Monitoring medium-scale dike breaching using photogrammetry: preliminary results.

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ABSTRACT: New medium-scale breaching experiments have been conducted to study the breach evolution of homogenous sand dikes. These experiments took place in an indoor facility with a 200 m^2 reservoir area allowing for testing frontal dikes up to 1-meter high. The dike is constructed using fine sand (d_{50} = 0.31 mm). The water inflow is continuously adjusted to maintain an almost constant water level in the upstream reservoir during breach formation replicating steady overtopping conditions. The close-range photogrammetry was used to monitor the breach evolution. It is shown that photogrammetry can generate accurate 3D models of the dike above water and is able to capture the water surface where the flow is turbulent and water aeration creates a white foam providing enough texture to be captured by the photogrammetric processing. Besides the whole breaching process is briefly described by referring to key moments during experiments.

1 INTRODUCTION

Reduced-scale models play a crucial role in the field of hydraulic engineering, serving purposes such as designing new defense structures and assessing the resistance of existing embankments. The data acquired from experiments conducted on scaled models significantly contribute to a better understanding and prediction of real-life structural failures. Typically, these predictions rely on numerical models developed based on physical processes. However, to ensure accuracy, these numerical models must undergo calibration and validation using reliable and extensive datasets within their applicable ranges.

While full-scale experiments offer the most faithful replication of real processes, they are often impractical due to their expense, time-consuming nature, and limitations in terms of manipulation and data collection. Therefore, designing reduced-scale models in a suitable and reliable manner becomes paramount. In these models, the breach temporal evolution, erosion rate (or breach widening), and the resulting outflow hydrograph stand out as the most sought-after parameters in all experiments (Wahl 1998, Morris et al 2007, Morris et al 2009).

Medium scale experiments are gaining more and more in popularity, appeared to undergo minimal or negligible scale effects (Walder et al. 2015, Mohamed and El-Ghorab 2019, Morris et al. 2021). Such experiments can thus help determining the links between small-scale and large-scale tests.

To this end, a series of new medium-scale breaching experiments is currently undertaken in collaboration with the Hydraulics Research Laboratory of the Service Public de Wallonie Mobilité & Infrastructures (SPW MI) located in Châtelet, Belgium. The experimental set-up and some preliminary results are presented in this paper. The application and limitation of close-range photogrammetry application to monitor the breach evolution is discussed.

2 MEDIUM-SCALE EXPERIMENTS

2.1 *Experimental Setup and Materials*

Two breach experiments were conducted on homogeneous embankments subjected to steady overtopping. As illustrated in Figure 1, the embankments were 1-m-high with an upstream reservoir of approximately 200 m^2 aiming at representing an infinite reservoir or bay because of the adjustable inflow discharge allowing for maintaining a constant upstream water level. The water was pumped into the reservoir from the adjacent waterway with a maximum flow rate of nominally 1 m^3/s. The embankment was constructed between two side walls 3.4 m apart as illustrated in Figure 1a, b. The embankments are 1 m high, with a width of 0.5 m at the crest and 6.5 m at the toe. A drainage system was installed to avoid piping through the embankment consisting of a pipe covered by geotextile placed on the floor level, at the section of the embankment crest, transferring the drained water towards the downstream reservoir. An initial pilot channel with a trapezoidal form was carved in the middle of the crest with a 0.15 m width at the bottom, 0.45 m width at the top and a depth of 0.1 m having lateral 1V:1H side slopes.

The tested embankments were constructed using fine sand with a median diameter of d_{50}= 0.31 mm. The standard Proctor test was conducted to determine the optimum moisture content ($\omega_{optimum}$=14%) and maximum bulk density of the soil. This criterion was opted for compaction of the embankment; however, it was difficult to achieve because water was drained rapidly from the soil due to the compactor vibrations. The compaction was carried out using a low-weight vibratory plate compactor (Ammann APF-10/33) in 10 cm layers.

