Experimental characterization of the failure by overtopping of homogeneous and zoned dams: hydrodynamics and morphodynamics

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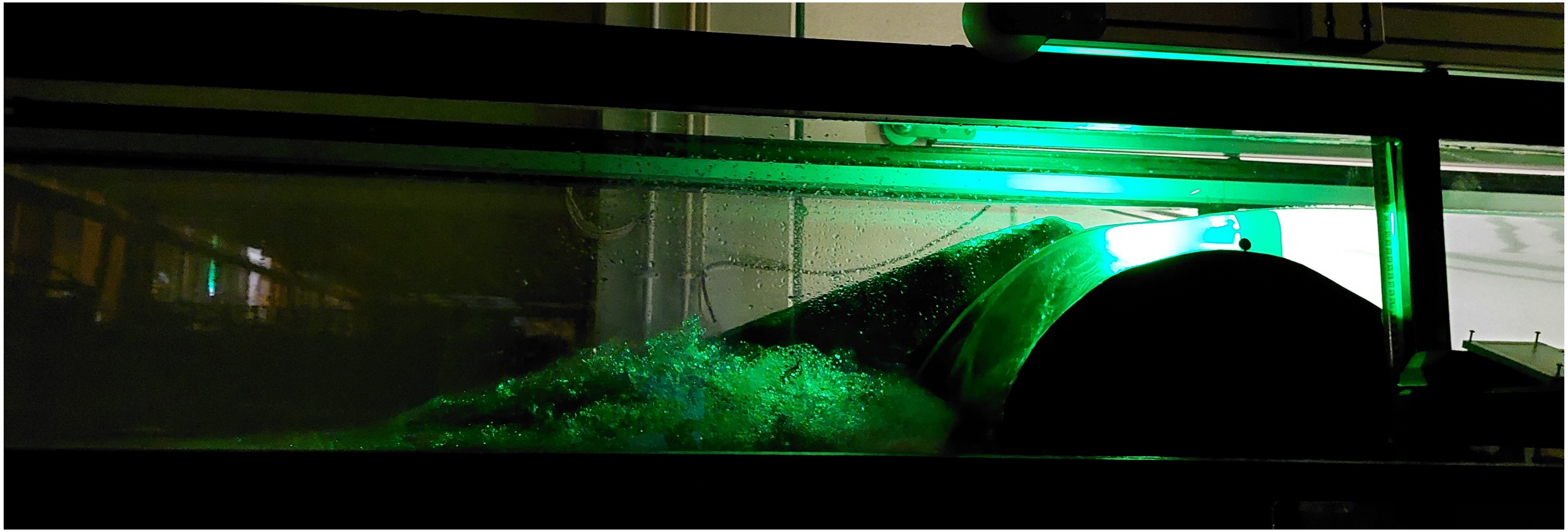


INTRODUCTION

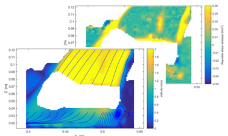
PhD theme: Experimental characterization of the failure by overtopping of homogeneous and zoned dams: hydrodynamics and morphodynamics

General objective:

To achieve a more accurate description of the hydraulic and geotechnical phenomena involved in the breach of overtopping embankments.

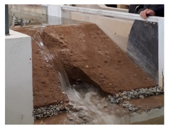
Characterization of the breach flow:

- capture relevant flow structures
- models similarity



Influence of the dam elements:

- drainage system
- impervious core



CHARACTERIZATION OF THE BREACH FLOW

CHARACTERIZING THE BREACH FLOW. CHALLENGES

To capture all relevant flow structures we need many instruments simultaneously

Which is not practical!

Or many repetitions!

