Photogrammetry measurements of wave overtopping erosion on a seashore dike

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ABSTRACT: The upward trend in construction in low-land coastal areas and loose restrictions on constructions on landside dike slopes is raising the essential need for in-depth examination of existing defense structures. In the context of the Polder2C's project and in terms of soil erodibility under wave overtopping condition, two main experimental set-ups were used to assess the strength of existing defense structures. Erosion progression of a seashore earthen dike under wave overtopping was monitored using close-range photogrammetry. Two principal experimental set-ups were considered: (1) measurement of the erosion rate and the residual strength of a clay cover layer protecting the dike sand core, the clay layer being located underneath a partially bared grass sod, (2) evaluation of the erosion resistance of lime-treated clay intended to increase soil resistance at the interface between soil and structures. The results show to applicability of the method in this challenging context.

1 INTRODUCTION

Deltas are often regions prone to uncontrolled urban and industrial development. Low-land coastal regions of the Netherlands and Belgium both suffer the issue of buildings and infrastructure construction located close to defense structures, which can significantly increase the loss of life, property damage, and infrastructure vulnerabilities associated with coastal flooding (Chen et al. 2017).

Rising sea levels and increased water levels due to storm surges in combination with rainfalls of increased intensity and frequency greatly increase the risk of inundation of densely populated coastal areas and river flood plains. The 'room for the river' idea was derived from the contemporary extensive flood events and subsequent damage in the Netherlands during the 1990s. Giving more room to the rivers can be achieved in various forms such as relocating dikes more landward, increasing the channels' capacity, or building flood control areas surrounded by a ring dike (Steendam et al. 2006). The concept is already accomplished through more than 30 projects in the Netherlands (Rijkswaterstaat, 2022). Among those, the Polder2C's project (https://polder2cs.eu/) is dedicated to coping with the upcoming consequences of climate change in the coastal regions along the Southern North Sea and the Channel area. A 6 km^2 surface is converted into a natural tidal zone in the Hedwige-Prosper polder at the borderline of Belgium and Netherlands (Figure 1) allowing a gigantic laboratory to conduct a wide range of experiments at different scales and to practice emergency response activities.

Figure 1. Arial view of Polder2C's site and erosion experiments location

The outcomes of the tests are important since they will serve as reference data for validation and calibration of numerical models aimed at flood modelling used in the process of developing new standards and guidelines for constructing more resilient structures. Therefore, a series of destructive full-scale tests with a focus on the soil erodibility were conducted under two dominant hydraulic conditions: river overflowing described in Rikkert et al. (2021) and wave overtopping presented here. Indeed, in more than 60 % of cases, these two factors are the failure causes of estuarine and coastal dikes.

To collect as much information as possible during wave overtopping erosion tests, the close-range photogrammetry method (Peter Heng et al. 2010, d'Odeigne et al. 2018) was applied to monitor erosion progression of the in-situ clay and a new clay mixture aimed at increasing the soil resistance. After placement of topographical control points on the field, photos were recorded using GoPro cameras and then treated using the Metashape software to extract elevation data during the process.

The paper is organized as follows: first, we present the test site and the field experiments, then the photogrammetry measurement technique applied to our site is presented, and finally we discuss the results.

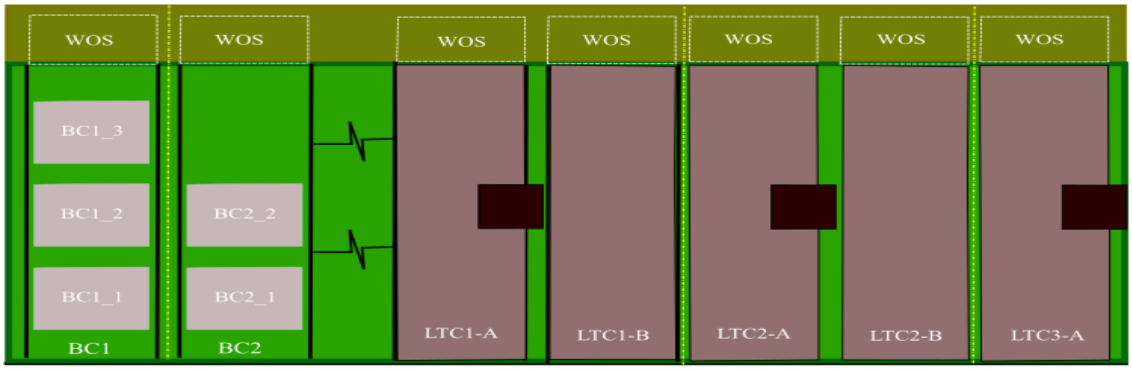
2 WAVE OVERTOPPING TESTS

Full-scale tests using a Wave Overtopping Simulator located on the dike crest were conducted at two different locations as indicated in Figure 2. The Wave Overtopping Simulator (WOS) performance is described in details by Van der Meer et al. (2007). It allows delivering prescribed water discharges or volumes under the form of a series of pulses, to mimic a natural wave overtopping of a dike.

