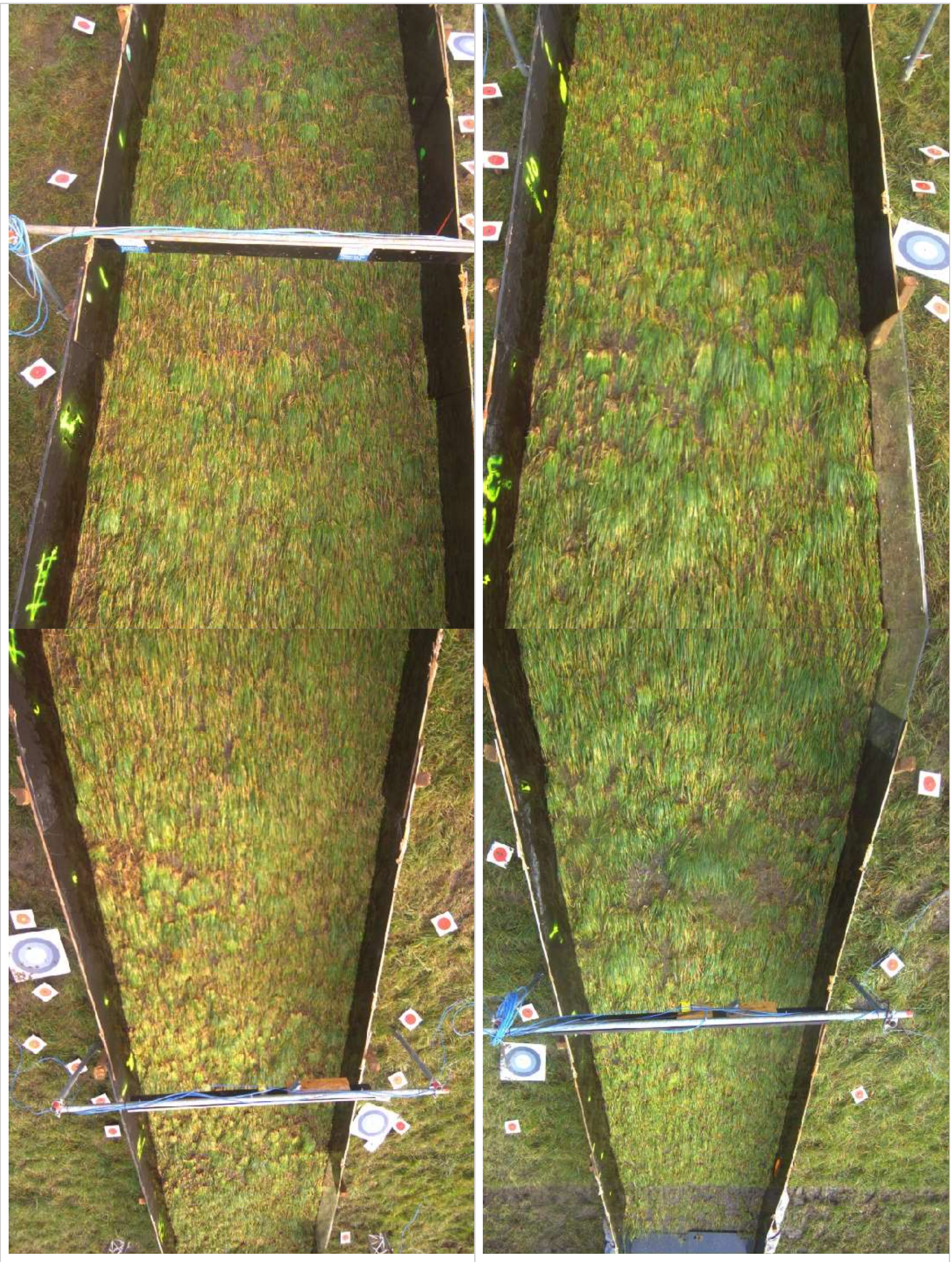

Figure 24 – Levee state after 1 hour of overflow. Left are camera 1 and 2. Right are camera 3 and 4. levee crest is in the upward direction, levee toe is in the downward direction.

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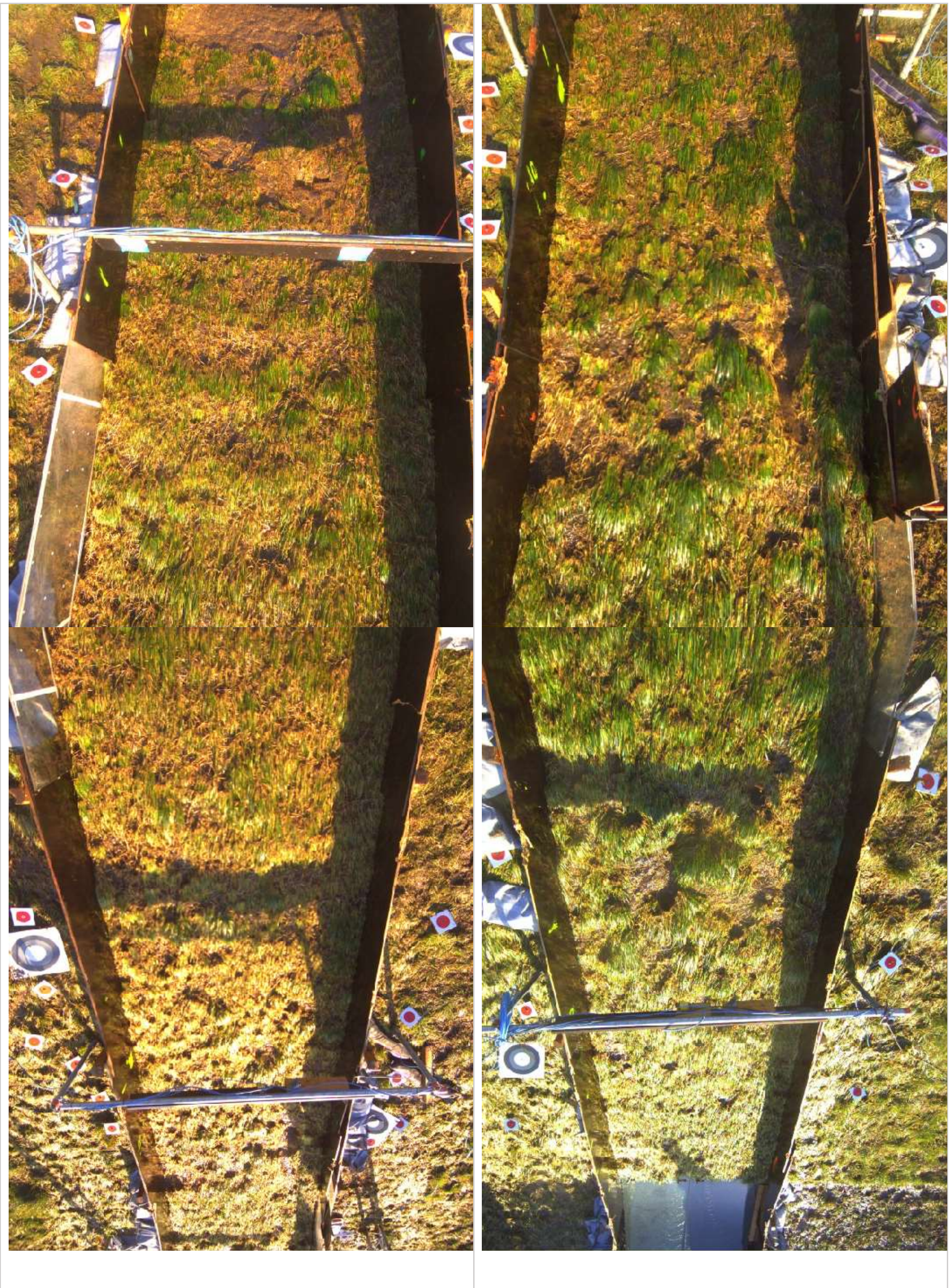

Figure 25 – Levee state in block B10. Left are camera 1 and 2. Right are camera 3 and 4. levee crest is in the upward direction, levee toe is in the downward direction.

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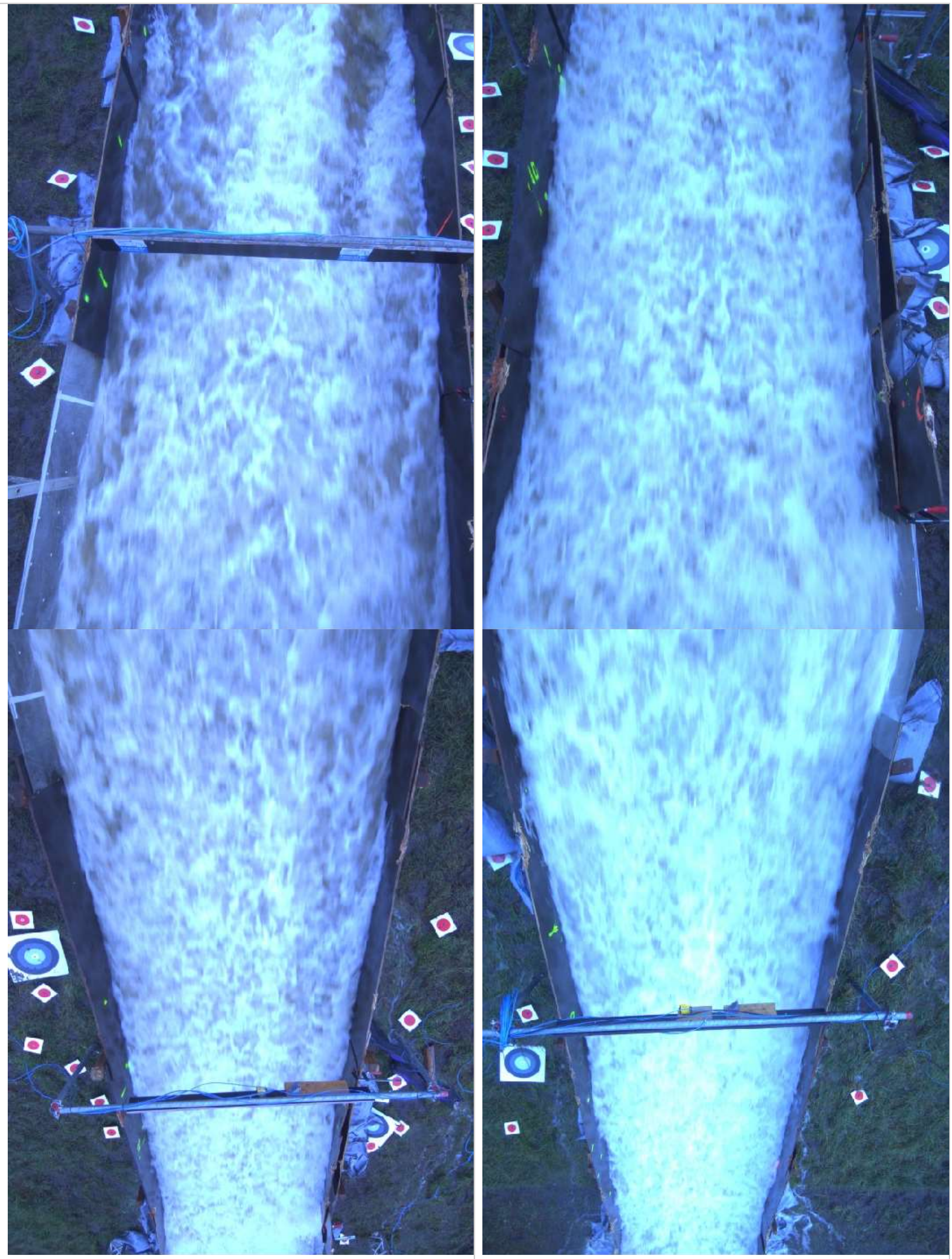

Figure 26 – Levee state during overflow in block B7.

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5.4.3 Monitoring timeseries

During the N-OF03 test, The WH_CREST sensor did not function correctly, and was even removed from the crest position. Therefore, only the data from the other sensors is shown. Note that the water height measured at location mobile is lower then measured at location upper. A possible explanation is that due to the less optimal feeding of the generator during the third period at the location of the upper portal there is still a centralized core of the flow.

During most of the test, the UPPER and LOWER velocity sensors are positioned on the crest. The MOBILE velocity sensor was not installed. It is recommended to consult the full timeseries information in the annex document. Note that the results shows a difference between both velocity sensors. These differences is probably due to the concentrated cores as a consequence of the less optimal feeding of the generator during the third test period.

The average statistics are shown in the images below.

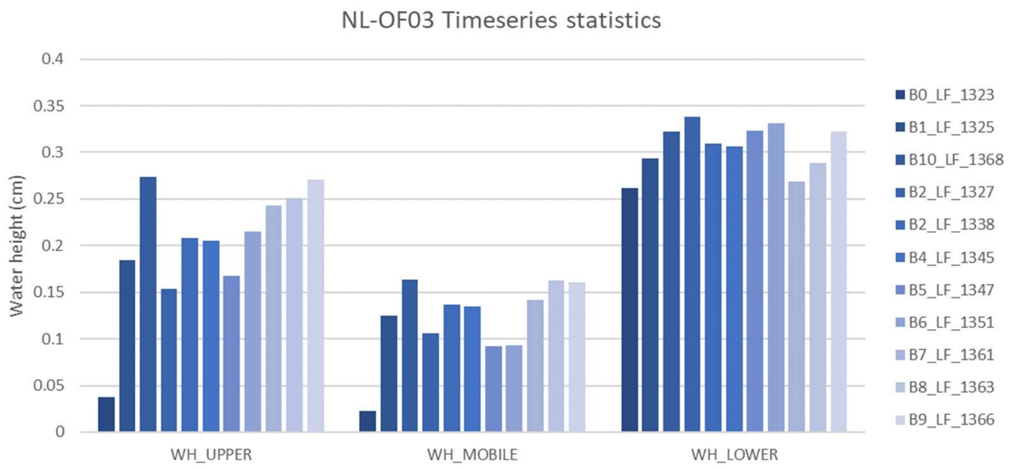

Figure 27 – Mean water level statistics per sensor and per block during the N-OF03.

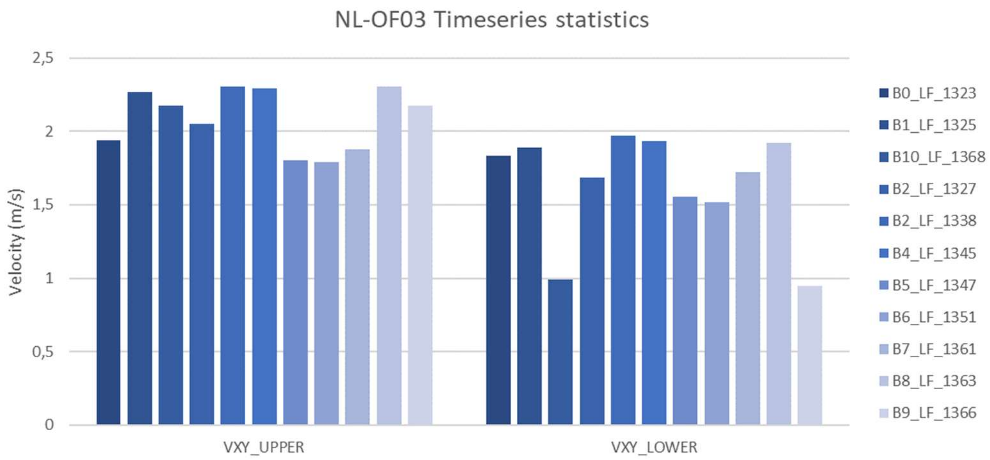

Figure 28 – Mean velocity statistics per sensor and per block during the N-OF03.