(a) (b)

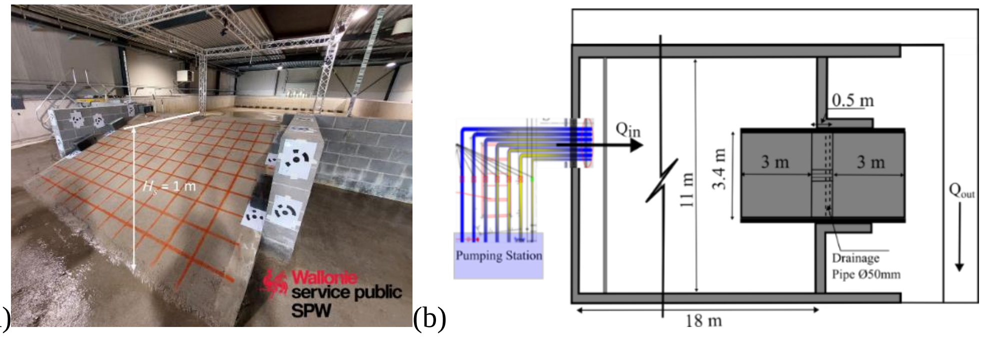


Figure 1. Experimental setup: (a) Test platform and embankment and (b) Plan view of embankment, upstream and downstream reservoir (not to scale).

2.2 *Instrumentation and measurement techniques*

The water level was continuously measured in the upstream reservoir, using hydrostatic and ultrasonic gauges spread over the entire surface of the reservoir floor. Based on the ultrasonic gauges records of the water level between 0.85 m to 1 m, the regulation system adjusted the inflow rate to maintain a constant water level in the reservoir during the breach formation and progression. In the present case, the water level in the reservoir was prescribed at 0.95 m, i.e. 0.05 m below the crest level.

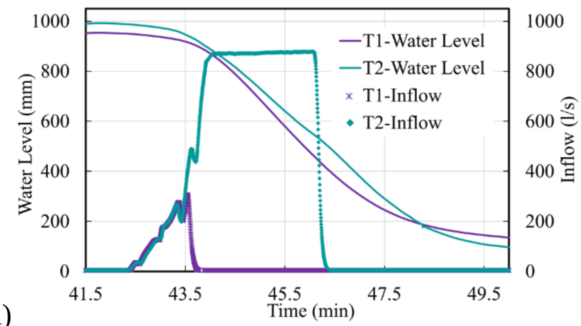
To monitor the morphological evolution of the dike, close-range photogrammetry was applied using the Agisoft Metashape software (Agisoft 2022). This allowed to measure the widening of the breach, as well as the flow surface through the breach during overtopping. The hidden part of the breach under the flow could not be captured by the photogrammetry due to highly turbid water. The resulting brown color of the water together with the highly turbulent water surface provided sufficient texture to the images in such a way that this surface could be captured by photogrammetry. The images were taken by ten fixed cameras installed on a structure assembled around the embankment. The cameras layout and orientations were adjusted to cover the entire testing zone and providing enough overlap between photos. Moreover, the wide angle of the camera lenses ensured a good overlap between photos, allowing to reconstruct a 3D view of the scene based on each set of 10 images acquired at each time step. The cameras were set to capture one photo per second in time-lapse mode. This technique was already used and verified during full-scale levee wave overtopping experiments (Ebrahimi et al., 2022) and proved to be highly accurate to monitor the morphological changes in absence of water. Moreover, Carlier d'Odeigne et al. (2017) have employed the technique (SfM) in laboratory environment to capture the water surface and bathymetry of an irregular channel. To transform the model coordinates into real-world or local coordinates, reference points known as Ground Control Points must be installed around the embankment for which the coordinates were measured. These checkpoints are essential for photo alignment and generating the elevation model of the embankment containing the *xyz* coordinates of any point in the study region.

The resulting 3D elevation models of the embankment were used to analyze the breach evolution.