The Wave Overtopping Simulator was used to reproduce a 2-hours storm duration considering irregular and regular waves. Irregular overtopping waves are characterized by their significant wave height (H_s) and the mean discharge released from the simulator during each pulse and usually expressed in l/s/m or m^3/s/m (Van der Meer et al., 2007). Regular waves are only defined based on the total volume of water per wave and on the number of pulses generated by the simulator to achieve this total volume.

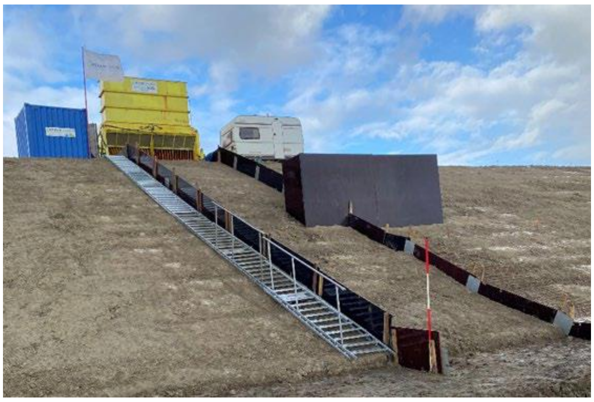
Two series of overtopping tests focusing on soil erodibility were conducted with different aims: (1) evaluate the performance of the existing clay underneath the grass sod, which acts as a protection layer for the dike's sand core, and (2), test the implementation of lime-treated clay to enhance the clay erosion resistance and resolve weak points at the interface between soil and structure. Hereafter, the first type of experiments is called bare-clay test series (BC) and the second type lime-treated clay test series (LTC). Figure 2a indicates the locations of these tests series on the dike, as well as the subsections for the bare clay series. For each test, the wave simulator is placed at the dike's crest and wooden walls were installed over the entire levee's slope to delimit the test section as illustrated in Figure 2. The details of the test sections are reported in Table 1.

The first series of experiments (BC experiments) aims to assess the residual strength of the clay underneath the grass cover, if the grass were to fail. Therefore, a 0.2 m upper layer of grass-covered soil was removed over a 14 m² area (4 m width and 3.5 m length), at several locations on the dike, in successive tests, as indicated in Table 1. Regular and irregular waves were considered. The regular wave generation for the BC1 tests is described in Table 2: at each stage of the wave overtopping process, the prescribed water volume is distributed in a series of *N* pulses, each pulse lasting a few seconds. This regular wave generation was also applied to one LTC test of the second series.



(a)

(b)



(c)

Figure 2. (a) Test sections layout of Bare clay tests (BC) and Lime-treated clay (LTC), (b) Typical bare clay test section, and (c) Lime-treated clay test section in presence of obstacle

The second series of tests aims to evaluate the erosion resistance of lime-treated clay intended to increase soil resistance, and to check its efficiency at the interface between soil and structures. Therefore, wooden structures were placed on the inland dike slope as illustrated in Figure 2c. As indicated in Table 1, tests LTCx_A denote the tests conducted with the presence of the wooden obstacle, while tests LTCx_B denote tests conducted without obstacle. For these tests, irregular waves were considered, with specific discharges and significant wave heights as mentioned in Table 3.

To increase experiments efficiency and avoid repetitive results, test program was adjusted following the observations made for the first subsection of each test type. For example, the waves pattern of the BC1_2 and BC1_3 was changed based on the soil performance during BC1_1 test.