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5.4.4 Other observation

During test N-OF03, PTV, LSPIV and high speed camera videography have been performed. The data has (partly) been used for validation of the monitoring, and description of hydraulics during overflow (see Vercruysse et al., 2022)

5.5 First insights

A levee in a well maintained state without any obvious anomalies, is able to withstand elevated discharges (specific discharges up to 500$l.s^{-1}.m^{-1}$) for several hours. In this case, more than 14 hours of overflow was conducted, including 2 hours during which small holes were drilled through the cover layer.

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6 N-OF04 Reference

6.1 Goal

Overflow test N-OF04 is a reference test, which means that it is executed at a selected location which is void of any anomaly or obstacle. This test was conducted close to overflow sections N-OF10 and N-OF11 to serve as reference for these two tests.

6.2 Setup

The N-OF04 Reference overflow test has been executed on the landward side of a Dutch levee in the Hedwige-Prosper Polder (Belgian Lambert coordinates: X=140431.5 m; Y = 226316.4 m or WGS84: 4°23143E, 51°34655N). The elevation of the crest is 11.88 m TAW[6] or 9.53 m NAP, while the landward toe is situated at +/- 4.5 m TAW. The slope angle is 22° halfway the levee slope (which equals to a "10/4 slope"). The vertical profile over the levee section is shown in Figure 21. At the far end of the toe, a gully is present (not shown on the profile).

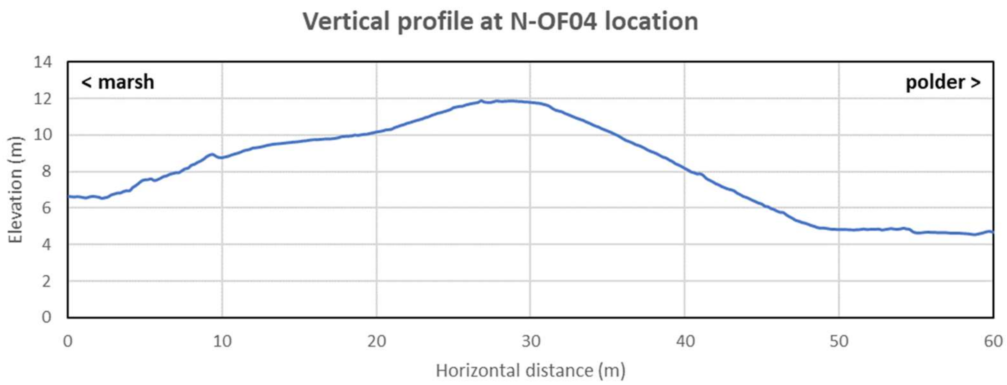

Figure 29 - Topographical profile at the N-OF04 test location.

The test section is 2 m wide, sided by wooden boarding, and the surface is considered to be in a good condition without any visible anomalies (such as burrows, objects or other damage) on the slope. At the toe, there are some crane track marks, but the distance to the slope is sufficient to expect no influence from this. The vegetation state is considered in a state after normal maintenance, with grass lengths of ca. 10 to 20 cm and subject to normal Dutch maintenance methods. A detailed vegetation survey has been performed on Belgian and Dutch levee stretches, reported in Vandevoorde & Lierop (2022). Granulometry analysis indicates a silty top layer, which is typically 80 cm thick. The sand core below the top layer consists of medium sand. An asphalt road is present at the toe of the levee.

The monitoring setup has been applied and is described (and validated) in Vercruysse et al. (2022). The monitoring setup includes 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

[6] *TAW = "Tweede Algemene Waterpassing", the Belgian vertical reference. The reference plane is situated 2.35 m lower than the Dutch reference plane ('NAP' = 'Normaal Amsterdams Peil').*

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damage evolution, and movies to visualize current patterns. Drawings of the damage have been made, as well as regular photographs by the test operators.

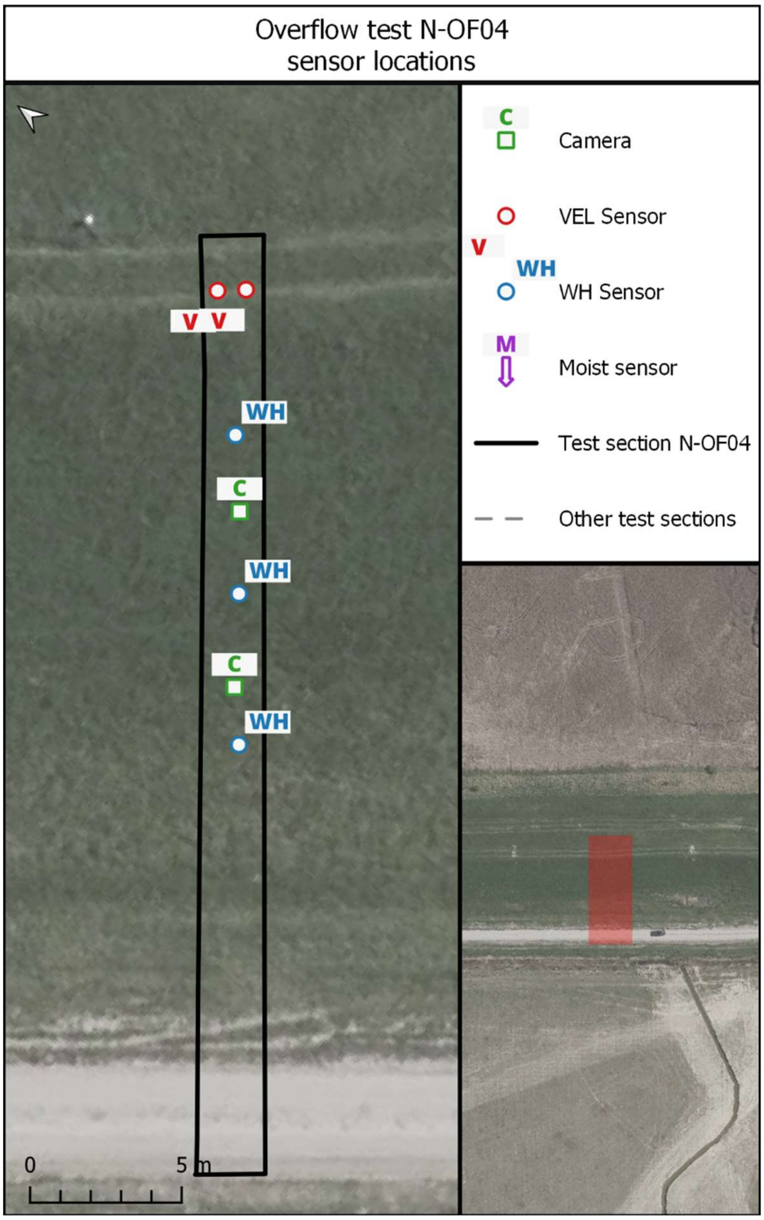

Figure 30 - Location of sensors at N-OF03.

Table 13 - Sensor coordinates (Lambert '72) on N-OF03.

Sensor	X	Y
WH_CREST	-	
VEL_CREST_L	140430.5	226316
VEL_CREST_R	140431.0	226315.6
WH_UPPER	140427.0	226312.9
WH_MOBILE	140422.9	226309.7
WH_LOWER	140418.9	226.306.6
CAM_UPPER	140425.1	226311.3
CAM_LOWER	140420.4	226307.9

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The overflow was generated by the setup provided by Waterschap Brabantse Delta, using two pumps (BA300 and BA500) which allow to vary discharge, and reach discharges up to 1100 l/s. The setup was controlled by engine RPM's and direct discharge measurement was not always successful. However, pump power – discharge relations were created on test N-OF02 and N-OF04 (see Vercruysse et al., 2022).

During the N-OF04 test, LSPIV and PTV and measurements and have been carried out for hydraulic validation (see Vercruysse et al., 2022).

The setup also included the installation of protective plates and an ERT acquisition system. A description of these elements is given in detail in Tsimopoulou & Koelewijn (2022).

6.3 Execution

The N-OF04 reference test was executed on 15-17/12/2021. 17 blocks of overflow were executed for a total runtime of 25 hours and 2 minutes. PTV and Lidar measurements were executed on 16/12/2021.

Table 14 – Execution summary of N-OF04.

Date	Blocks	Runtime	Total Discharge	Specific discharge	Remarks
15/12/2021	5	4h 05'	660	330	
16/12/2021	6	6h 02'	660	330	PTV, Lidar
17/12/2021	4	7h 51'	360 – 660	180 - 330	
20/12/2021	3	7h 03'	660	330	

6.4 Results

6.4.1 Visual observations

Prior to the test, the section did not appear to have any noticeable discontinuities, such as damage by machinery, irregular vegetation patterns or large animal burrows. Through a thorough visual inspection before commencement of the test a number of small burrows were detected within and adjacent to the test section. Their depths were in the range of 8-12 cm and their diameters in the range of 3-5 cm, while none of them seemed to have penetrated beyond the clay layer. Their geometry and spatial distribution resembled mice burrows.

During the test, surface erosion and burrows were monitored every 2 test blocks of flow. Surface erosion started with the uprooting of grass and exposure of small patches of clay with diameters in the order of 2-3 cm, which gradually expanded and connected with adjacent patches of clay. This is a common pattern that has been observed in all overflow tests. Most of the mice burrows in the test section were within the first patches that formed, which shows that the burrows may have played a role in the early formation of surface erosion. Similar observations in other overflow tests are needed to validate this finding.

Regarding the depth of erosion, in every monitoring cycle the patches in the area of the toe were noticeably deeper than the rest, while a relatively deeper patch started forming on the crest, at the point of transition between the EPDM protection and the bare levee surface. A third point of interest regarding erosion depth was the transition between asphalt and soil at the downstream side of the road. At that spot a scour hole with a diameter of about 30 cm and a depth of about 45 cm was formed after 4 hours of flow.

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After the test, the most significant damages could be observed at the transition between EPDM and bare soil on the crest (erosion depth 1-2 cm in an area approx. 20 x 80 cm), at the toe (erosion depth 5-10 cm in an area approx. 10 x 80 cm) and at the downstream transition between asphalt and soil (erosion depth 45-50 cm in an area approx. 30 x 30 cm).

These findings are also further discussed in the report concerning burrows in levees (Tsimopoulou & Koelewijn, 2022).

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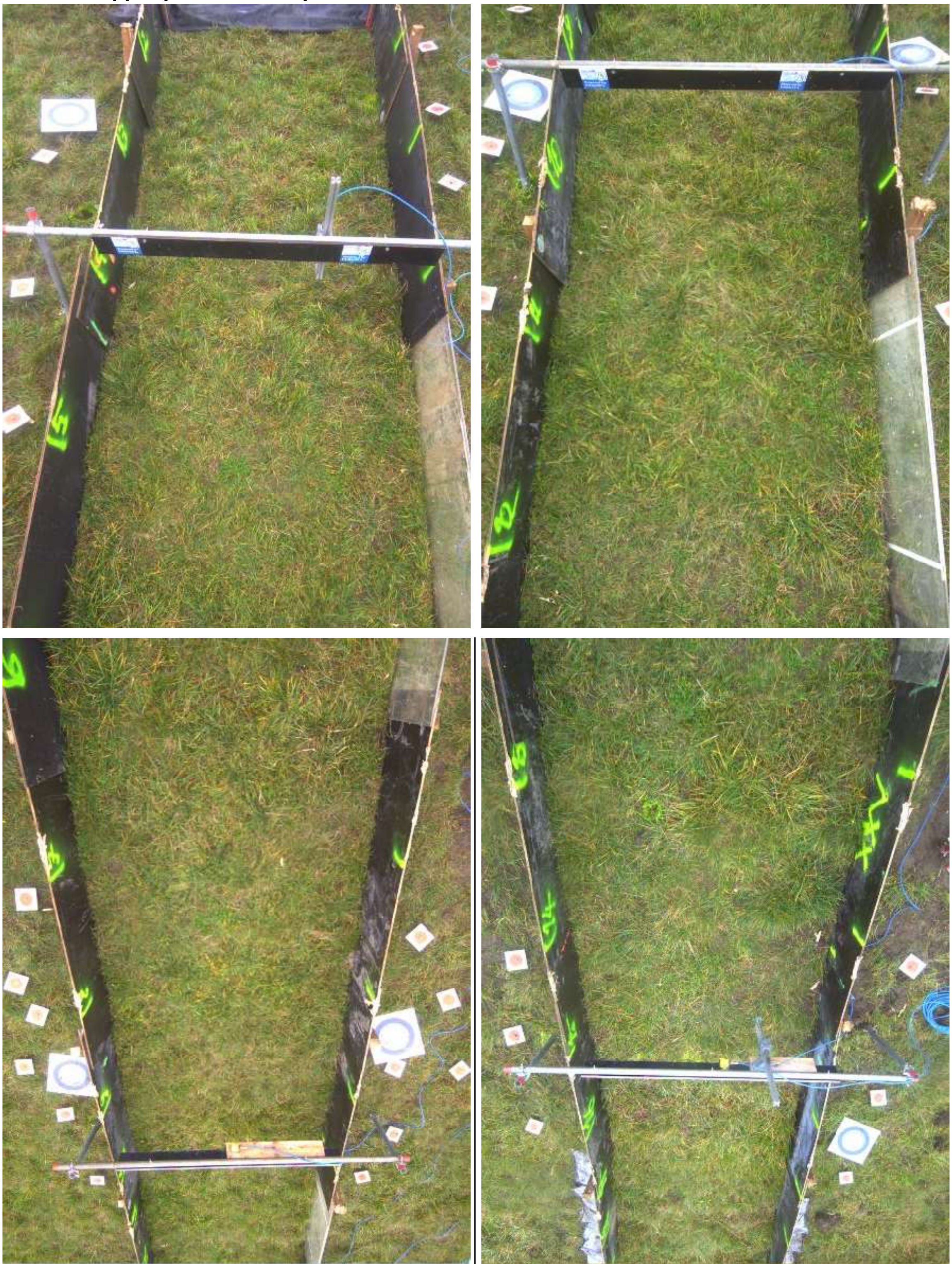
6.4.2 Video and photo imagery

Upper part of the slope (crest)



Lower part of the slope (toe)

Figure 31 - T0 surface photography (ID: NL_OF04_Q000_B0_S_1376)