3 TEST PROCEDURE, PRIMARY RESULTS AND DISCUSSION

3.1 *Test procedure, inflow, and outflow hydrographs*

Figure 2a and b show the inflow and outflow hydrographs during the two different tests. The experiments started by pumping water into the reservoir for approximately 20 min, until a 0.95 m water level, which is 0.05 m above the initial pilot channel. Time zero, or the start of experiments, corresponds to the moment when the prescribed water level has been reached in the reservoir. At the beginning of the experiment, water mainly infiltrates in the embankment and little flow is observed through the initial pilot channel. Then, when water starts to flow through the pilot channel, the breaching process starts. As the breach progressively deepens and enlarges, and hence the breach outflow increases, the regulation system activates the pumps to compensate for the decrease of the reservoir's water level. However, as can be observed from Figure 2a, even with the higher inflow discharge in test T2, it was impossible to maintain a constant water level during the whole experiment. It can even be observed from Figure 2a that the decreasing trend of the reservoir water level is very similar in tests T1 and T2, despite the very different inflow discharge pattern where the pumps were operational until the end of the breaching process in T2, whereas they stopped earlier in T1.



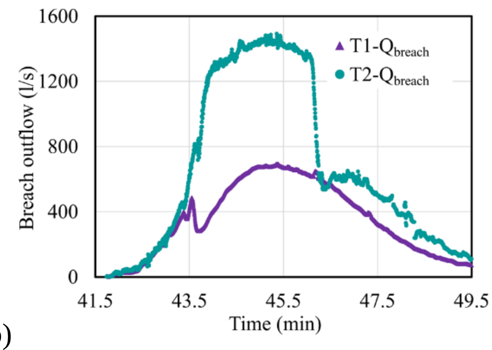


Figure 2. (a) Water level and reservoir inflow; (b) breach outflow (Time is measured from the beginning of test procedure).

It must be noted that the initial water level in the reservoir was slightly higher in Test T2 (0.98 m). Still, the breaching duration, i.e., the time until the full erosion of the embankment over the width of the test facility, was almost the same in the two tests (approximately 280 s).

The breach outflow hydrograph was determined as follows:

$$Q_{breach} = Q_{in} - A(z)\frac{dz}{dt} \quad (1)$$

Where Q_{in} is the volumetric inflow rate, t is time, $A(z)$ is the plane area of the reservoir at level z. The breach outflow follows a similar trend to the inflow hydrograph, and the maximum peak outflow is significantly higher in case test T2 comparing to T1.

3.2 *Close-range photogrammetry to monitor breach evolution.*

Several 3D models of the embankment were reconstructed at regular intervals of 20 s to capture the breach evolution. The process is illustrated in Figure 3 for time 100 s of the T1 experiment, when the breaching process has started and the breach is mainly deepening (early-stage breaching), as can be seen in Figure 3a. While the elevation models of the embankment are highly accurate for areas located above the flow surface, they only include the information about the flow surface where it is highly turbulent and aerated. This can be observed in the dense point cloud illustrated in Figure 3b: the software recognizes key points where air bubble and splashes appear as well as the dense muddy water while leaving voids in the Dense Point Cloud elsewhere, even if water is present. Meanwhile, it can interpolate between recorded points to generate a continuous digital elevation model (DEM, as illustrated in Figure 3c). Obviously, the interpolated zone is less accurate and requires improvements in the measurement technique. In this regard, the photogrammetry cannot be used as a stand-alone method to monitor the deepening of the breach.