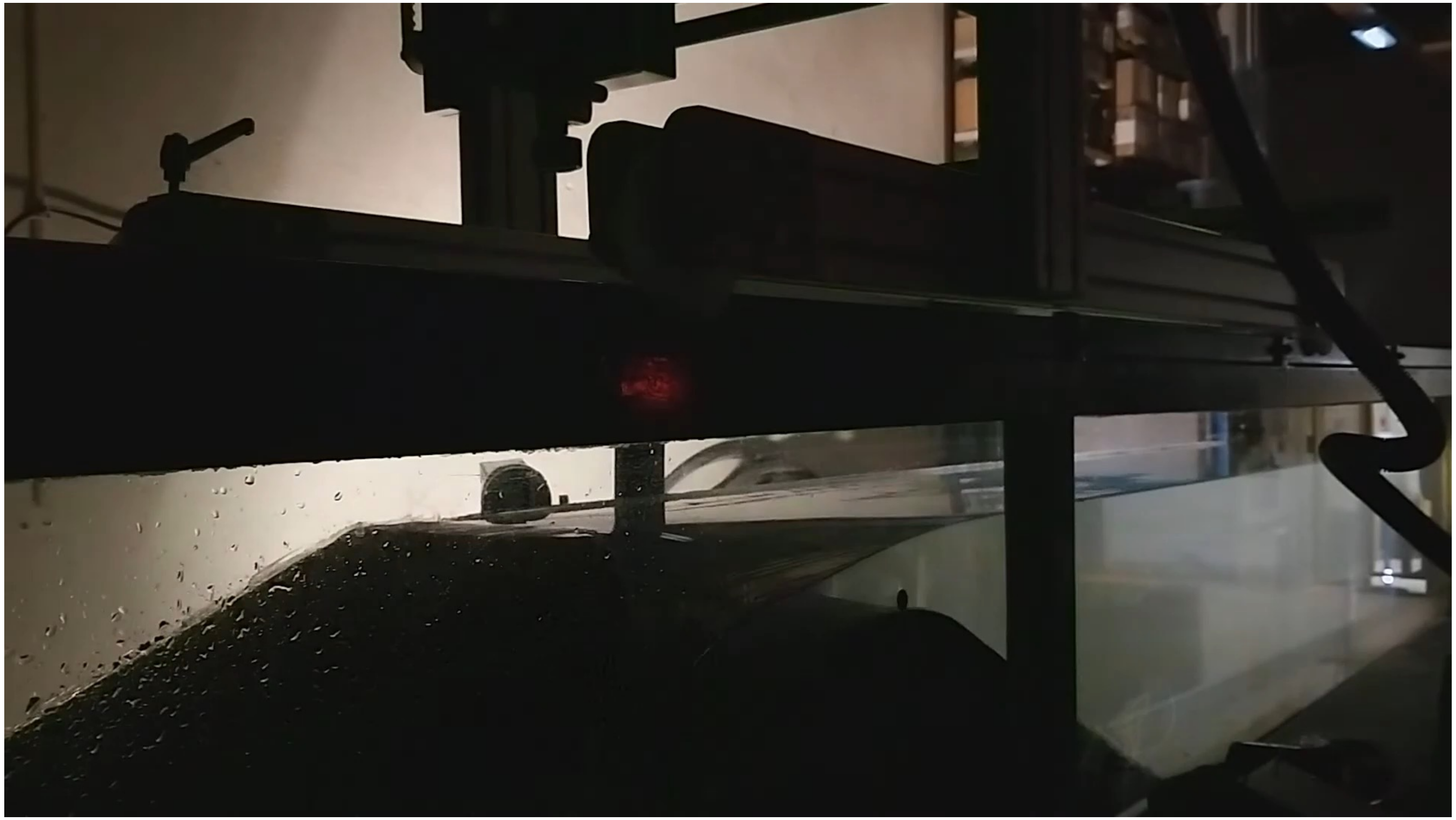
No - each test takes a week to prepare!

We need optical access and non-intrusive instrumentation

We do not have optical access.

We either have flow or optical access!

CHARACTERIZING THE BREACH FLOW. CHALLENGES

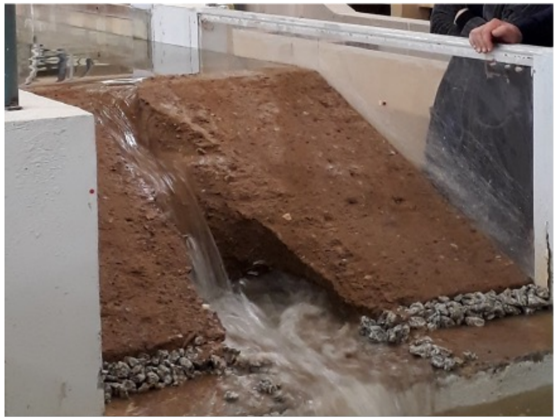


Solution: to STOP time

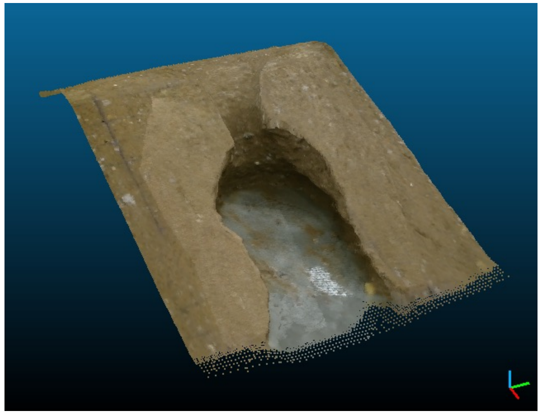
Freezing time allows for unlimited (sort of) time to study fluid flow with adequate non-intrusive instrumentation - PIV