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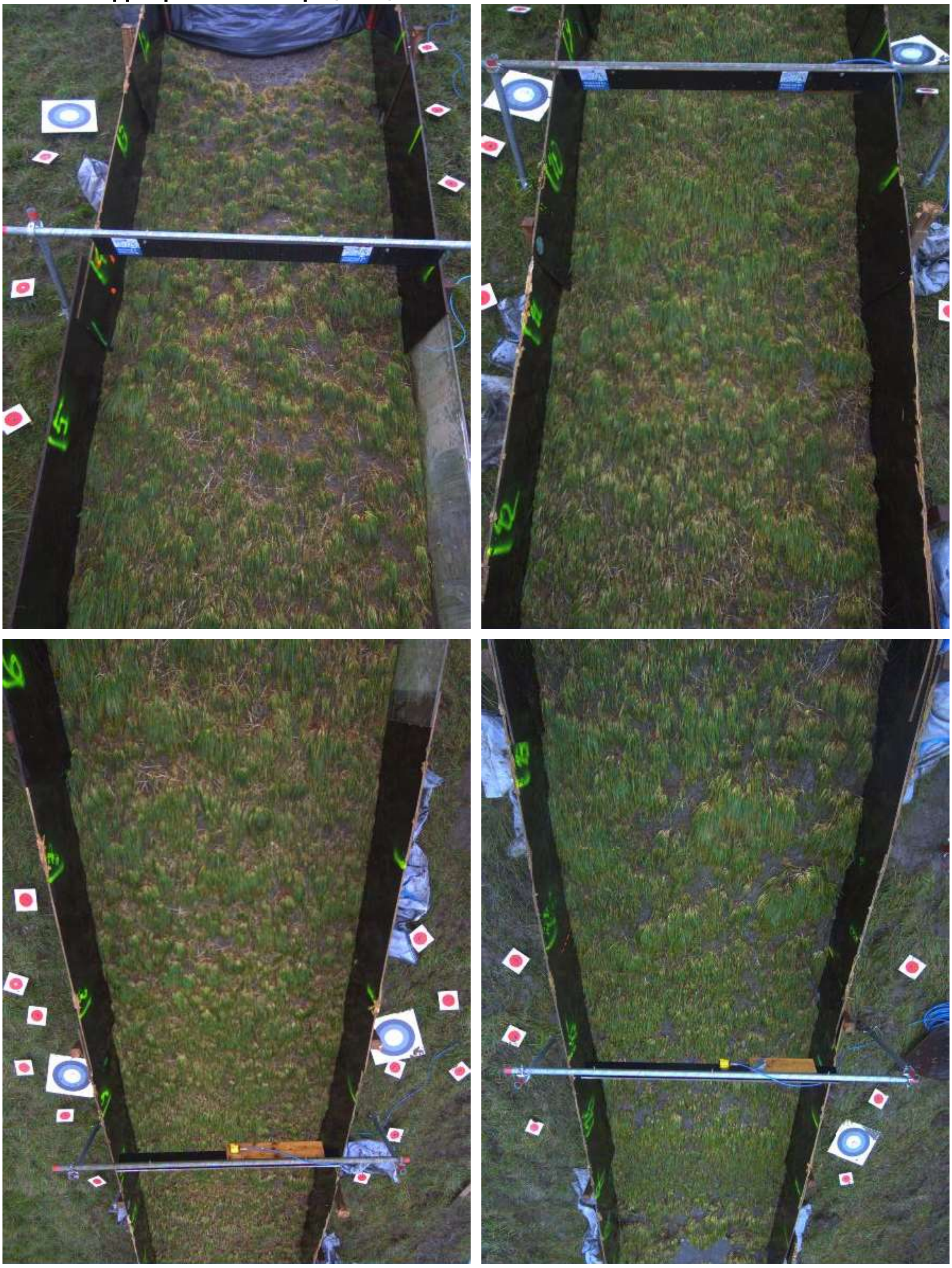
Upper part of the slope (crest)



Lower part of the slope (toe)

Figure 32 - Final surface photography (ID: NL_OF04_Q000_B18_S_1429)

6.4.3 Monitoring timeseries

The water level and velocity sensors are identified as 'UPPER', 'MOBILE' and 'LOWER'. These identifiers refer to the standard sensor location on the levee (with 'MOBILE' in between 'UPPER'

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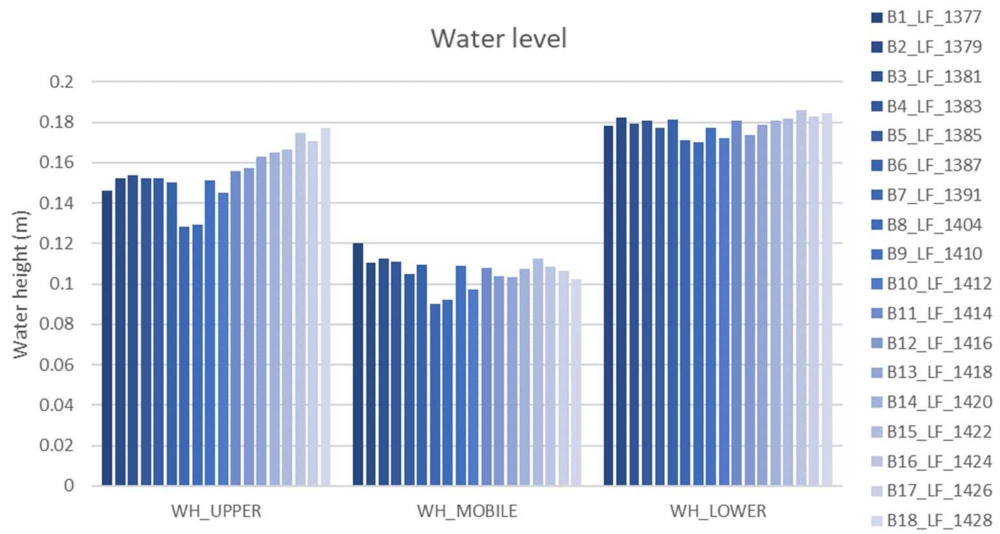
and 'LOWER'), although in reality the sensors have been placed in other positions. This is mentioned alongside with the figures in Annex A.



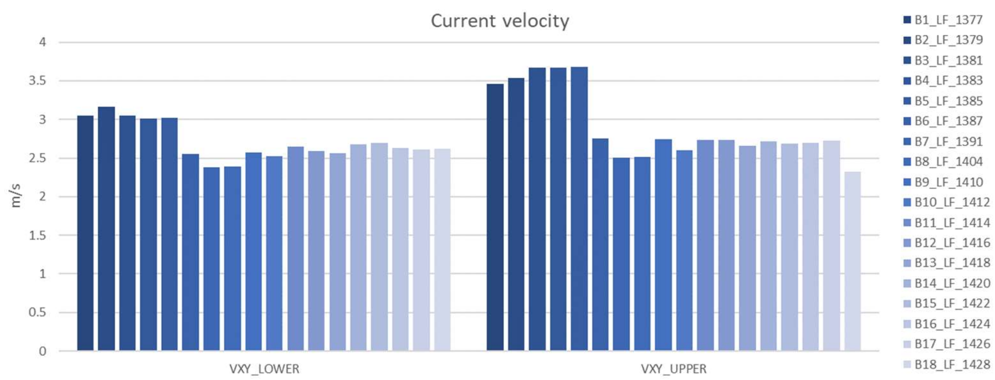


Figure 33: Mean water levels and Current Velocities measurement during Overflow test NL-OF04.

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

6.5 First insights

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

- A levee in a visually good shape, even with small burrows that do not pierce the clay cover layer, is able to withstand overflow during at least 25 hours without leading to significant failure processes.

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7 N-OF05 Large Burrow

7.1 Goal

The N-OF05 Burrow overflow test is aimed at assessing the influence of the presence of a large (rabbit or fox) burrow on the levee slope. As portrayed on the image below, a large burrow is present halfway the slope of at section N-OF05. Sand from the sand core has been dug out of the levee and forms a small pile in front of the burrow entrance.

Figure 34 - Downward view of the rabbit burrow on the levee slope in N-OF05 prior to testing.

7.2 Setup

The N-OF05 Burrow test section is situated on the landward side of a Dutch levee (coordinates in Lambert '72: X=140257.8 m; Y=226535.6 m). The levee crest is situated at a height of 11.88

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m TAW (TAW = NAP + 2.35). The levee slope above the burrow is 20.8° which is in between a 10/4 and 11/4 slope.

The levee profile is depicted in Figure 35. On the profile, the presence of the burrow is clearly visible, as well as the small sand mound in front of the burrow entrance.

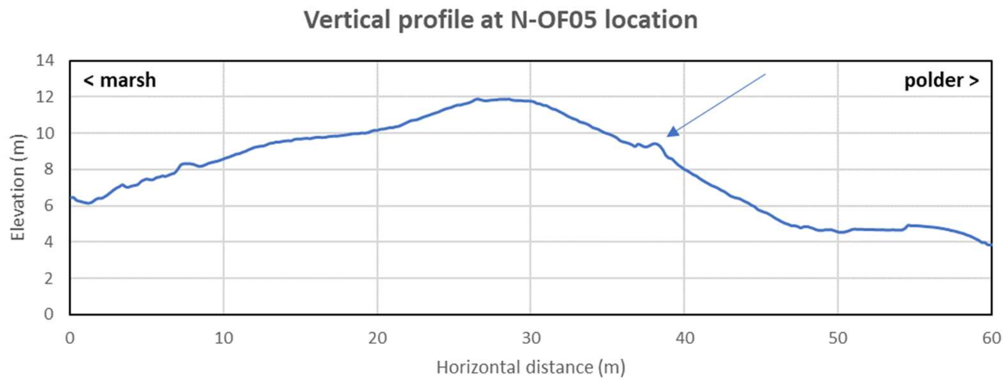

Figure 35 - Topographical profile over the N-OF05 site. Arrow indicates the sand mound in front of the burrow.

The sensor setup for the experiment follows the normal setup consisting of several velocity meters, water height meters, a discharge meter and overhead camera portals. See the design and application report (Vercruysse et al., 2022) for more information. The pump employed to generate the discharge was a twin parallel Hidrostal F10K-HD submerged pump system supplied by Eekels BV.

7.3 Execution

The execution of the experiment has been done with caution. Because the expectation was that erosion would occur quickly, a large number of shorter than normal overflow runs have been executed. In total, 10 blocks have been executed, for a total overflow time of 1 hour and 19 minutes. The discharge applied was 180 l/s (nominal), yielding a water height on the crest of +/- 18 cm.

7.4 Results

7.4.1 Visual observations

The rabbit burrow on the N-OF05 section is situated in the middle of the section. A mound of sand is located around the burrow (Figure 36). During the first block of the experiment, the sand mound around the rabbit burrow was washed away, coloring the overflowing water, muddy brown (Figure 37). This event exposed a piece of wire fence. From levee watches, it was confirmed that a rabbit hole had existed on this location and had been repaired before (Figure 39). Apparently, this repair included the placement of a wire fence to cover the old burrow (unsuccessfully, apparently).

During the subsequent blocks, the current started to divert around the burrow (due to topographic differences). The current stayed like this for several minutes, whilst the wire fence was slowly being undercut. It appeared that this wire fence was effectively stabilizing the top layer. This undercutting process took place because the top clay layer was exposed to the current and mostly unprotected by vegetation because of the sand mound that rested on top of it before. After 20 minutes in the test, an erosion 'pit' started to form in front of the protected

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area, cutting into the cover layer (Figure 39). This developed continuously and a waterfall-like feature became present. The erosion became very outspoken after +/- 45 minutes into the test.

Finally, after 1 hour and 13 minutes, the test was ended because the cliff that had developed suddenly destabilized and gave rise to a large slope failure. During the minutes that followed, it was observed how the head scarp migrated another 2 meters upwards (Figure 40).

Figure 36 - Rabbit burrow before thestart of the experiment.

Figure 37 – Initial erosion of the sand mound of the rabbit burrow.

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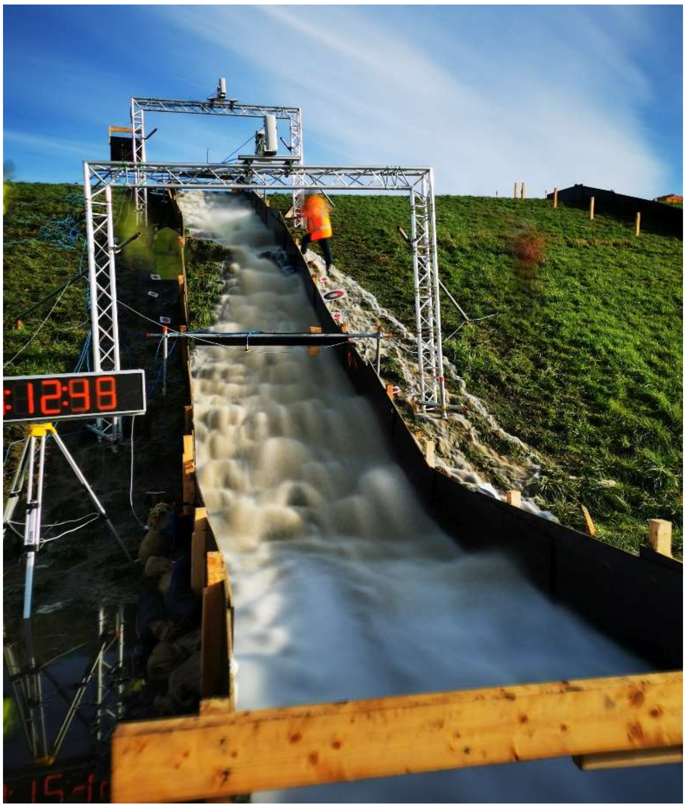

Figure 38 - Diversion of the flow around the rabbit burrow.

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Figure 39 - Erosion ongoing: at the bottom, soil somewhat stabilized by wire fence, an erosion pit upstream of it, at the base of a small cliff.

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Figure 40 - Outcome of the test: within minutes, the damage evolved into a large instability.

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7.4.2 Video and photo imagery

The overhead camera frames installed on the section, have been used to produce two types of images: 1) in between overflow runs, images of the levee surface have been taken. These images can be used to evaluate and track damage evolution; 2) images of the surface current flows to visualize current patterns, e.g.

Surface images are available as a T0 situation (B0), and at later times (after B1, B5 B6, B7, B8, B9 and B10). Here, the area of the burrow is illustrated at different timesteps.

Figure 41 shows the initial state of the burrow. In front (downward) of the burrow entrance, a mound of sand can be observed, without any vegetation. The burrow entrance is about 20 cm wide and will thus easily allow water to infiltrate the levee.

Figure 41 - Initial state of the burrow.

Figure 42 shows the next state of the experiment. After block 1, the sand mound in front of the burrow has been washed away. The clay cover layer is now exposed, mostly barren of vegetation, although some roots are present.

Figure 43 shows the state when the erosion of the burrow area is starting to advance: in front (left) of the burrow entrance, an erosion pit has formed, but the soil is still being stabilized because of the wire fence that is present in the clay layer. The burrow itself is starting to collapse.

Finally, Figure 44 shows the end state: the damaged area extends several meters upwards from the original burrow position. A large scarp has developed and this erosion cliff has migrated upwards several meters before stabilizing again.

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Figure 42 - Composed image of the burrow area after the sand mound has been eroded (B1).

Figure 43 - Composed image of the burrow area after the an erosion pit has formed and the burrow starts to collapse (B5).

Figure 44 - Composed image of the damaged area at the end of the experiment (B10).

7.4.3 Monitoring timeseries

A constant (nominal) discharge of 180 l/s was applied for all the overflow runs (blocks). Only during the last block, a discharge measurement had taken place, indicating a discharge of 184 l/s.

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Statistics for the water height and velocity are shown in Figure 45Figure 46. Details about the measurements are reproduced in Annex A.

The water heights measured at the CREST and UPPER are fairly stable. The MOBILE sensor was not placed well compared to the current (which only covered part of the section). The LOWER water height sensor has irregular measurements due to the nature of the flow in that location.

- WH_CREST 7.7 cm
- WH_UPPER 4.3 cm
- WH_MOBILE (approx. 3 cm, but not representative)

The velocities observed during the individual blocks show some variations (e.g. due to dirt or grass sticking to the sensor). Nevertheless, averages for the UPPER and MOBILE sensors are available. The LOWER velocity sensor displays an upward velocity trend; this is due to local current conditions of very unstable or turbulent flows.

- VXY_UPPPER 3.16 m/s (excluding blocks 3)
- VXY_MOBILE 1.27 m/s (excluding block 2)
- VXY_LOWER 1.59 m/s (excluding blocks 7-10)

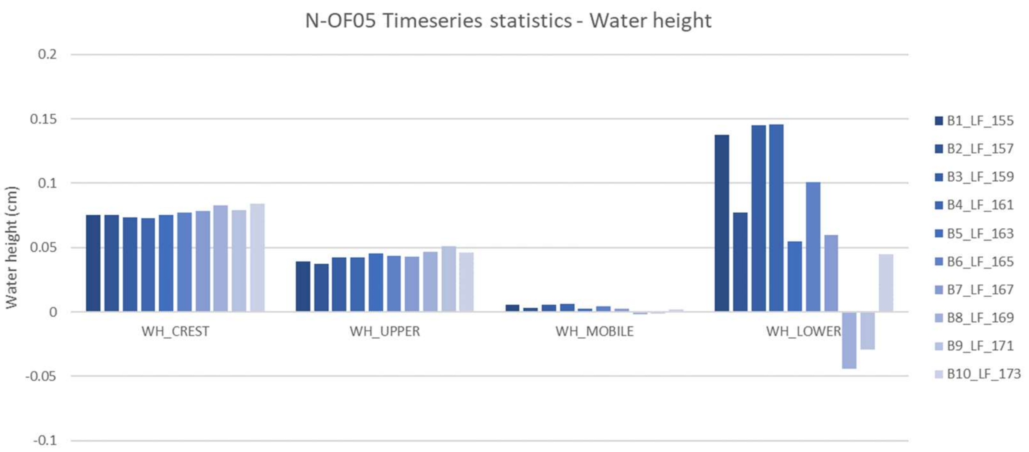

Figure 45: Water height statistics for N-OF05 individual overflow runs.