Table 1. Wave overtopping test types

Test name	Test type	Overtopping wave
BC1_1	Bare clay	Regular waves with constant discharge
BC1_2	Bare clay	Regular waves with constant discharge
BC1_3	Bare clay	Regular waves with constant discharge
BC2_1	Bare clay	Irregular waves
BC2_2	Bare clay	Irregular waves
LTC1_A	Lime-treated clay	Irregular waves – with obstacle
LTC1_B	Lime-treated clay	Irregular waves
LTC2_A	Lime-treated clay	Irregular waves – with obstacle
LTC2_B	Lime-treated clay	Regular and irregular waves
LTC3_A	Lime-treated clay	Irregular waves – with obstacle

Table 2. Regular Wave Overtopping: wave patterns and pulses

Bare clay: Section 1 (BC1)														
BC1_1	N	20	20	20	20	20	20	20	10	10				
	Vol [l/m]	100	150	200	350	500	700	1000	1500	2000				
BC1_2	N	10	10	10	20	20	20	20	20	20	10			
	*V*ol [l/m]	1500	2000	1500	1000	700	500	350	200	100	1500			
BC1_3	N	10	10	10	10	10	20	20	20	20	24	20	5	5
	*V*ol [l/m]	1500	2000	2500	2000	1500	1000	700	500	350	200	100	2500	3000
Lime-treated clay														
LTC2_B	N	200	200	100	100	50	25	20						
	*V*ol [l/m]	100	250	500	1000	2000	3000	3400						

Table 3. Irregular Wave Overtopping Wave height and discharge

Test name	Height H_s (m)	Discharge q ($m^3/s/m$)
BC2_1	0.5	0.060
BC2_2	1	0.050
All LTC tests	1	0.010
	1	0.030
LTC1_A, LTC1_B, LTC2_A, LTC3_A	1	0.050
	1	0.190
	2	0.050

3 FIELD MEASUREMENTS BY PHOTOGRAMMETRY

Besides the observations and interpretations that had been made during the experiments to evaluate the soil erodibility and speed of erosion progression, two different methods were used to record the erosion: photogrammetry measurements to monitor the whole test section, and a RTK GNSS system to measure the bed elevation as some locations within the test sections.

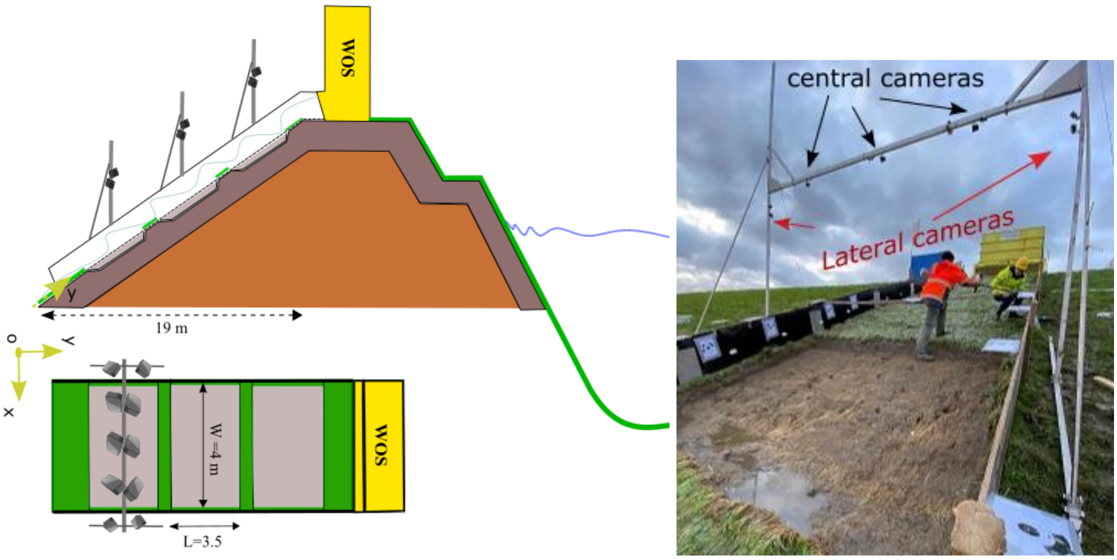
Photogrammetry has been widely used to measure the morphological evolutions of the rivers over time (Lane 2000, Baker, & Lane 2017, Carrivick, & Smith2019), and a good accuracy can be expected (Gesch et al. 2015). In this work, the Agisoft Metashape software is used to process the images and construct a Digital Elevation Model (DEM) of the test section, defined in the global coordinates system thanks to the control points with known coordinates. DEM are built for each test to quantify the soil erosion rate. Comparisons between with the RTK GNSS measurements allow to assess the accuracy of the photogrammetry measurements.

The image acquisition process for each test series is described below: it consisted of several fixed cameras for the BC tests, and of one moving camera for the LTC tests.