Building the frozen-in-time dam

Run a real soil dam beach experiment



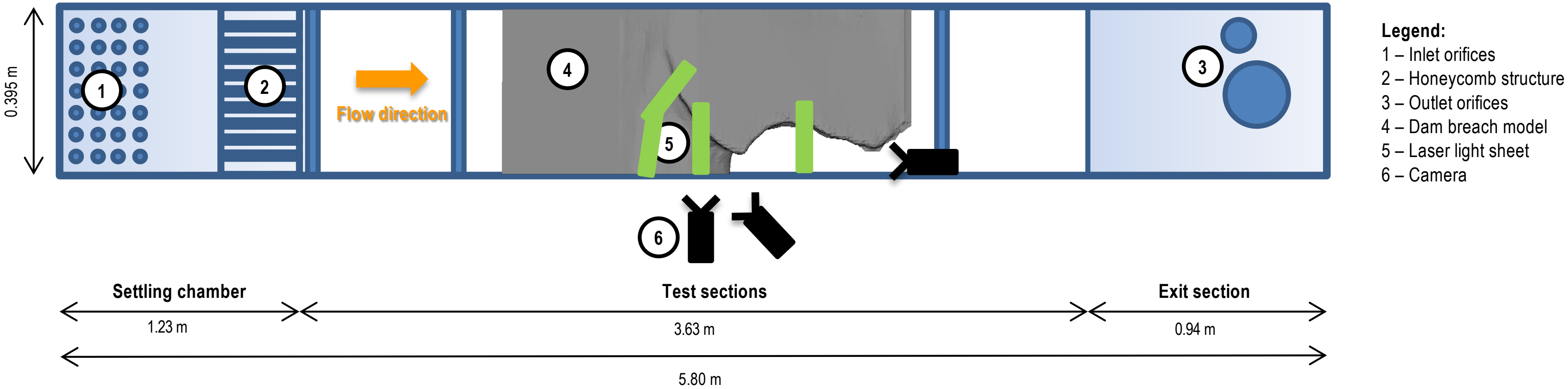
Reconstruct the 3D geometry with a Kinect system



Print a 3D scaled model

Install it in the lab and test it

EXPERIMENTAL FACILITY



Investigated Regions

1. Upstream slope and breach crest

1.1 Flow adjacent to the dam crest

1.2 Flow over breach crest

2. Contracted flow over the breach

(15 planes along the breach channel)