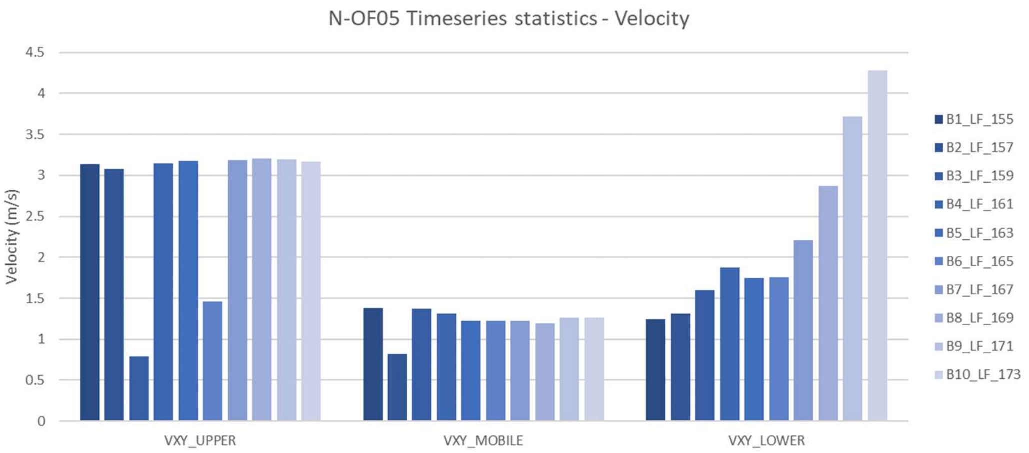

Figure 46: Velocity statistics for N-OF05 sensors.

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As a remark, it is noted that the manual water level on the crest, as shown in Annex A, of 18.4 cm is much higher than the value depicted above. The reason for this is that the manual water level measurement is taken where the water is building up, near to the generator. The sensors (water level and velocity) are however placed somewhat downstream where the water is already accelerated. The calculation of an average discharge based on the sensor data on the crest (WH_CREST and VXY_MOBILE) does indeed approach the measured discharge:

$Q = A.H.v = 2\,m\,.0.077\,m\,.1.27\frac{m}{s} = 1.96\,m/s$ which is comparable to the reported discharge in block 10 of 1.84 m/s.

7.4.4 3D Laser scanning

On 12/10/2020 and 2/12/2020, a T0 (original state) and T1 (damaged state) 3D laser scanning was performed by Wijnand Vanhille, DMOW. These data can be used for geometric analysis and comparison. The point cloud contains RGB values as well.

From the difference map T0-T1, it is clear that the deepest erosion is 1.07 m, but in general, the erosion depth is 0.2 to 0.8 m (Figure 47).

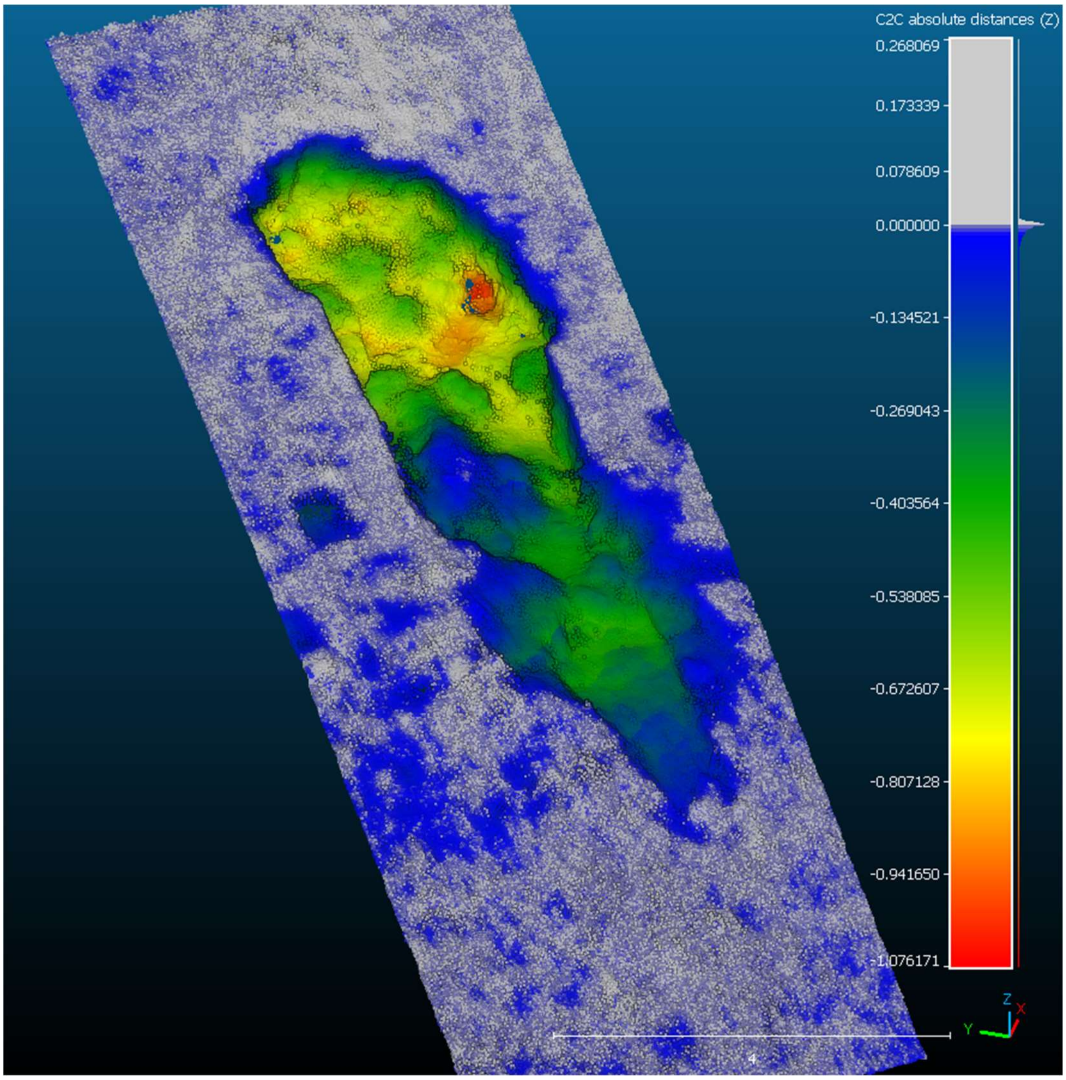

Figure 47 - 3D view of the height difference between the T0 and T1 measurement.

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7.5 First insights

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

- The presence of large burrows on a levee slope (with connection to inner core sands) give rise to fast and large erosion of the sand mound around the burrow.
- The burrow is thought to act as a entry point for water to flow into the levee and hereby saturating the sandy inner core. It is thought that this process is responsible for fluidization of the inner core and therefore lowering the strength of the levee cover layer, and ultimately giving rise to mass wasting.
- The levee slope collapses in little more than 1 hour under influence of overflow when a large burrow is present on the levee slope.

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8 N-OF05 B+C Damage repair retested

The repair of the damage in N-OF05 consisted of a clay infill (B) and a clay infill combined with a reinforced turf mat, type … (C) on which a seed mixture was applied.

These two subsections were retested, but failed very quickly. Although the vegetation may not have been developed as in a well-maintained grass cover, it was observed that on each section, gullies developed from the top of the levee downward. These gullies appeared to be about 2.5 m apart, the width of the tracks of the cranes that were used during the repair.

The differential compaction of the soil and the infill of the track depression with looser soil gave immediately rise to erosion of the soil in these track depressions, and thus forming gullies. The gullies cut through the cover layer and exposed the sand core. Whilst performing overflow on the 05C section, water flow was observed in the exposed sands of 05B.

The artefact of the crane tracks prevents from making any significant statement about the efficacy or quality of the damage repair solutions. Therefore, no detailed reporting about these tests is included in this report.

Figure 48 - Detail of the RTM solution on section N-OF05C.

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9 N-OF06 Reinforced Turf Mat

9.1 Test goal

The N-OF06 overflow test is part of a series of tests that involve Reinforced Turf Mats (RTMs). These RTMs are a form of protection that has been applied to a section of the levee after the top vegetation layer has been removed. After this removal, the underlying clay cover layer was exposed and subsequently covered with different solutions.

One of these solutions consisted of a geogrid that had been supplied by AWS Hydroseeding. The goal of the test is to assess the use of Reinforced Turf Mats, such as the Armormax® system combined with a hydroseeding applied under the RTM, as a fast and reliable repair measure after a vegetation layer has been removed after an overflow event and/or damage repair. We will refer to 'RTM solution' instead of the specific brand names in the subsequent text.

Figure 49 - Detail of the RTM solution.

9.2 Test setup

The N-OF06 RTM overflow test has been executed on the landward side of a Dutch levee in the Hedwige Prosper Polder (X = 140262.0 m; Y=226530.5 m or 4.22899451°E, 51.34846996°N). The maximum elevation of the crest is 11.9 m TAW[7] or 9.6 m NAP, while the landward to is situated at +/- 4.5 m TAW resp. 2.2 m NAP. The slope angle is 22° halfway the levee slope (which equals to a "10/4 slope"). Beyond the 52-m point on the horizontal axis in the profile figure, an asphalt road is present. At the end of the profile, a gully is present. Note that the marsh elevation is higher than the polder elevation.

[7] *TAW = "Tweede Algemene Waterpassing", the Belgian vertical reference. The reference plane is situated 2.33 m lower than the Dutch reference plane ('NAP' = 'Normaal Amsterdams Peil').*

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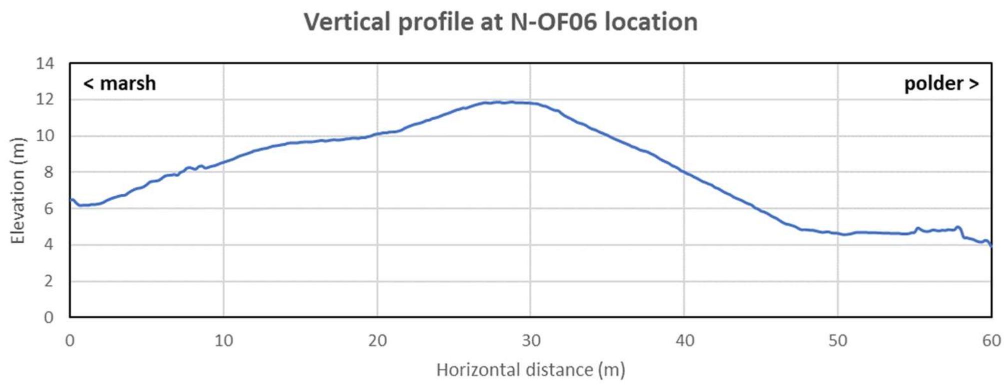

Figure 50: Vertical profile of the N-OF06 location.

The entire section has been stripped from its original vegetation and soil layer (approx. 10 to 15 cm of soil was removed). Over the whole length of the section, the RTM solution has been installed. The RTM consists of a hydroseeding layer (i.e. a layer of sprayed seeds) on which the geogrid has been placed and anchored.

The test setup for the execution of the test consists on and near the crest of a 2 m wide section that is boarded by wooden plates. The rest the section has not been constrained with the side boards so that the flow can find its way across the grass sods.

Sensors have been installed at the regular locations, however their functioning (VEL, WH) was very limited due to the fact that the overflow current took place through and under the RTM solution, hence the readings are meaningless. Two overhead cameras were installed as well.

9.3 Execution

The N-OF06 RTM overflow test was executed on 22/11/2021 between 8:30 and 12:10. The overflow test consists of 1 block of overflow with a duration of 1 hour and 5 minutes. A discharge of 10 m^3/min was applied.

A second block of overflow was started within the namespace of N-OF06 although it was a test in which the flow was diverted outside the test section and thus is not counted within the actual experiment.

9.4 Results

9.4.1 Visual description

From the onset of the overflow test, it was observed that the water was flowing through and under the RTM solution. Discharge water appearing at the toe was heavily sediment laden, which was an indication of strong erosion below the RTM.

During the experiment, it was observed that water was flowing out along two lines from the top to the bottom of the crest all the way down. These lines were about 40 cm wide and were separated by 2.5 m. It was considered and confirmed afterwards that these lines were actually corresponding to the tracks of the crane that was used during the removal of the grass cover and installation of the RTM solution. In this process, gullies were formed that were filled with (less compacted) soil afterwards. It is thought that this soil was quickly eroded and formed very

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deep (0.5 m) erosion channels. Simultaneously, the vegetation that is growing through the RTM solution was being torn away so that the geogrid itself is exposed on many places.

Given the artifact created by the crane track, it is considered unreasonable to make any conclusions regarding the RTM solution for slope stabilization and therefore, the test should be considered as a failure.

Note: adjacent to N-OF06, a different RTM solution was applied (not shown). To test the hypothesis of the crane tracks, a brief overflow was carried out on that section, which led to the same gully formation very quickly.

9.4.2 Video and photo imagery

The camera portal has been used to create following data:

- "B0": Initial state of the test (Folder: "NL_OF06_Q000_B00_S_1240")
- "B1": End state of the test (Folder: "NL_OF06_Q000_B01_S_1242")

Figure 51 - View on the gully after partial and complete removal of the RTM solution on section N-OF06.

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Figure 52: Surface state of N-OF06 before (left; B0) and after (right; B1) the overflow test. Top picture = camera 1; lower picture = camera 2).

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Figure 53: Surface state of N-OF06 before (left; B0) and after (right; B1) the overflow test. Top picture = camera 3; lower picture = camera 4).

9.4.3 Flow

During Block B01, images have been collected in order to visualize the current patterns. An example is shown in Figure 54. The flow pattern appears to be very irregular, which is caused by the flow under the RTM solution.