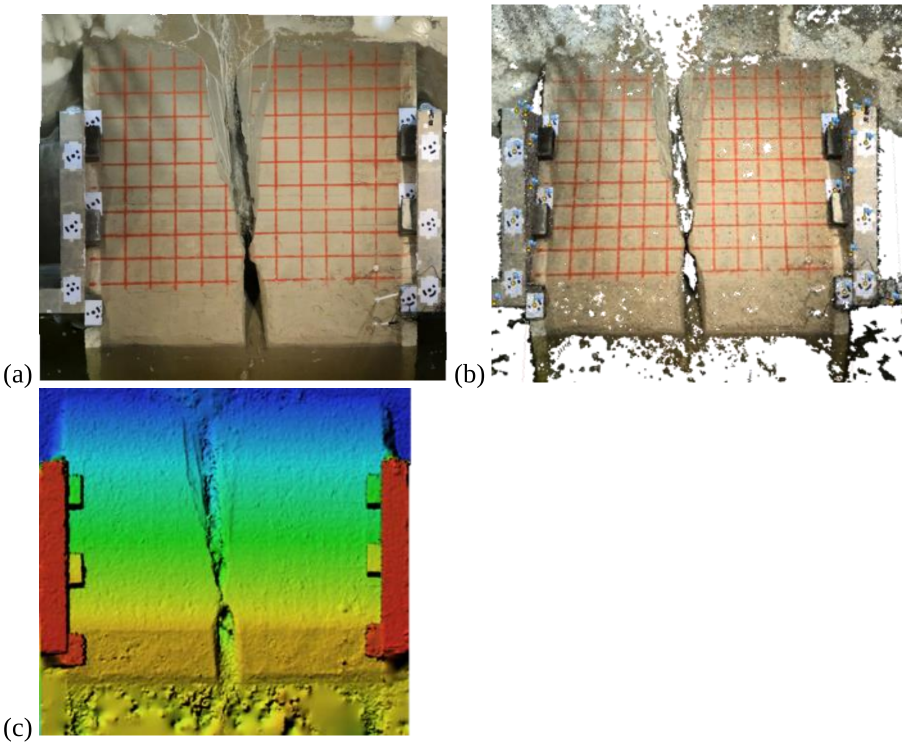


Figure 3. Reconstruction of 3D models of the embankment using close-range photogrammetry: Orthophoto of embankment at (a) 100 s, (b) 3D Dense Point Cloud, (c) Digital Elevation Model.

From the reconstructed DEM, profiles at given locations can be extracted. Figure 4 illustrates such profiles at the middle of the crest of the dike, showing the progressive evolution of the breach cross section during test T1. The zone of uncertainty is indicated by dashed lines in the cross-section profiles.

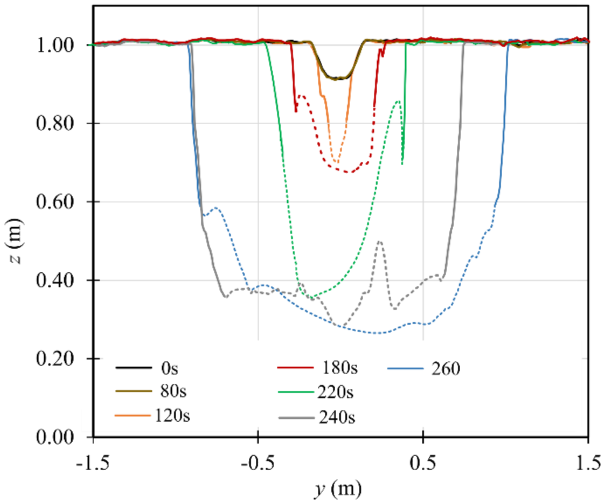
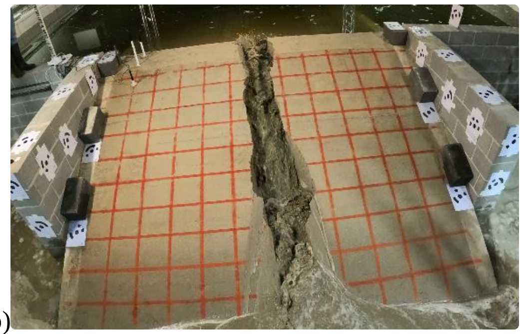
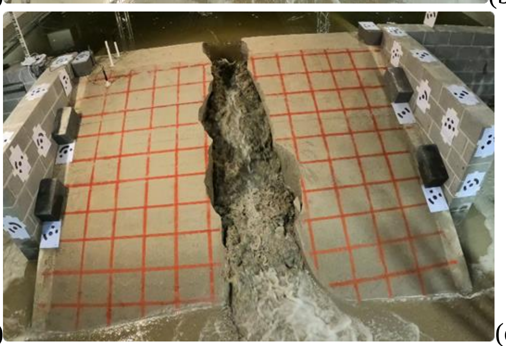
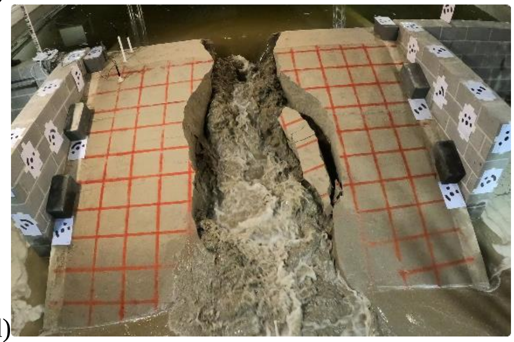


Figure 4. Breach cross-section at the middle of the crest (dashed lines indicate the water surface captured by photogrammetry).