3. Plunging flow

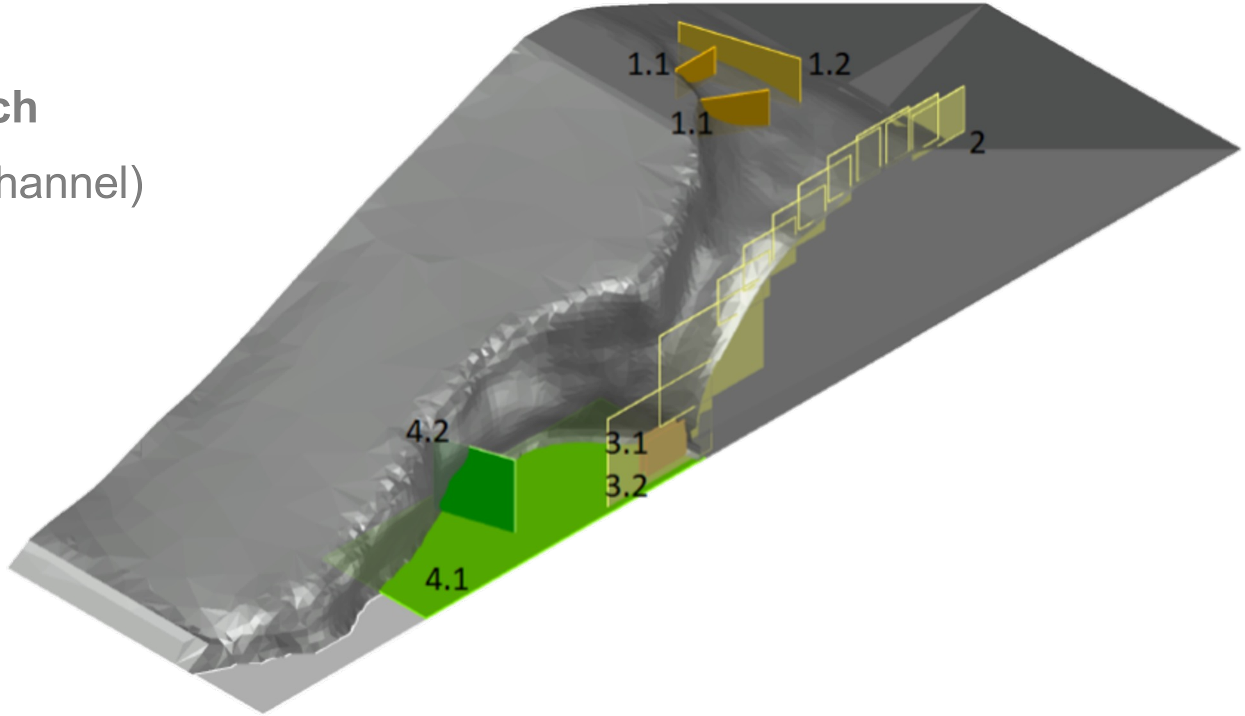
3.1 Separated flow

3.2 Stagnation point

4. Flow in the plunging pool

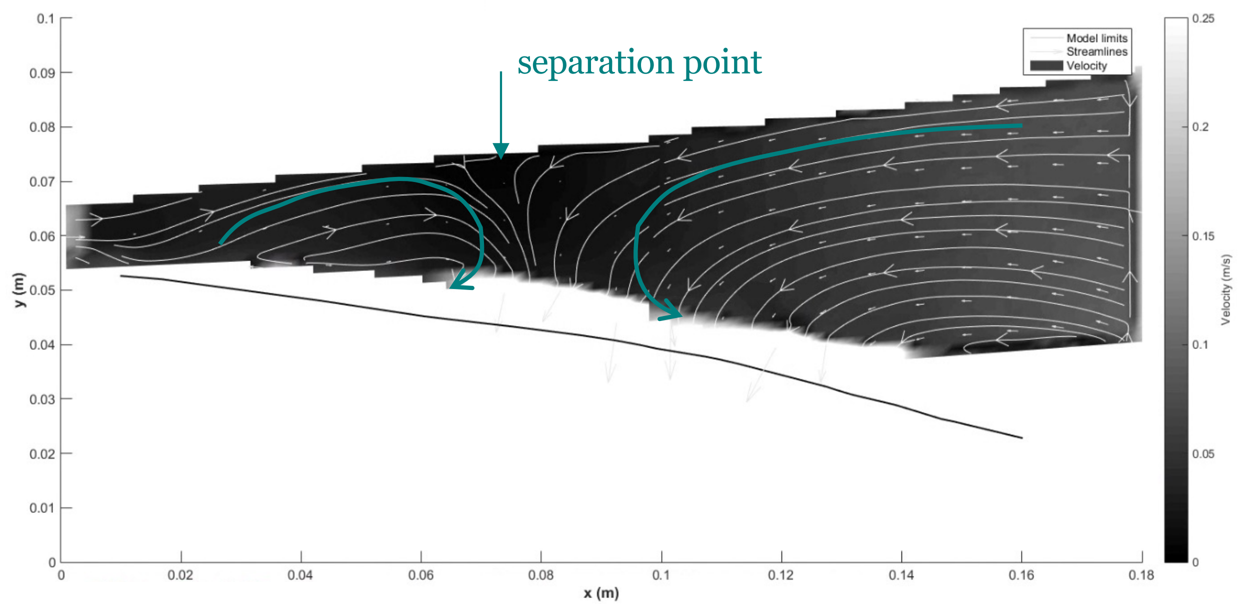
4.1. Flow in the horizontal plane

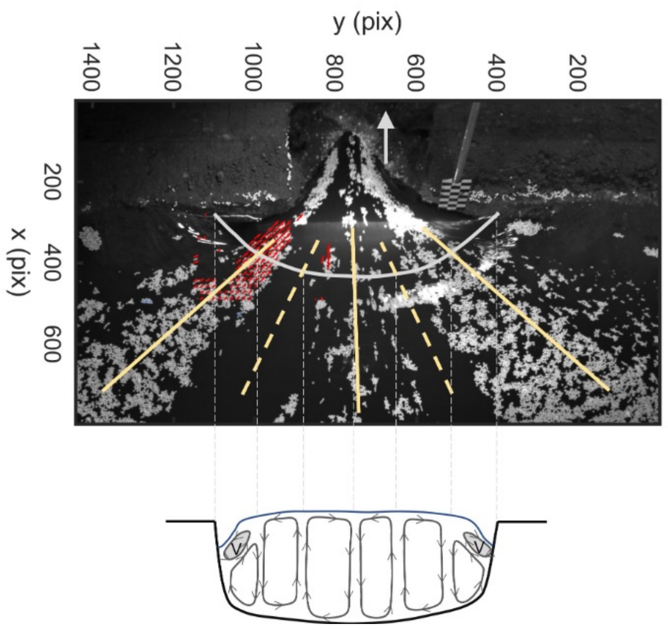