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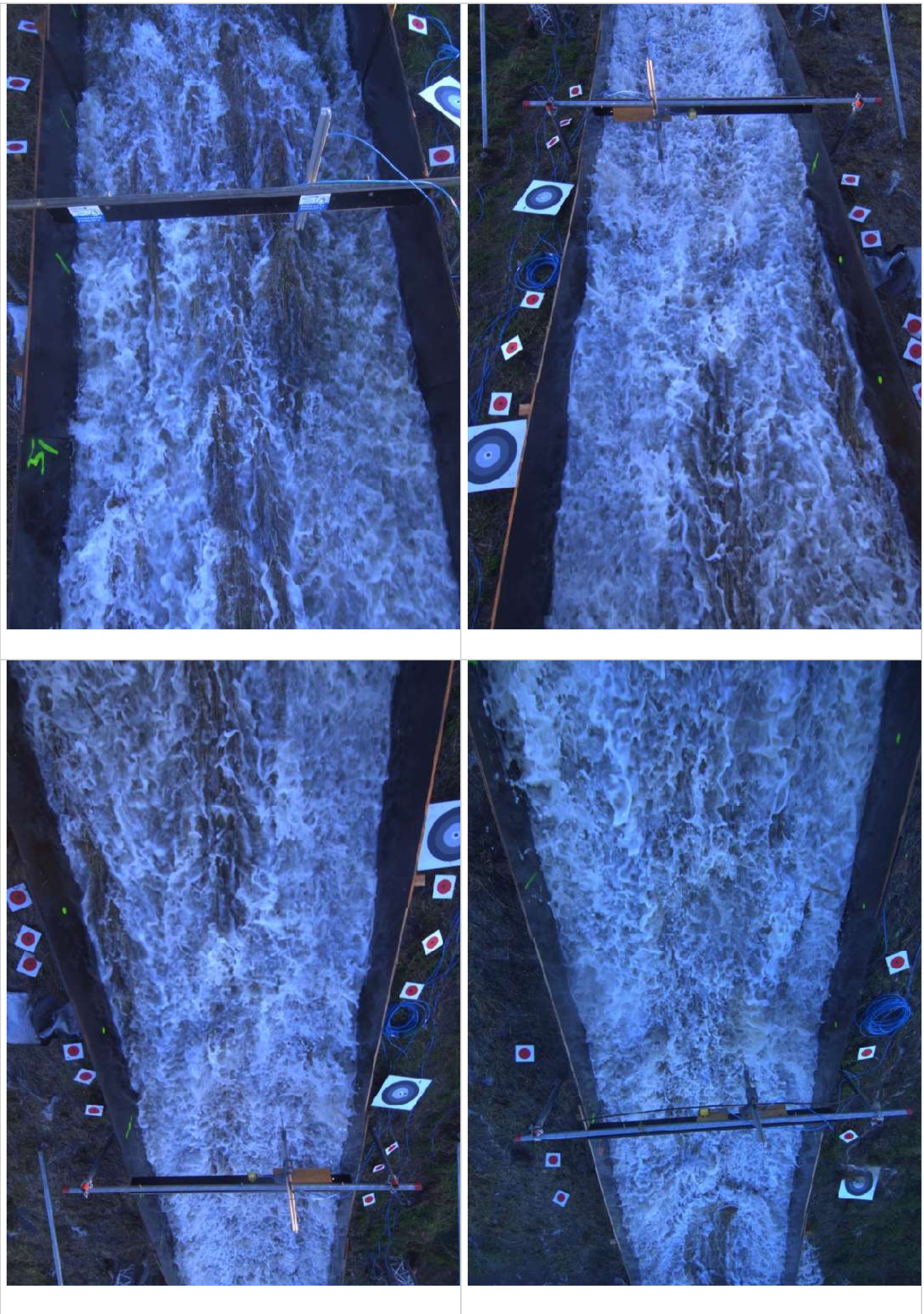

Figure 54: Flow pattern during the overflow test N-OF06. Left: camera 1 and 2; Right: camera 3 and 4.

9.4.4 3D Handheld lidar

The week after the experiment, the RTM cover was removed from the section (except for a couple of meters above the toe). At this moment, the damage created was measured by 3D Laser Scanning by DMOW and by Handheld Lidar (Ipad Pro) by STOWA.

Based on these measurements a comparison of quality and resolution was made.

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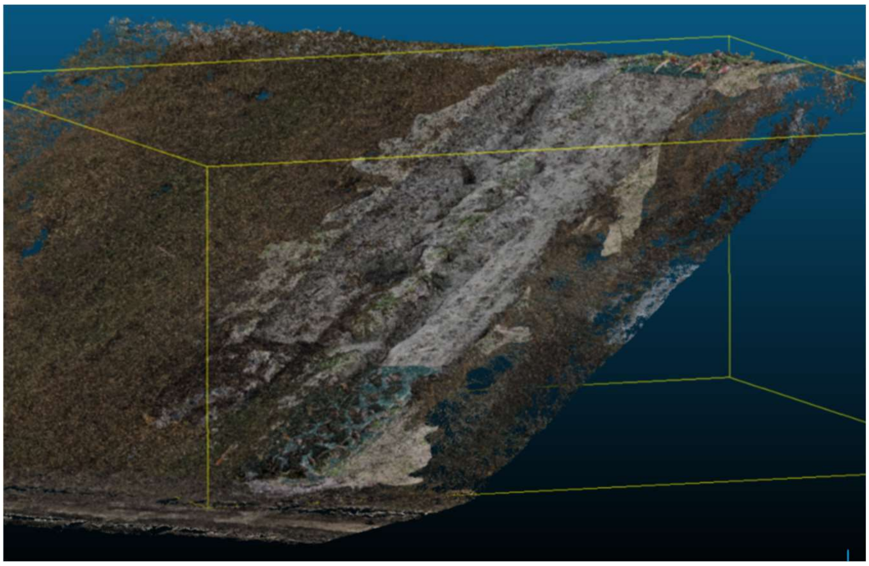

Figure 55: 3D view on the levee slope of sections N-OF05B and N-OF06 (Depreiter, D., 2022); Handheld lidar draped over terrestrial laser scanning data.

The preliminary conclusions in Depreiter (2022) are reproduced below, and will be further elaborated in a report:

1. The acquisition with IPad lidar yields internally consistent data.
2. The external referencing with IPad lidar includes no (external) georeferenced. Therefore, the data needs calibration to points measured with RTK-GPS or other methods with high absolute precision.
3. Comparison with 3D terrestrial laser scanning (georeferenced) yields a scaling error of 1 to 2% which does not seem to affect the qualitative results too much.
4. After registration (calibration) with an externally georerenced data source (here it is the 3D lidar scan) it appears that the overall error of the IPad point cloud is very small. Surface areas have generally errors of ~1 cm or better, and in areas with difficult topography (edges, depressions, ...) the error is no worse than 15 cm.
5. The quantitative differences indicate that IPad lidar acquisition may be very useful for quick and fairly accurate measurements of terrain surfaces.

9.5 First insights

- Given the artifact created by the crane track, it is considered unreasonable to make any conclusions regarding the RTM solution for slope stabilization and therefore, the test should be considered as a failure.

RTM's werden getest als noodmaatregel. Ze geven duidelijk geen instante sterkte...

- It appears from a first test that the 3D model generation based on handheld lidar measurement (using an iPad Pro 12) looks promising for operational use, and will be further investigated.

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10 N-OF07 Reinforced Turf Mat

10.1 Goal

The N-OF07 overflow test is part of a series of tests that involve Reinforced Turf Mats (RTMs). These RTMs are a form of protection that has been applied to a section of the levee after the top vegetation layer has been removed. After this removal, the underlying clay cover layer was exposed and subsequently covered with different solutions.

One of these solutions consisted of a geogrid. The goal of the test is to assess the use of Reinforced Turf Mats, such as the Tensar TriAx® (TX) Geogrids, as a fast and reliable repair measure after a vegetation layer has been removed after an overflow event and/or damage repair. We will refer to 'RTM solution' instead of the specific brand names in the subsequent text.

10.2 Setup

The N-OF07 RTM overflow test has been executed on the landward side of a Dutch levee in the Hedwige Prosper Polder (X = 140275.0 m; Y=226513.9 m or 4.22918148°E, 51.3483211°N). The maximum elevation of the crest is 11.9 m TAW[8] or 9.6 m NAP, while the landward sided toe is situated at +/- 4.5 m TAW resp. 2.2 m NAP. The slope angle is 22.5° halfway the levee slope (which equals to a "10/4 slope"). Beyond the 52-m point on the horizontal axis in the profile figure, an asphalt road is present. At the end of the profile, a gully is present.

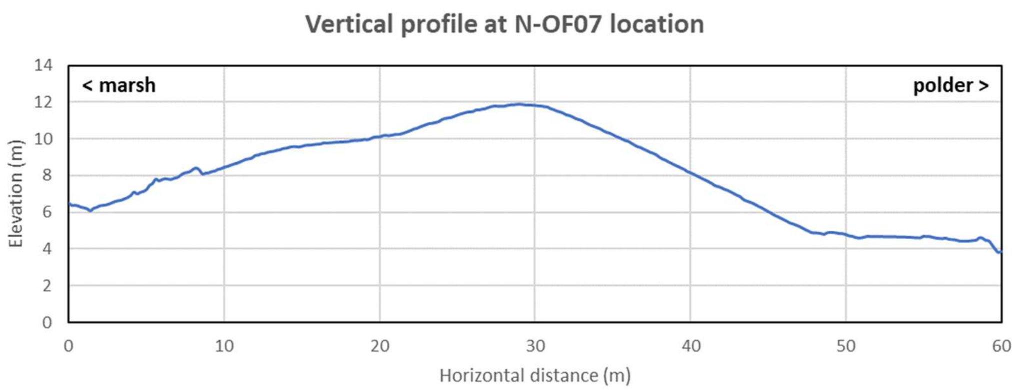

Figure 56: Vertical profile accross the N-OF07 test location.

The entire section has been stripped from its original vegetation and soil layer (approx. 10 to 15 cm of soil was removed). On the entire section, the RTM solution has been installed (Figure 58). The complete description and analysis of this solution is part of other Polder2C's reports and out of scope for the present report.

The setup for the execution of the test consists of a 2 m wide section that is restricted by wooden sideboardings limited to the upper part of the slope. Further down, the water is left free to search its way down the slope, over or though the geogrid. No sensors have been place,

[8] *TAW = "Tweede Algemene Waterpassing", the Belgian vertical reference. The reference plane is situated 2.33 m lower than the Dutch reference plane ('NAP' = 'Normaal Amsterdams Peil').*

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other than 1 camera frame. The reason for this limited setup is that the goal is to observe the performance of the RTM rather than assessing damage evolution or hydraulic behaviour.

Figure 57: Sensor locations on N-OF07.

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Figure 58: View of the Tensar Grid RTM installed on the N-OF07 section. The grass line in the middle is mainly due to grass growing through the solution where anchors have been placed.

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10.3 Execution

The execution of the overflow test was performed on 23/11/2021 between 12:40 and 13:10, and 1 block with a duration of 30 minutes. A discharge of 91 l/s was applied. The test was stopped due to severe erosion of sediments.

10.4 Results

10.4.1 Visual observations

From the onset of the overflow test, it was observed that the water was flowing through and under the geogrid solution. Discharge water appearing at the toe was heavily sediment laden, which was an indication of strong erosion below the RTM.

During the experiment, it was observed that water was flowing out along two lines from the top to the bottom of the crest all the way down. These lines were about 40 cm wide and were separated by 2.5 m. It was considered and confirmed afterwards that these lines were actually corresponding to the tracks of the crane that was used during the removal of the grass cover and installation of the RTM solution. In this process, gullies were formed that were filled with (less compacted) soil afterwards. It is thought that this soil was quickly eroded and formed very deep (0.25 - 0.5 m) erosion channels.

It was also observed that some of the anchors became partly loosened due to the erosion and the current action that created a drag force on the RTM solution.

10.4.2 Video and photo imagery

One camera portal has been placed on top of the section, close to the crest. An installation further downward was not possible because the RTM solution would have been damaged by this. An example is shown in Figure 59.

10.4.3 Monitoring timeseries

Only one block of data is present, and only 1 sensors (WH_CREST) was installed. The measurement yielded a water height at the crest of 15.4 cm, under a (nominal) discharge or 183 l/s corresponding to a specific discharge 92 l/s.m.

10.5 First insights

- The geogrid as a RTM solution is "transparent" to the flow of water and thus does not protect the underlying soil from erosion. Geen instant sterkte!
- The installation of the RTM solution by crane driving perpendicular to the crest line, up and down the slope, is not a suitable technique for this purpose.

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Figure 59 - Illustrations of the RTM solution at N-OF07 before and during overflow..

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11 N-OF08

This overflow test is "Under embargo". The N-OF08 test has been carried out as part of the PhD research of Kim van den Hoven of Wageningen University. Results, interpretations will be published via different channels.

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12 N-OF09 Burrow protection

12.1 Goal

The NL-OF09 overflow test section is characterized by a series of small (mice) burrows. It is know from previous tests that the presence of burrows may compromise the strength of the levee cover and invoke collapse if contact exists between the outside of the levee and the sand core, in which situation the outflow of sand through burrows may lead to collapse of the levee cover.

In order to prevent such process from occurring, a burrow protection mechanism has been devised, consisting of plastic plates that are anchored to the surface and to promote water to flow over the plates, and thus preventing from significant amounts of water to enter the levee surface layer (and sand core).

The test has been closely monitored by ERT measurements in the test section, as well as visual descriptions.

12.2 Setup

The N-OF009 Burrow Protection overflow test has been executed on the landward side of a Dutch levee in the Hedwige-Prosper Polder (X=140295.8 m; Y = 226487 m). The elevation of the crest is 12.1 m TAW[9], while the landward toe is situated at +/- 4.5 m TAW. The slope angle is 21° halfway the levee slope (which approximately equals to a "10/4 slope") (Figure 60). At the far end of the toe, a gully is present.

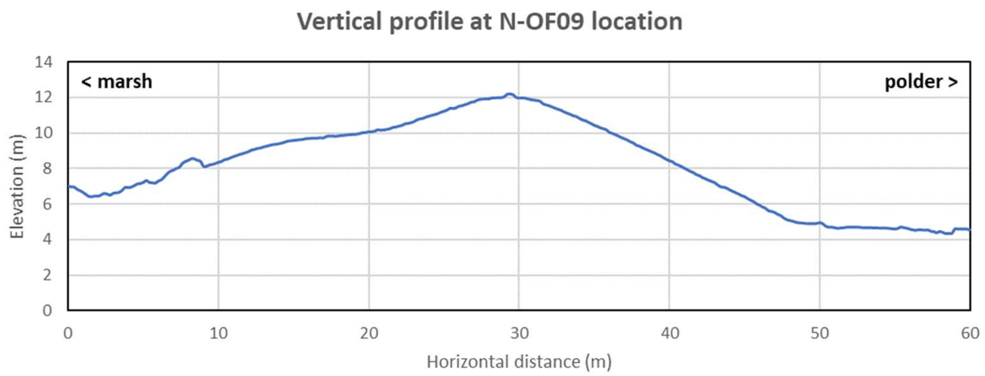

Figure 60: Topographical profile at N-OF09.

The monitoring of the test consisted of the default setup with water height and velocity sensors and overhead cameras as indicated on Figure 61. In addition to this, a geophysical setup has been executed with Electrical Resistivity Tomography to measure and image the impact of overflowing system on an underground burrow system.

[9] TAW = "Tweede Algemene Waterpassing", the Belgian vertical reference. The reference plane is situated 2.35 m lower than the Dutch reference plane ('NAP' = 'Normaal Amsterdams Peil').