3.1 *Bare clay erosion tests- Fixed cameras installed on a rigid frame*

The bare clay tests were run under regular waves with short time delay between pulses. After each pulse, the water leaves the test section by flowing downward in such a way that pictures can be taken without the presence of water. As the time delay between two successive pulses was too short to move one single camera around the test section, it was decided to place 10 GoPro Hero 9 cameras on a rigid frame with a proper arrangement to cover the entire test area simultaneously. This is illustrated in Figure 3 where the ground control points (GCP) allowing to transform the results into global coordinates, can also be identified around the test section. The exact coordinates of these GCPs was measured using the RTK GNSS system.

Sufficient overlap between the images acquired by the different cameras ensured that the photogrammetry treatment could be performed successfully. This overlap is made easier by the use of GoPro cameras equipped with a fisheye lens with a 3-mm focal length. The images resolution is 5184 × 3888, resulting in a pixel size of about to 1.34×1.34 µm considering the placement of the cameras.



(a) (b)

Figure 3. (a) Sketch of the experimental setup for the BC test series, and (b) rigid frame with the 10 mounted cameras.

3.2 *Lime-treated tests- Structure from motion (SfM)*

These tests were run under irregular waves with variable discharge and height, as illustrated in Table3. In this case, it was possible to walk around the test section after the water had left region of interest with one GoPro camera fixed on a 3 m long stick, to capture a sufficient number of images to perform the photogrammetric treatment. A typical image that was recorded during such a test is illustrated in Figure 4.

Here the overlap between images is ensured by the continuous record of images at a rate of one image per two seconds and an overall 70 pictures per section. So, for one single test, the total number of images could be significantly higher than in the previous case, allowing for an easier treatment.

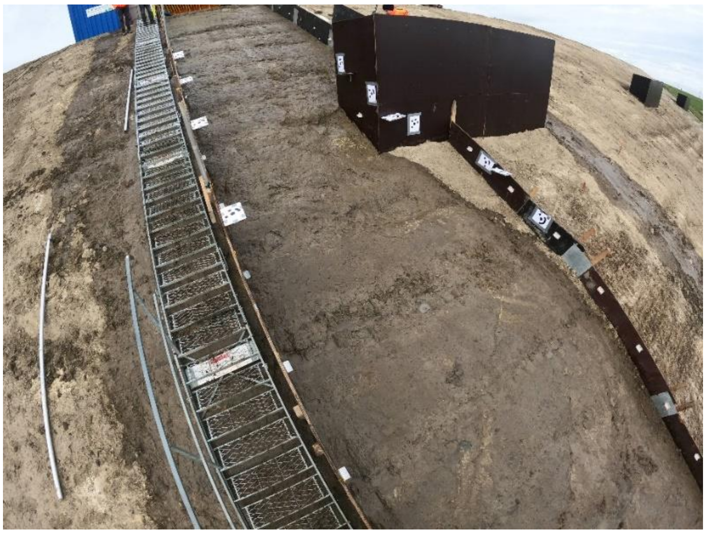


Figure 4. Test section for the lime-treated clay tests

4 RESULTS AND DISCUSSION

To assess the validity of the photogrammetric measurements, the final bed elevation after test BC1_1 was compared to the manual GPS measurements at several points distributed along the test section. As illustrated in Figure 5, the results show a good agreement, with a RMSE of 0.04 m.