4.2. Flow around the dam cavity



Upstream Slope and Breach Crest

Flow over breach crest



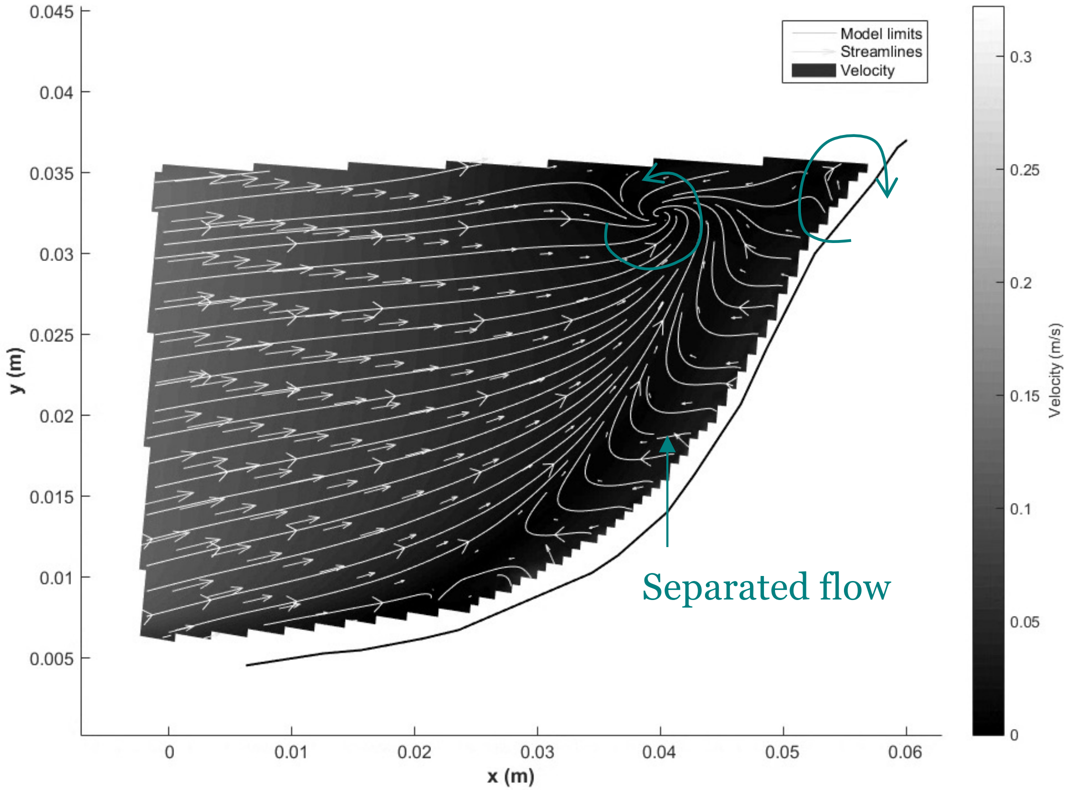


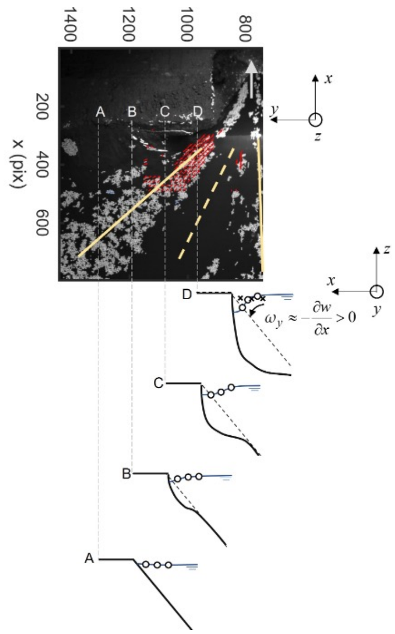
Secondary currents – envisaged by the surface flow