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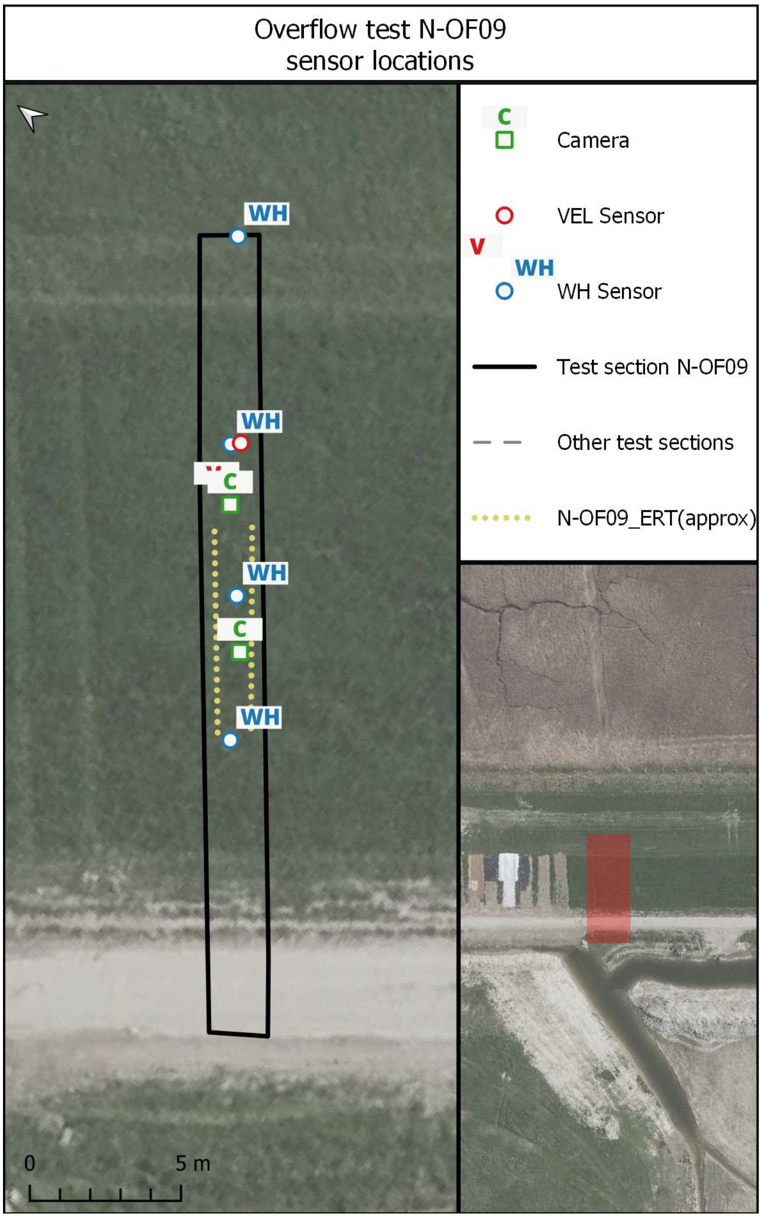

Figure 61: Sensor locations at N-OF09.

The pump employed to generate the discharge was a BA500 pump supplied by Waterschap Brabantse Delta. More details are given in Vercruysse et al. (2022).

12.3 Execution

For the execution of the N-OF09 test, 11 separate blocks of overflow have been executed between 25/11/2021 and 30/11/2021. The total amount of overflow added to 10 hours and 18 minutes.

Different discharges have been applied, ranging from) 39 l/s.m to500 L./s.m (1000 l/sec). Note that these are specific discharges based on the pump RPM settings during the experiments.

More details are listed in the annex with the timeseries images.

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12.4 Results

12.4.1 Visual observations

A detailed narrative of the N-OF09 test is given by Tsimopolou & Koelewijn (2022), focussing on the ERT measurements and the effect of the protection / cover of the slope anomalies (small burrows).

The ERT imaging showed the air-filled burrows and subsequently the filling with water. The cover with plates appeared to have worked well in this specific case as no damage evolution could be observed. Sandbags were put in place as well, but were displaced by the current very quickly.

12.4.2 Video and photo imagery

On the next pages, examples images of the setup are shown.

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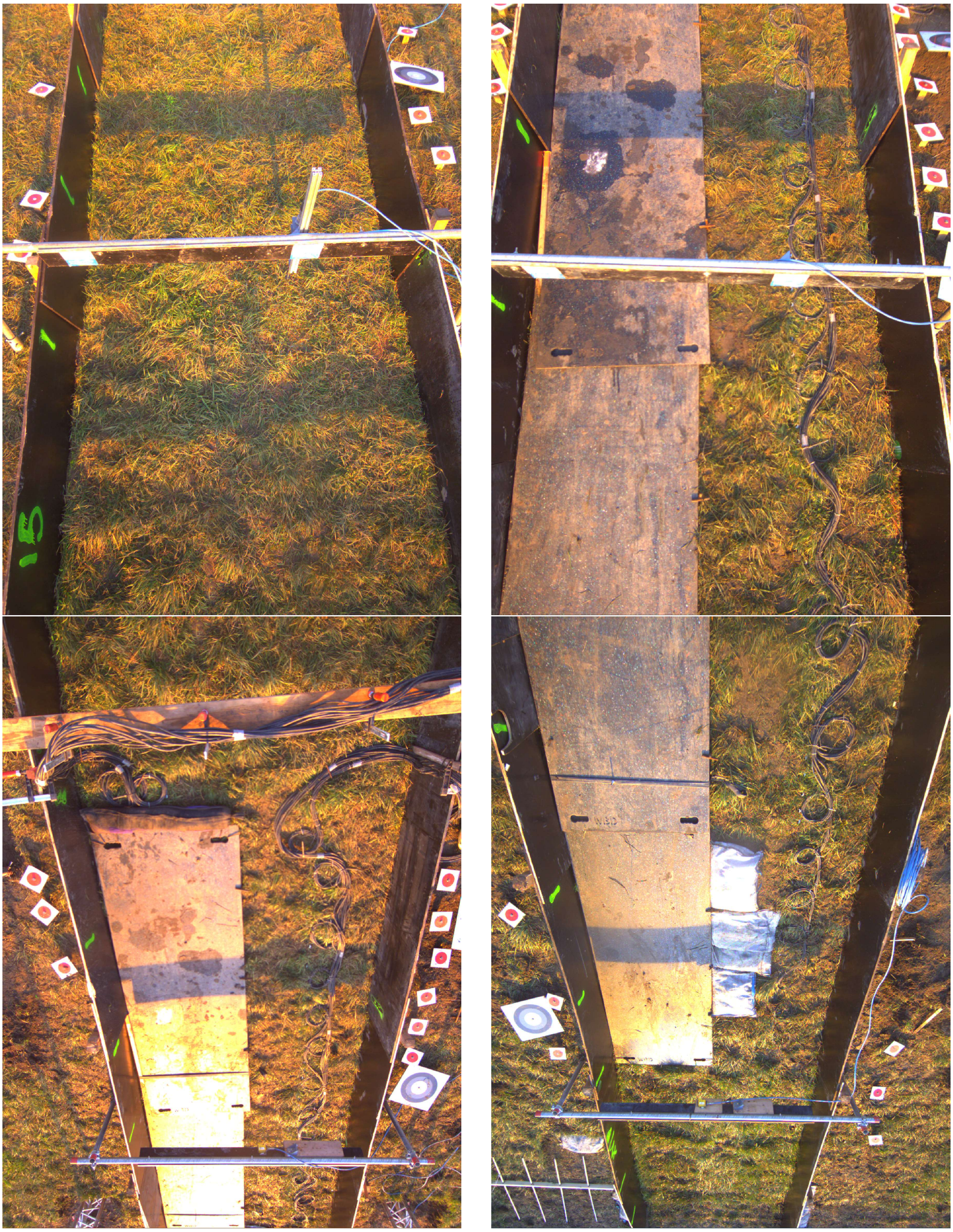
T0 with the protection plates installed (S1267)

Looking towards crest



Looking towards toe

Figure 62 – Setup of the N-OF09 experiment with protective plates and ERT equipment.

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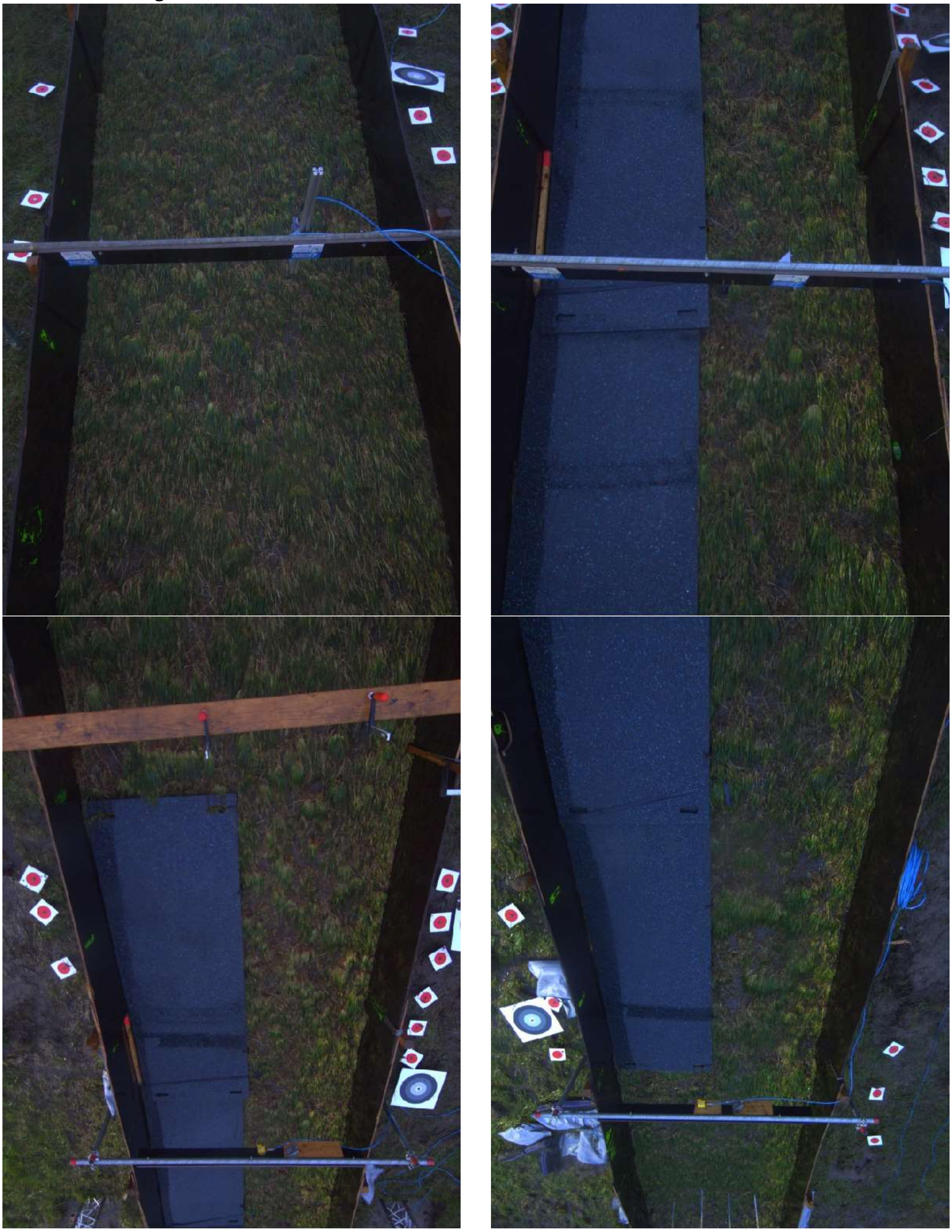
12.4.3 T0 with the protection plates installed

Looking towards crest



Looking towards toe

Figure 63 – Setup of the N-OF09 experiment with protective plates after overflow.

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12.4.4 Monitoring timeseries

The discharge applied during N-OF09 was variable from block to block, therefore it is not relevant to give overall statistics. Per-block details are given in the Annex document.

The discharges ranged from 65 l/s.m for the first block to 500 l/s.m for the last block; this variation is clearly reflected in the water levels at all but the WH_MOBILE sensor (Figure 64).

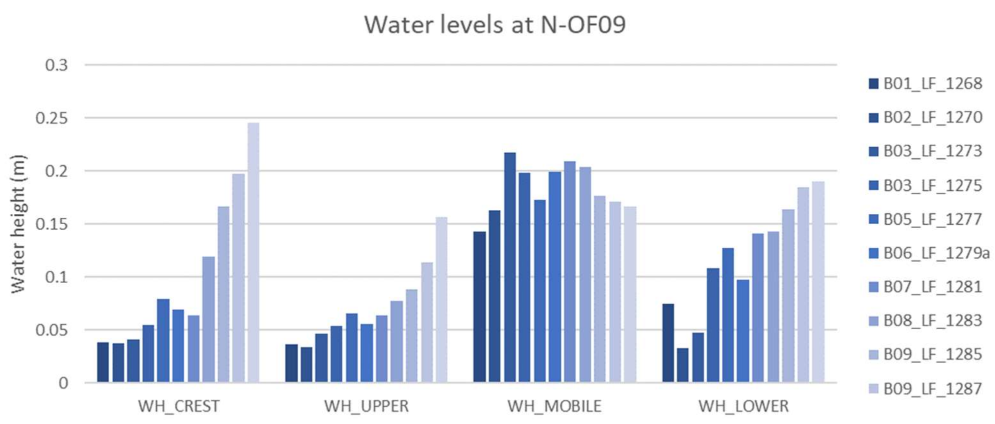

Figure 64 - Water level statistics for the N-OF09 experiment.

12.5 First insights

The complete conclusions based on this test are given in Tsimopolou & Koelewijn (2022).

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13 N-OF10 Reed vegetation

13.1 Goal

The N-OF10 overflow test was conducted to assess the impact of the presence of a wet spot on the lower half of the levee slope, on which a dense reed vegetation field had developed. Although the origin of the wetted part is thought to be due to a clogged drain at the levee toe, it is a good proxy for a levee on which seepage may occur, and/or combined with bad maintenance (no mowing and overgrowth).

13.2 Setup

The N-OF11 Reed Vegetation overflow test has been executed on the landward side of a Dutch levee in the Hedwige Prosper Polder (X = 140454.1 m; Y=226288.3 m or 4.2317508°E, 51.3462963°N). The maximum elevation of the crest is 11.8 m TAW[10] or 9.5 m NAP, while the landward to is situated at +/- 4 m TAW resp. 1.7 m NAP. The slope angle is 21° halfway the levee slope (which equals to a "11/4 slope"). Beyond the 55-m point on the horizontal axis in the profile figure, an asphalt road is present. Beyond the asphalt road a gully is present (not shown on the profile).

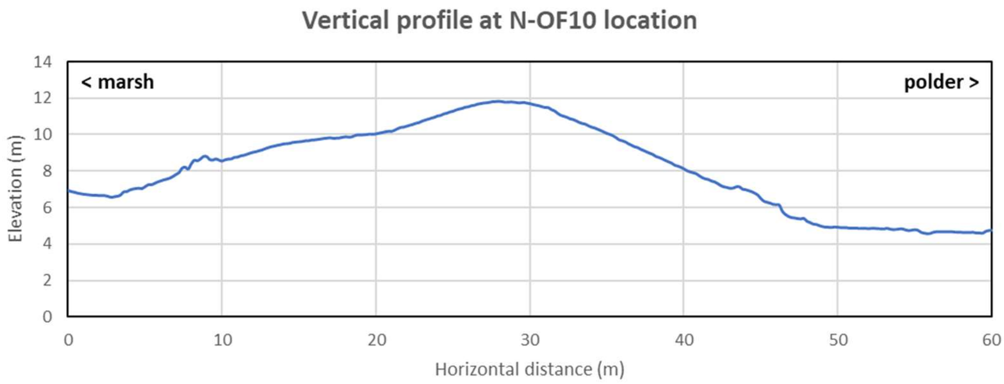

Figure 65: Vertical profile across the N-OF11 test location.

The upper part of the slope is characterized by normal vegetation without any significant visible anomalies or damage. However, the lower part of the levee is overgrown by higher vegetation and reed of +/- 5 m wide. The reed area corresponds to an area with very soft, moist soil. The reason for this 'wet area' is thought to be caused by a clogged drain at the toe of the levee (M. Booltinck, *pers. comm.*). The soil condition lead to the impossibility to mow the area by tractor, and has therefore not been mowed since many years.

The N-OF10 test setup comprises of a 2 m wide test section on which side boarding has been placed on the upper half of the slow. The lower part of the slope has not been constrained with side boards at 2 m but about 4m because the soil structure was very soft and a complex of roots of the vegetation. As a consequence, the overflowing water would spread wider than

[10] *TAW = "Tweede Algemene Waterpassing", the Belgian vertical reference. The reference plane is situated 2.33 m lower than the Dutch reference plane ('NAP' = 'Normaal Amsterdams Peil').*

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when it would be constrained. Sensors and 1 camera portal have been positioned above the vegetation area (see Figure 82).