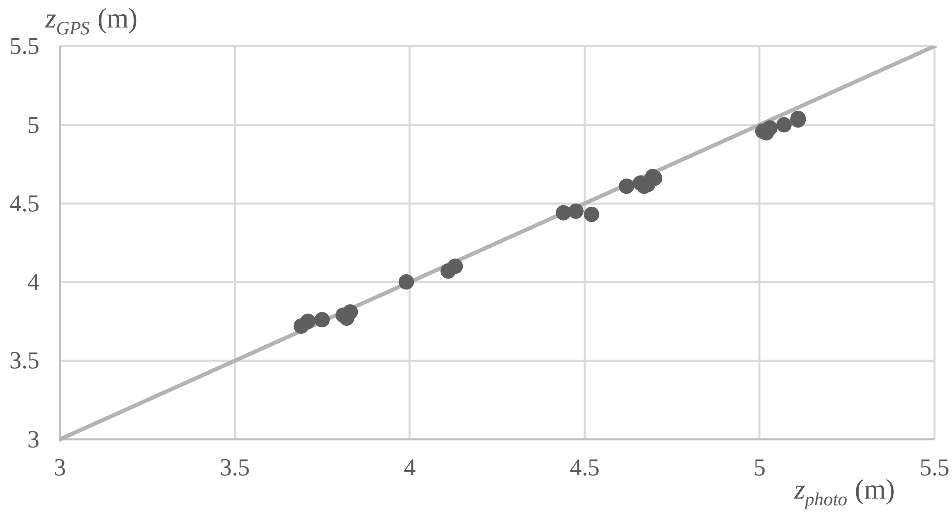


Figure 5. GPS measurements comparing to photogrammetry analysis

The time evolution of the bed elevation in the test section is shown in Figure 6, for a profile along the slope located at the centerline of the flow area. The slope breaks at y = 3 m and y = 7 m indicate the location of the test section where the grass cover was removed. The progressive erosion of the downstream part of the test section can be observed. Overall the clay shows high resistance against the overtopping waves because the remaining parts of the test section are almost not impacted by the wave. Also, the quality of the photogrammetric measurements is confirmed by comparing the final state and the results after the last discharge pulse with Q = 2000 l/m.

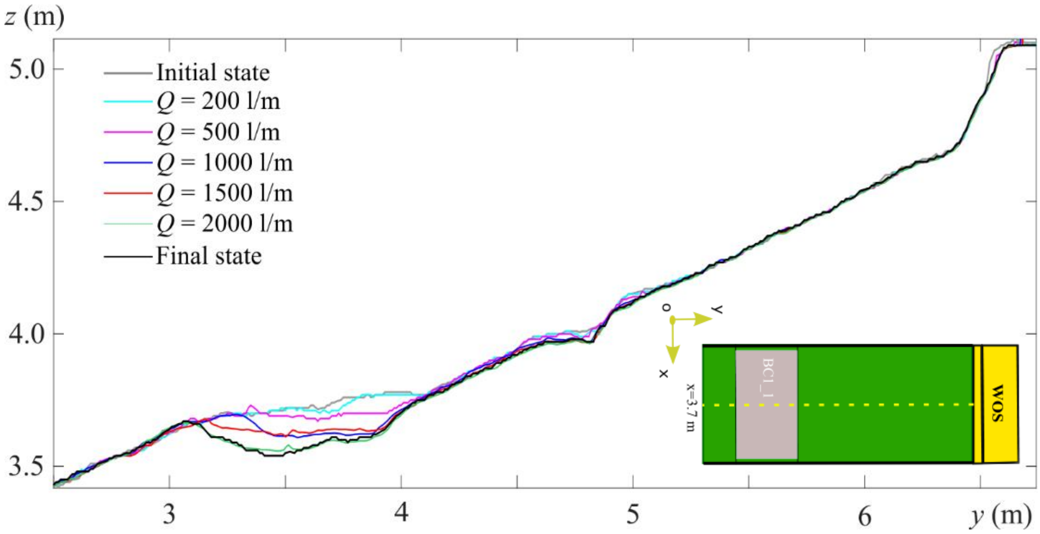


Figure 6. Bed level evolution at width middle (x=3.7m) for BC1_1

As regards the LTC tests, sample results are shown in Figure 7. The erosion depth after 2 hours storm with $H_s = 1$ m and q=0.01 m^3/s/m is illustrated. The erosion hole around the object placed along the slope can be identified (lower left corner of the object in Figure 7), with a depth of about 0.3 m. This significant erosion is due to the removal of less compacted and loose soil. It was also observed that the clay treatment provides a significant reinforcement of the soil.

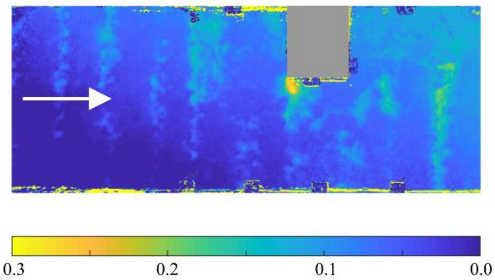


Figure 7. Lime-treated clay test results

5 CONCLUSIONS

Field tests were conducted to investigate the resistance of clay-covered seashore dikes. The morphological evolution following the application of synthetic waves was monitored using a photogrammetry-based technique. A comparison with classical GPS measurement showed the accuracy of the method. One possible limitation to be further investigated is the influence of the presence of water on the measured surface: in the present experiments, measurements were taken when the water had left the test section. However, it appears that when water is present in depressions, the measured bed elevation is misinterpreted by the photogrammetric technique.

As regards the dike resistance, the clay cover appeared to be highly resistant, even to severe waves. When an obstacle is placed on the dike slope, scour hole is formed, but the depth remains limited if the clay cover is treated with lime. Further experiments and analyses are needed to quantify the soil resistance, in relation with the material composition and the presence of grass cover.

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