Essentially generated by an inviscid mechanism

Upstream Slope and Breach Crest

Flow along dam crest

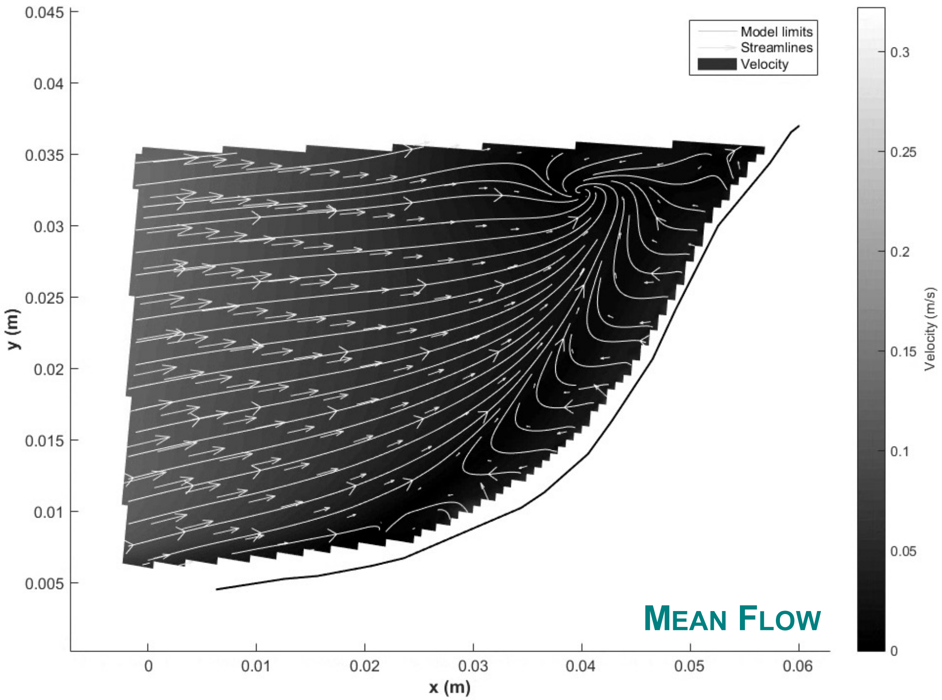


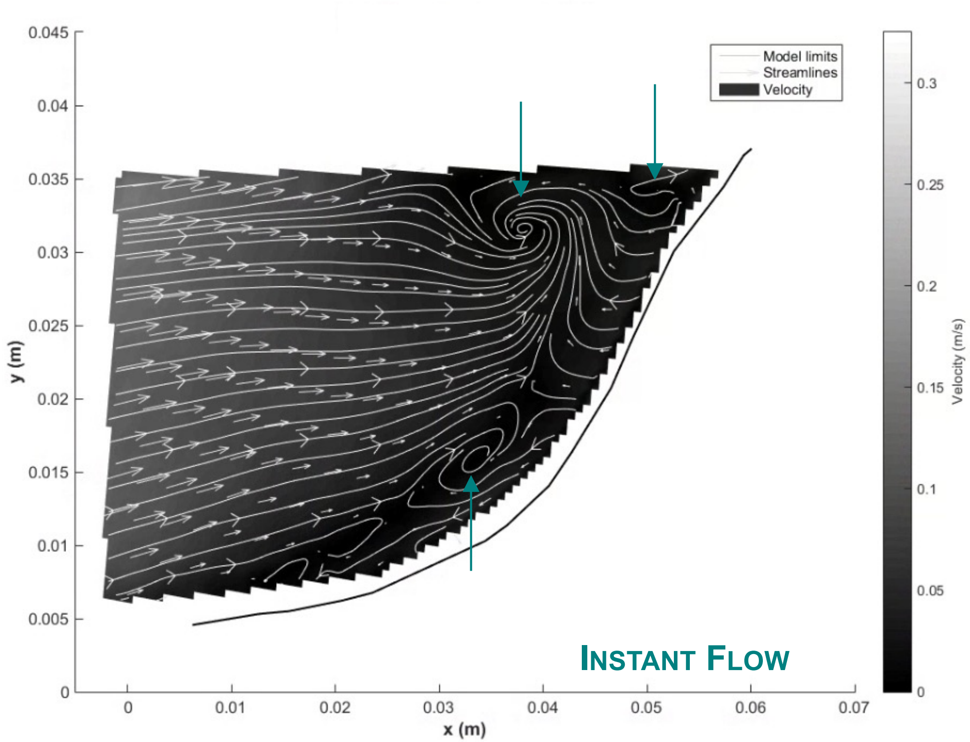


Attached vortex along the crest – a kinematic effect of flow approaching the breach, essentially inviscid