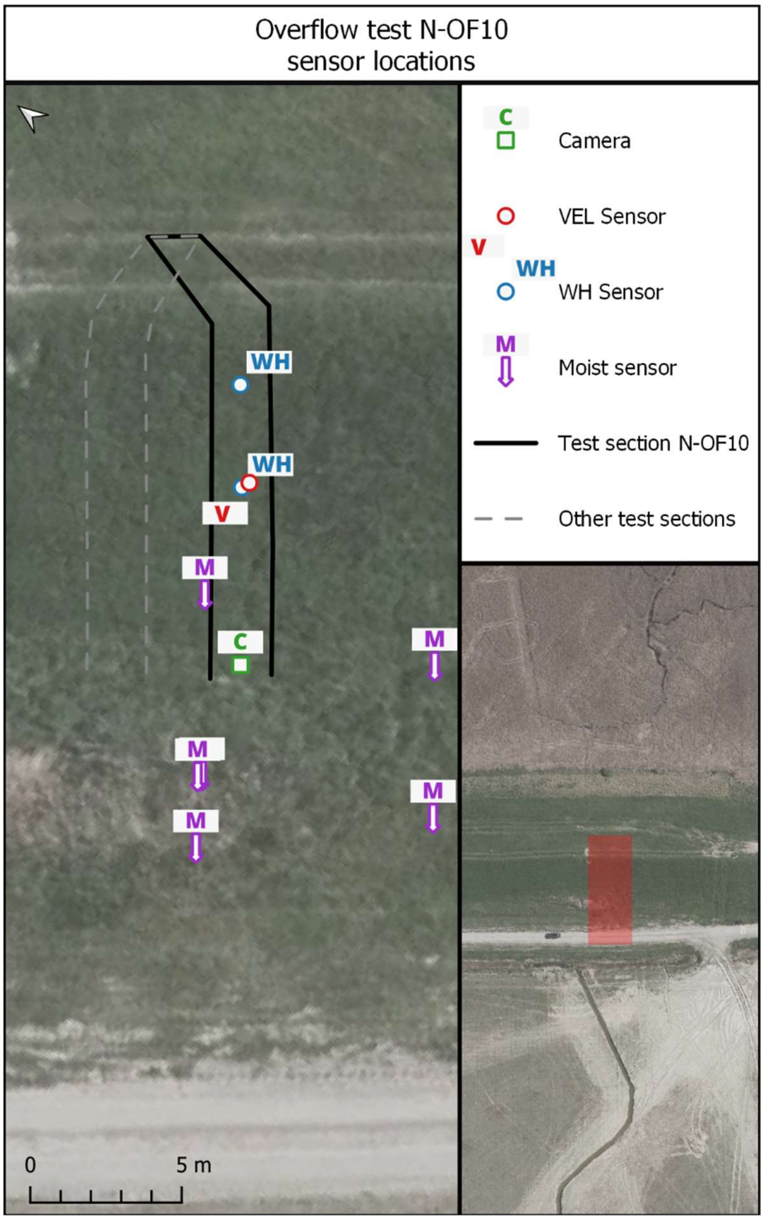

Figure 66: Sensor locations at N-OF10.

In the reed field, a number of soil moisture sensors have been placed to illustrate the evolution of this parameter over longer time.

The pump employed to generate the discharge was a BA500 pump supplied by Waterschap Brabantse Delta.

The N-OF10 test has been conducted shortly before the test N-OF11 (See Depreiter et al., 2022b); both test sections are parallel with a 2 m wide separation. The generator was placed in between the two sections and the overflow current was diverted with a bend in the boarding on the crest of the levee.

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Figure 67: Setup of NL-10 (right) and NL-11 (left).

Figure 68: View on the reed field in both sections N-OF10 and N-OF11.

13.3 Execution

The NL-OF10 overflow experiment took place on 13th of December 2021 between 11:38 and 12:39. Discharges applied were 330 to 450 l/s.

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As the role of these experiments was to see the influence of the reed and high vegetation presence on the overflow erosion process (or the lack thereof), the instrumentation with sensors was limited: 1 water level sensor at a higher position on the slope, and 1 water level sensor at a position about 3 m upwards from the reed vegetation patch. At this lowest position, a point velocity meter was installed as well.

On each of the sections, just 1 camera portal was installed and slightly slanted so that the vegetation patch would be well in view.

Figure 69: Setup of NL-10 (right) and NL-11 (left).

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Figure 70: Setup at NL-OF10

13.4 Results

13.4.1 Visual observations

During the overflow test on N-OF10, fast erosion of sediment from between the reed root system was observed. The water seemed to be following "stream channels" in between patches of reed that withheld better against the current. Just upward the reed, longer grass and other vegetation was present and those patches started to loosen quickly and erode. The vegetation layer was being 'undercut' by the current so that the vegetation layer started to loosen. Under the loosed vegetation, erosion progressed rapidly (as the soil itself was rather most and muddy). The sandy inner core appeared was reached quickly, after which sediment outflow

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over the toe of the levee was being observed. The experiment was stopped at the moment collapse and cracks appeared in the test section.

Some images are shown to illustrate the events from N-OF10.

Figure 71: Initial flow over N-OF10 (30 seconds into the test).

Figure 72: Impact of overflow on the reed at N-OF10.

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Figure 73: Flow through the reed at site NL-OF10.

Figure 74: Flow through the reed: aftermath of NL-OF10.

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Figure 75: Image of the vegetation roots exposed were soft soil has eroded.

Figure 76: Erosion down to the sand core of the levee.

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13.4.2 Video and photo imagery

The video portals have not been located on similar sites as in regular experiments. Here the placement was made so that the damage evolution would be visible.

The camera portal has been used to create following data:

Surface state (damage) images

Pictures have been taken before and after the experiment.

Surface flow images

Short episodes of images have been taken during the flow. An example is shown on the next pages.

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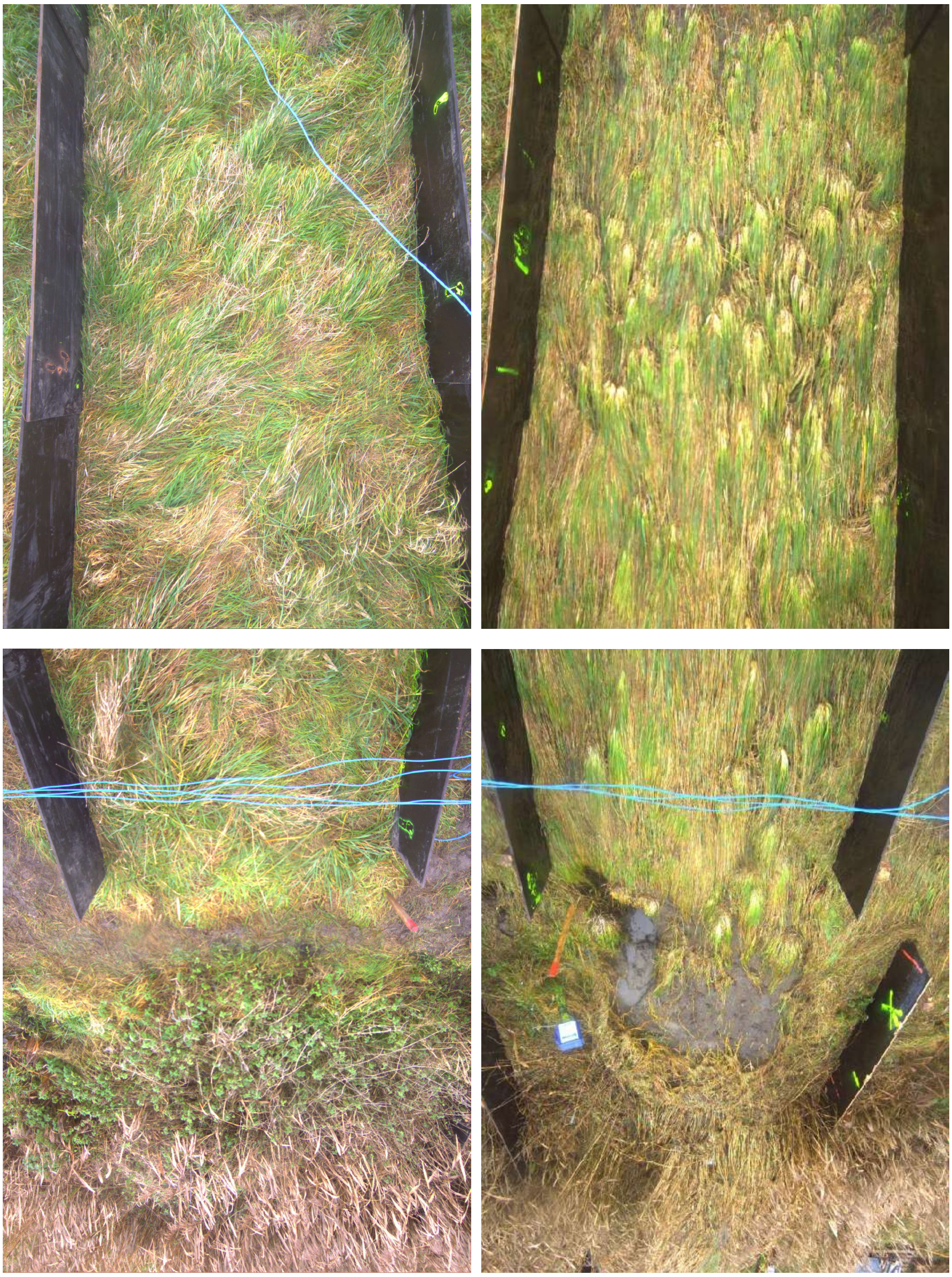
NL-OF10 initial state (B0) NL-OF10 end state (B1)

Looking towards crest



Looking towards reed field / toe

Figure 77: Damage state at the start and the end of the overflow test on section N-OF10.

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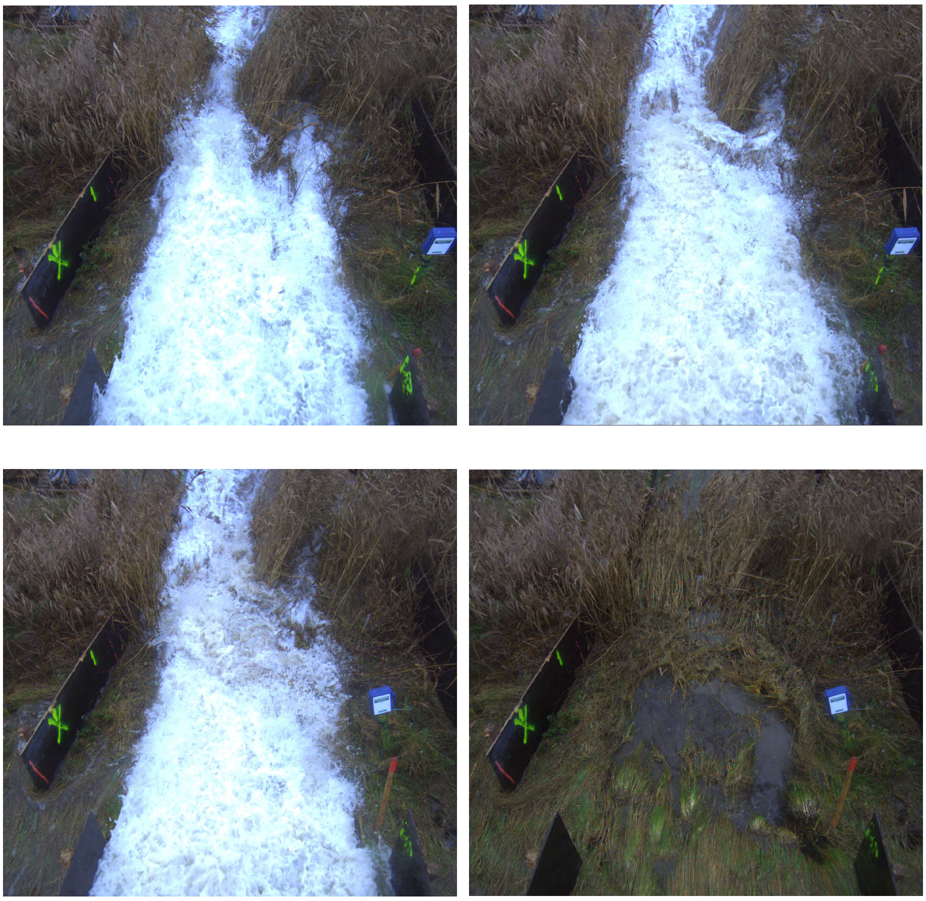

Figure 78: Evolution of damage at N_OF10 at 12:04 (top left), 12:30 (top right), 12:38 (bottom left, note the tilted sensor box) and 12:40 (bottom right, at the end of the overflow).

13.4.3 Monitoring timeseries

No discharge data is recorded, but the discharge applied corresponded to a pump power of 1200 and 1300 RPM which is similar to a specific discharge of ca. 180 resp. 230 l/s.m.

The average water level at the upper part of the slope was 5.1 cm, and at the middle part, just upwards of the vegetation, 13.98 cm (increased water height due to turbulence and foaming). At this place, the velocity averaged to 3.97 m/s.

The timeseries data are shown in the Annex document.

13.4.4 Soil moisture monitoring

A set of soil moisture sensors has been installed near the N-OF10 location in order to:

1/ register the long-term variations in soil moisture (seasonal drying and wetting)

2/ evaluating the moisture evolution in the reed patch (also in response to seasonal drying and wetting) and

The sensor system used, consists of a set of Irrometer Watermark sensors and a Irrometer 900M datalogger (https://irrometer.com/sensors.html).

The raw timeseries are shown in **Fout! Verwijzingsbron niet gevonden.**, the sensor positions in Figure 66. The sensor positions are chosen so that the following locations are monitored:

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- Above the reed vegetation area (Sensor name: "ABOVE")
- At the top of the reed vegetation area (Sensor name: "TOP")
- Inside the reed vegetation area (at 2 depths, inside the top layer and touching the sand core at +/- 60 cm) (Sensor names: "MID_SHALLOW" and "MID_DEEP")
- Below the reed vegetation area (most wet area) (Sensor name: "TOE")
- At the southeastern border of the reed vegetation area, above and inside the vegetation area (Sensor names: "SIDE_HI" and "SIDE_LO")

The sensor data is expressed as soil moisture tension in kPa. A low value of 0 indicates saturated conditions, whereas the maximum registered value of 254 kPa indicates dry conditions.

The sensors show two different behaviours:

- The sensors "ABOVE", "TOP", and "SIDE_HI" indicate cycles of drying and wetting, in response to meteorological conditions. The data in this sensors uses the range of full saturation to full drying.
- The sensor "MID_SHALLOW", situated in the reed patch but only 20 cm below the surface, shows partial drying cycles, especially during the extended periods of drought.
- The sensor "MID_DEEP" remains mostly or close to saturation during a long period. Suction remains below 20 kPa.
- The "SIDE_LO" and "TOE" sensors also remain saturated during the entire monitoring period, with a soil moisture suction of less than 5 kPa.

The measurements indicate that the normal surface vegetation layer dries and becomes wet during the months, in response to meteorological conditions. However, inside and at the base of the reed patch, the recordings indicate a continuous wet condition. This supports the visual observation of moist, wet soil in this area, but confirms that water must be present inside the levee structure. The presence of a clogged drain at the toe, would be a suitable explanation for the presence of stagnant water.

When compared to meteorological timeseries from a nearby station (Melsele, Belgium, situated about 15 km south of the location), it can be seen that the decrease in soil moisture tension often corresponds to the precipitation recorded. A perfect correspondence cannot be expected however due to the distance (approx. 13 km) between the meteorological observation station and the soil moisture sensor location.

From this data, it is also apparent that an extended drought period was present from mid-august '21 to mid-october '21.