3.3 *Embankment breaching morphological evolution.*

The entire breaching process can be divided into two dominant stages once the water finds its way towards the downstream slope. The first stage is mainly involving the progressive vertical erosion i.e., deepening of the initial breach channel (see Figure 5a). This results in the formation of steps or a headcut retreating from the toe towards the crest. This stage, strikingly slow, results in a modest breach outflow (around 41.5 min in Figure 2b). The second stage concerns mainly the lateral development of the breach channel. Once a retreating step or headcut intersects the crest (see Figure 5b), lateral erosion in forms of soil blocks slumping (not only due to the undermining but also due to formation of tension cracks), dominates the whole process and leads to a rapid widening and complete failure of the embankment (see Figure 5c, d, e, and f). The mass blocks slumping starts from the toe and propagate towards the crest. An example of this phenomenon is shown in Figure 5d. It can also be observed that the banks of the breached area are almost vertical, highlighting the role of apparent cohesion.

(a)  (b) 

(c)  (d) 

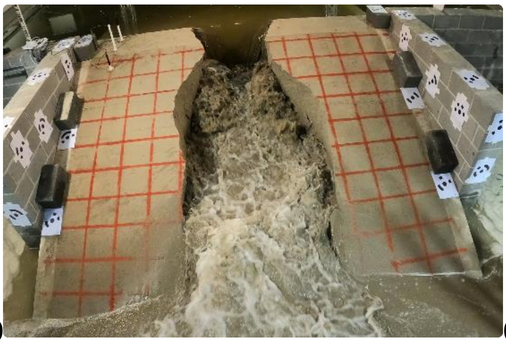
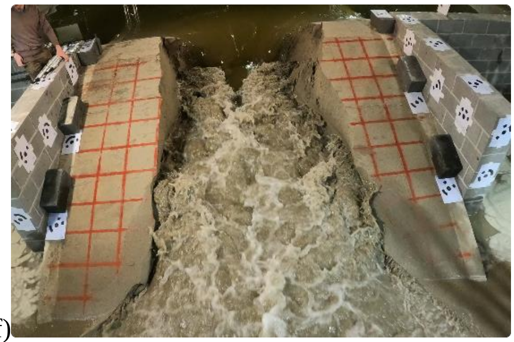
(e)  (f) 

Figure 5. Temporal evolution of breach channel after: (a)100 s; (b) 150 s; (c) 180 s, (d)210, (e) 220; and (f) 280 s.

Despite quite random mass failures of the breach side slopes, the resulting cross-section is quite symmetric and in accordance with the descriptions provided by Visser (1995), Coleman et al. (2002), Morris et al (2007), and more recently by Walder et al (2015). As indicated by Coleman (2002), embankment material is eroded by the processes of tractive shear and turbulence, with lateral erosion occurring at all points along the breach channel side slopes. Coleman (2002) and Morris et al (2007) who performed small scale experiments also observed the undermining of the breach channel side slopes causing large volumes of unsupported material to collapse into the center of the channel. However, the mass volume did not remain as an integrated, coherent block which can hang over, tilt or slump into the breach flow. This could be linked to the smaller size of models and or lack of enough apparent cohesion due to the coarser nature of soils in those experiments. The breach channel had a gentler side slope in those tests.

4 *Conclusions and perspectives*

New medium-scale breaching experiments were designed and being conducted with the aim of providing new insights into the breaching process and a detailed data set for the validation of numerical models. In particular, the photogrammetry was applied to monitor the breach evolution during the experiment. The technique allows to accurately measure the breach widening but fails in the identification of the bed elevation because of the important water turbidity making it impossible to “see” through the water.

Future experiments will focus on alternative techniques to record the breach depth, using buried sensors. Besides, additional measurement such as particle image velocimetry will be used to measure the flow velocity in the breach.

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