UPSTREAM SLOPE AND BREACH CREST

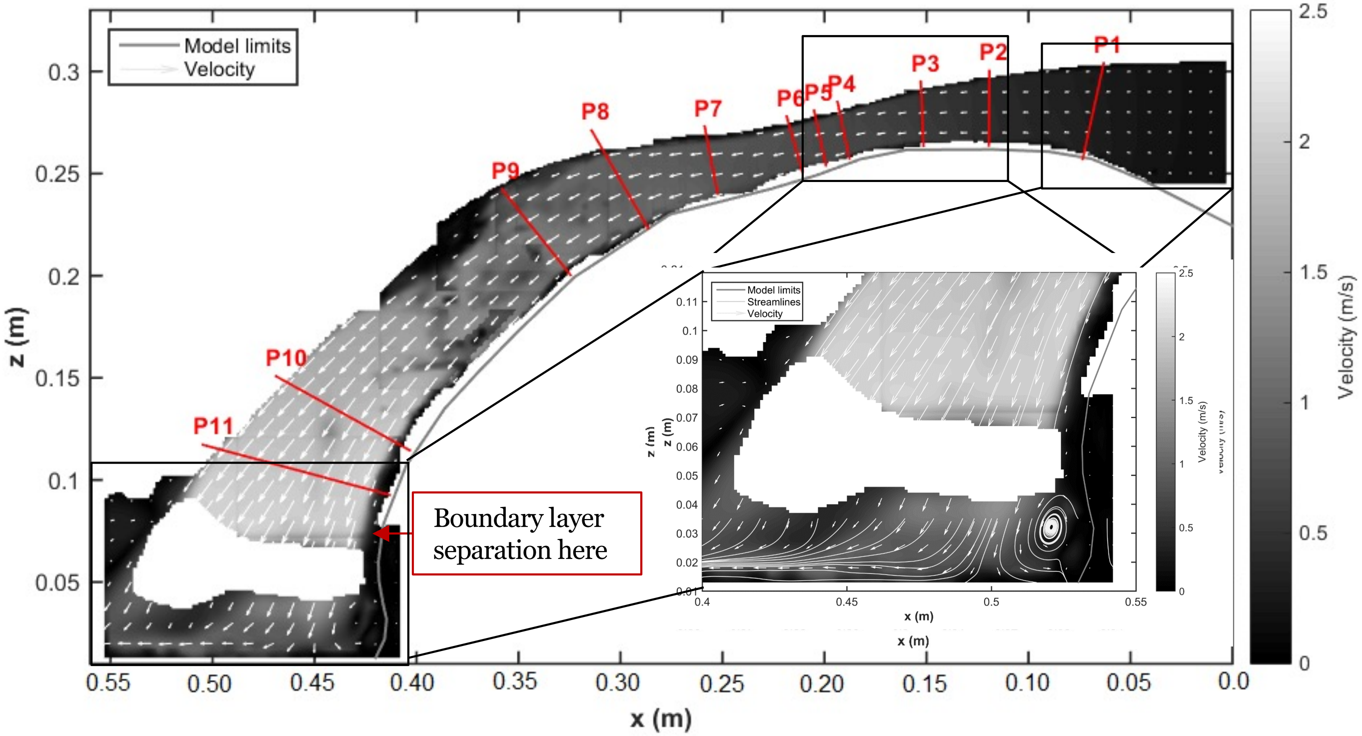
Flow along dam crest





Attached vortex along the crest – a kinematic effect of flow approaching the breach, essentially inviscid

CONTRACTED FLOW OVER THE BREACH



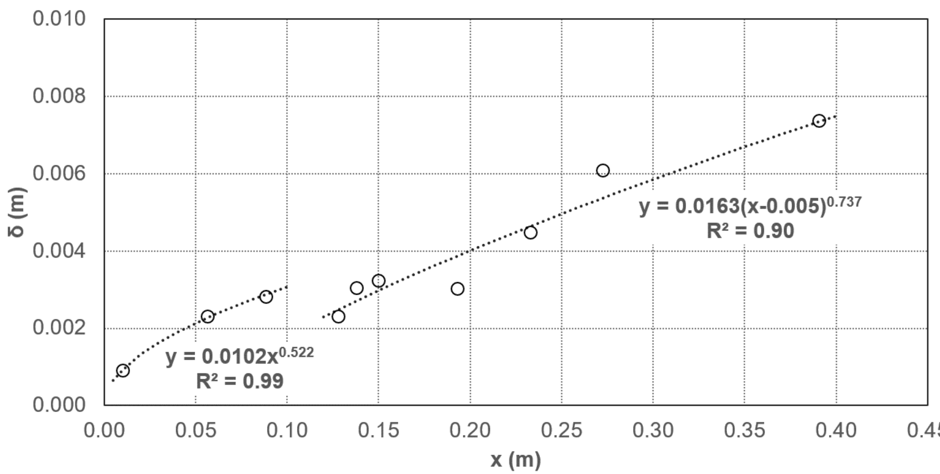
Development of a boundary layer (viscosity and roughness are relevant).