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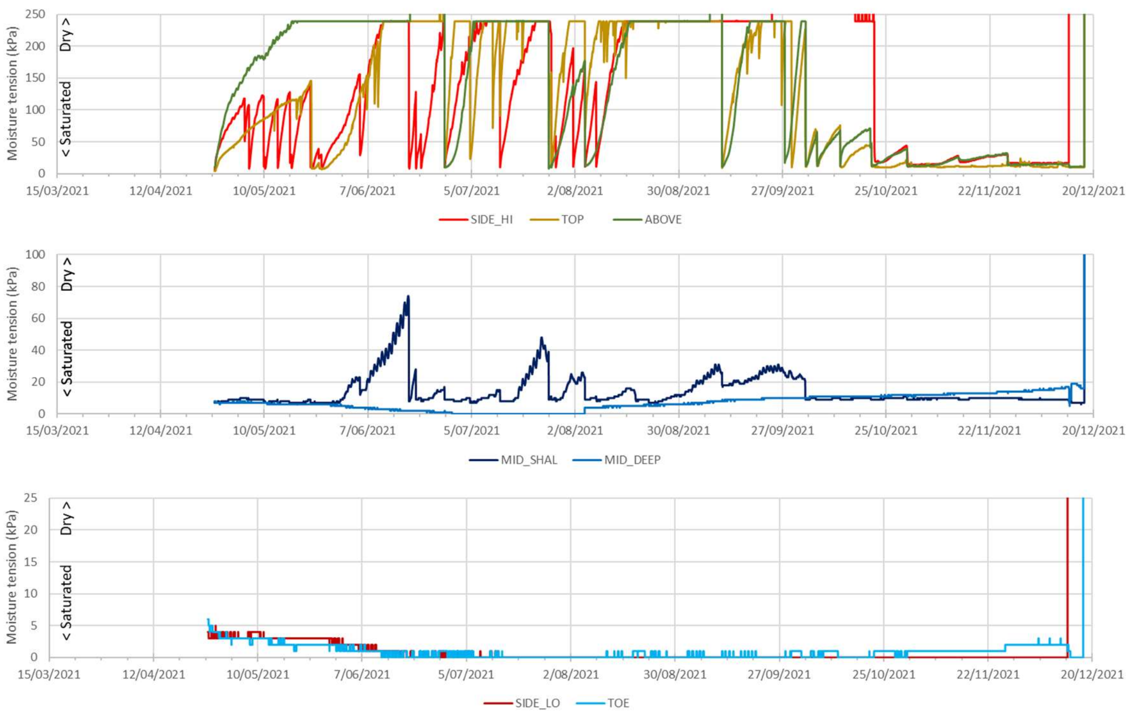

Figure 79 -Soil moisture and temperature evolution timeseries.

13.5 First insights

Based on the test results described in Chapter 3.3, first insights and conclusions can be formulated.

- The presence of a reed on a soft and moist soil patch, does not withstand an overflow event. After little more than 1 hour, significant damage is present.
- The root system of given reed patch does not stabilise the soil in between the roots, but give rise to fast significant erosion.

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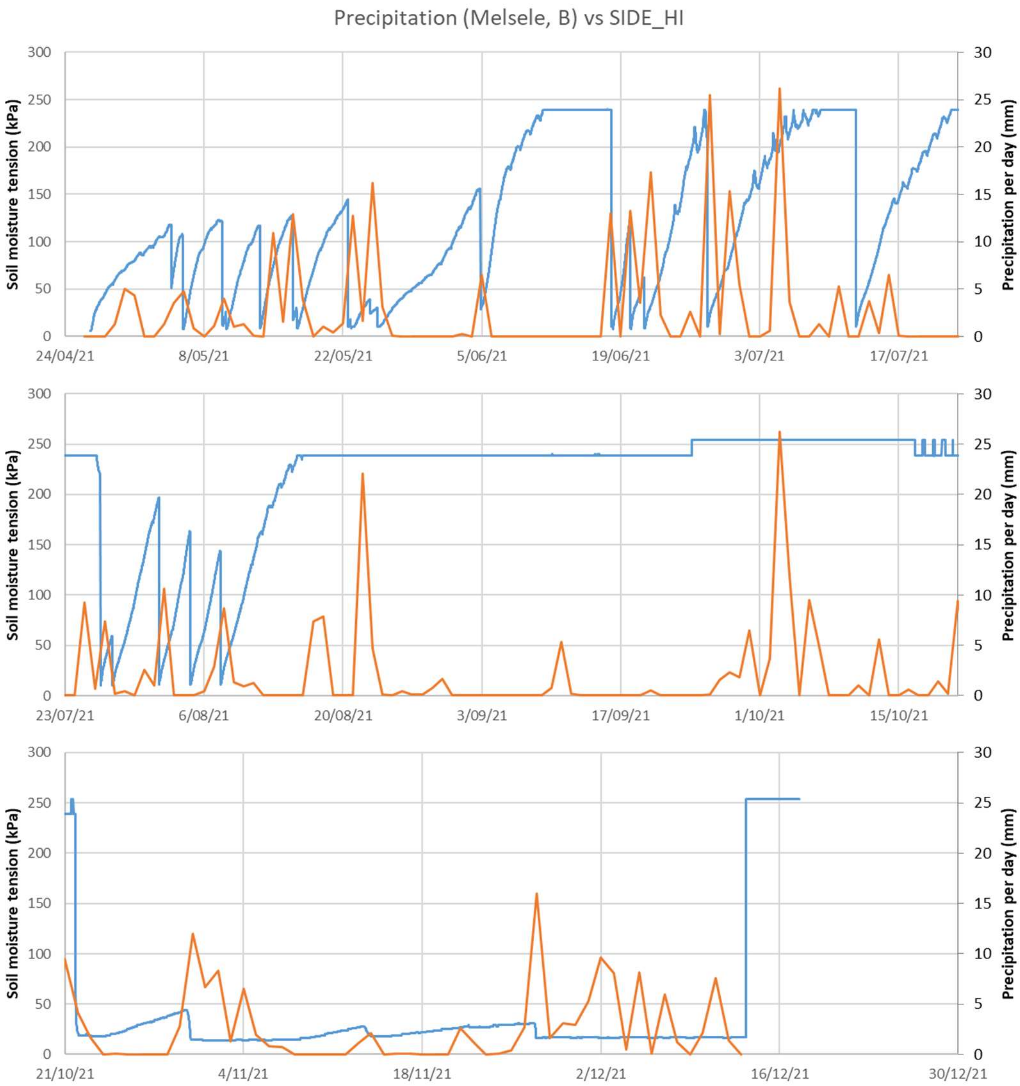

Figure 80: Precipitation (orange) vs soil moisture (blue).

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14 N-OF11 Reed vegetation

14.1 Goal

The N-OF11 overflow test was conducted to assess the impact of the presence of a wet spot on the lower half of the levee slope, on which a dense reed vegetation field had developed. Although the origin of the wetted part is thought to be due to a clogged drain at the levee toe, it is a good proxy for a levee on which seepage may occur, and/or combined with bad maintenance (no mowing and overgrowth). Note that the test on section N-OF11 is a double of the test on section N-OF10.

14.2 Test setup

The N-OF11 Reed Vegetation overflow test has been executed on the landward side of a Dutch levee in the Hedwige Prosper Polder (X = 140451.4 m; Y=226291.7 m or 4.23171917°E, 51.34632681°N). The maximum elevation of the crest is 11.8 m TAW[11] or 9.5 m NAP, while the landward to is situated at +/- 4 m TAW resp. 1.7 m NAP. The slope angle is 21° halfway the levee slope (which equals to a "11/4 slope"). Beyond the 55-m point on the horizontal axis in the profile figure, an asphalt road is present. Beyond the a gully is present (not shown on the profile) which was used for water recirculation.

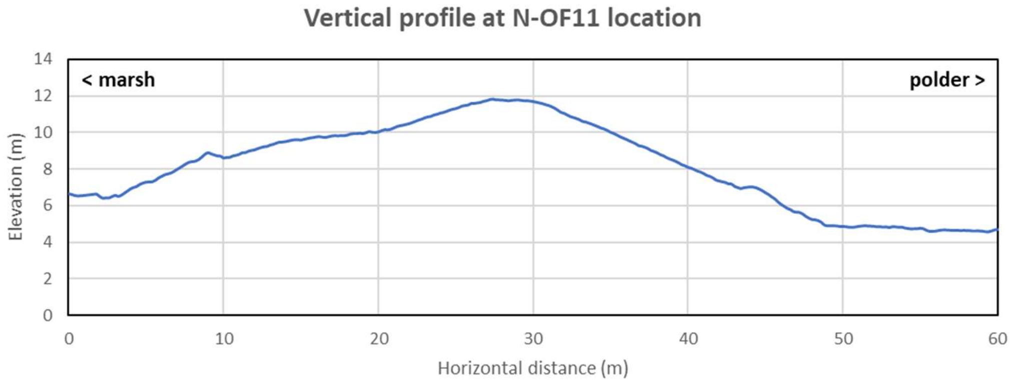

Figure 81: Vertical profile across the N-OF11 test location.

The setup and description is similar as for the setup of N-OF10 (see previous chapter). See Figure 82 for the setup of the sensors.

[11] *TAW = "Tweede Algemene Waterpassing", the Belgian vertical reference. The reference plane is situated 2.33 m lower than the Dutch reference plane ('NAP' = 'Normaal Amsterdams Peil').*

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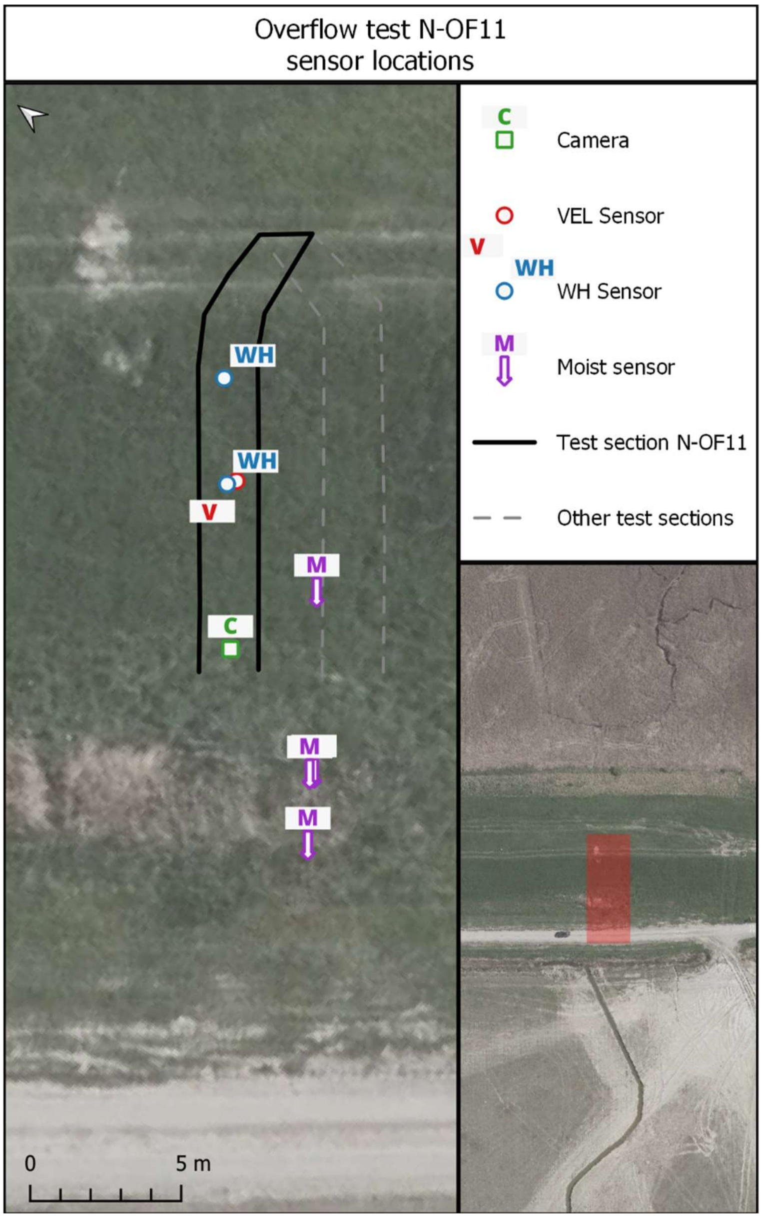

Figure 82: Sensor locations on N-OF11.

The pump employed to generate the discharge was a BA500 pump supplied by Waterschap Brabantse Delta. See Vercruysse et al. (2022) for more information.

The N-OF11 test has been conducted shortly after the test N-OF10 (see previous chapter); both test sections are parallel with a 2 m wide separation. The generator was placed in between the two sections and the overflow current was diverted with a bend in the boarding on the crest of the levee.

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Figure 83: View on the reed field in both sections N-OF10 and N-OF11.

14.3 Execution

The NL-OF10 overflow experiment took place on 13th of December 2021 between 13:58 and 14:25. Specific discharges applied were 167 to 250 l/s.m. The overflow test on N-OF11 consisted of 1 block of overflow with a duration of 28 minutes.

14.4 Results

14.4.1 Visual observation

From the onset of the test, very fast erosion of sediment in between the reed root system is observed. The colour of the water downstream the reed is very dark brown, hence very turbid. The erosion evolves quickly and a washed out root / vegetation layer becomes visible within 10 minutes (Figure 84). The water flow is detaching the vegetation layer above the reed section from the soil, and flowing under it. Therefore, the erosion process is not visible anymore.

However, due to the pre-existing cracks and cliff formation nearby (N-OF10 test section), the soil destabilizes after +/- 25 minutes and large instability occurs (Figure 85). This evolution started at the side closest to N-OF10 and evolved over the rest of the width of the section. At this point, it is decided to stop further testing.

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Figure 84: Impact of the overflow onto the reed path – note that the root is increasingly being exposed.

Figure 85: Outcome of the N-OF11 test after merely 28 minutes of overflow. The erosion on the right side of the picture is also due to the N-OF10 test.

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14.4.2 Video and photo imagery

The video portals have not been located on similar sites as in regular experiments. Here the placement was made so that the damage evolution would be visible.

The camera portal has been used to create following data:

Surface state

Images of the surface state of the levee slope have been taken only of the transition area between the slope and the reed filed. Images were taken before and after the test.

The dataset also contains additional field pictures and videos.

Figure 86: Situation of the high vegetation and reed patch before the start of the overflow experiment (13:37).

Figure 87: Example of flow patterns at the moment of the collapse (note the outflow on the left of the section) (left, 14:17) and after the overflow event was stopped (right; 14:24)

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Figure 88: Situation of the high vegetation and reed patch after the overflow experiment (14:30).

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14.4.3 Timeseries

Only 1 block of overflow was executed. Sensor positions (see Figure 82):

- WH_UPPER: Water level sensor in upper portal position
- WH_MOBILE: Water level sensor in lower portal position
- VEL_UPPER: Velocity sensor in lower portal position. Sensor data is not reliable.

No discharge data is recorded, but the discharge applied corresponded to a pump power of 1200 and 1300 RPM which is similar to a specific discharge of ca. 185 resp. 230 l/s.m.

Average values are:

- Mean water level at upper portal: 7,0 cm.
- Mean water level at lower portal: 9,9 cm.
- Mean velocity on slope above reed field: 1,8 m/s (deemed not reliable, see figure below).

The complete timeseries information is shown in the Annex document.

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14.5 First insights

Based on the test results of N-OF11 described in Chapter 3.3, first insights and conclusions can be formulated. Further integration of test results are discussed in a summary report [Depreiter et al., 2022a] and other future analysis reports.

- The test on reed section N-OF-11 confirms the findings from test N-OF10.
- The presence of a reed on a soft and moist soil patch, does not withstand an overflow event. After less than 30 minutes, significant damage is present.
- The root system of given reed patch does not stabilise the soil in between the roots, but give rise to fast significant erosion.

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