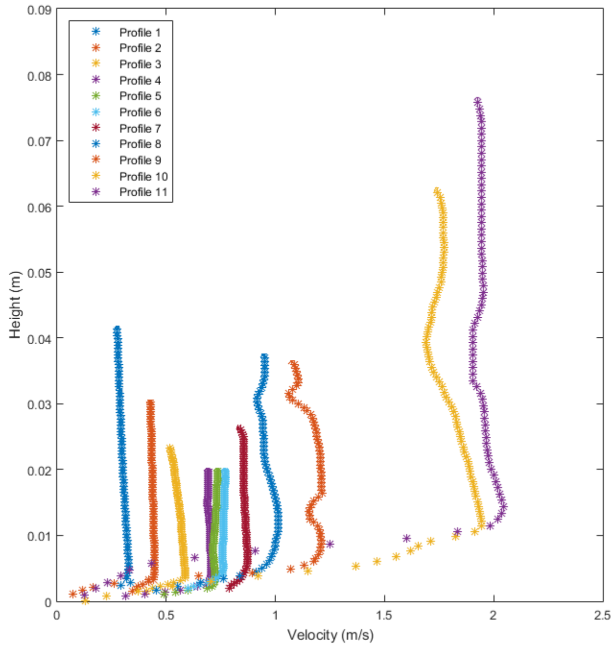
Flow accelerates, contracts and forms a “blade” as it reaches the bottom.

Boundary layer separates before hitting the bottom.

CONTRACTED FLOW OVER THE BREACH

Development of a boundary layer





Laminar boundary layer in the first 10 cm?

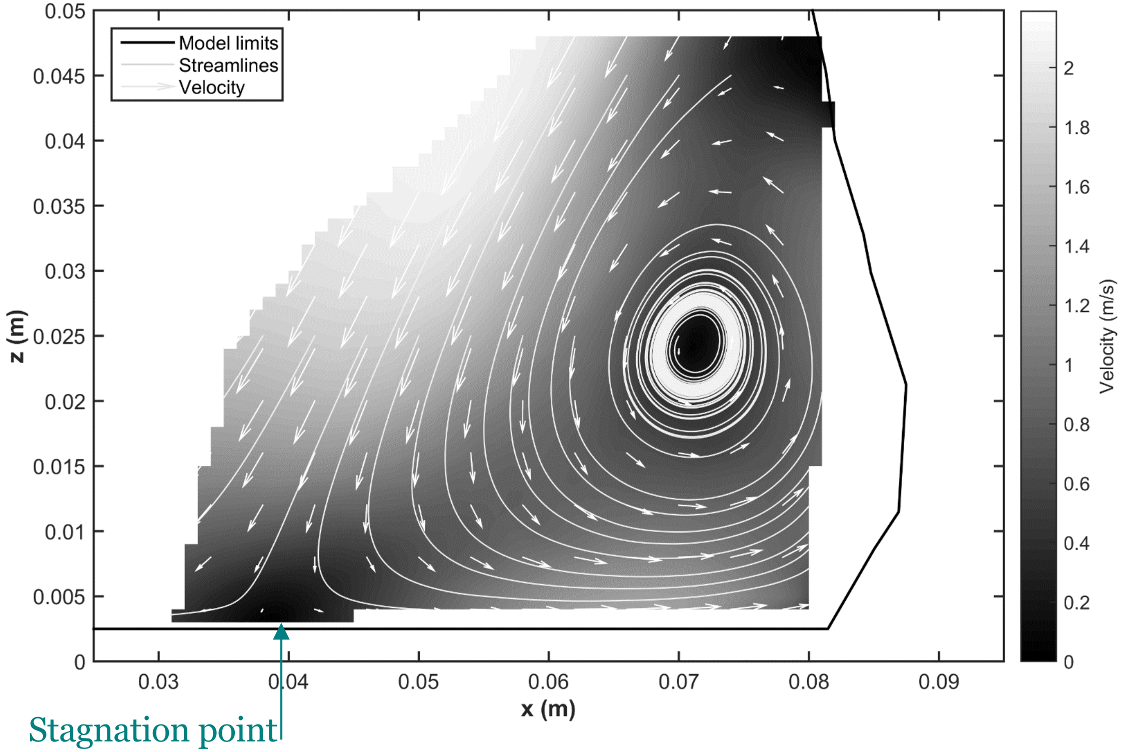
Turbulent boundary layer (with a viscous sublayer)

The scale of roughness is approximately ks = 0.0005 m

$$\delta(x) = \frac{ax}{\mathrm{Re}_x^{0.26}}$$

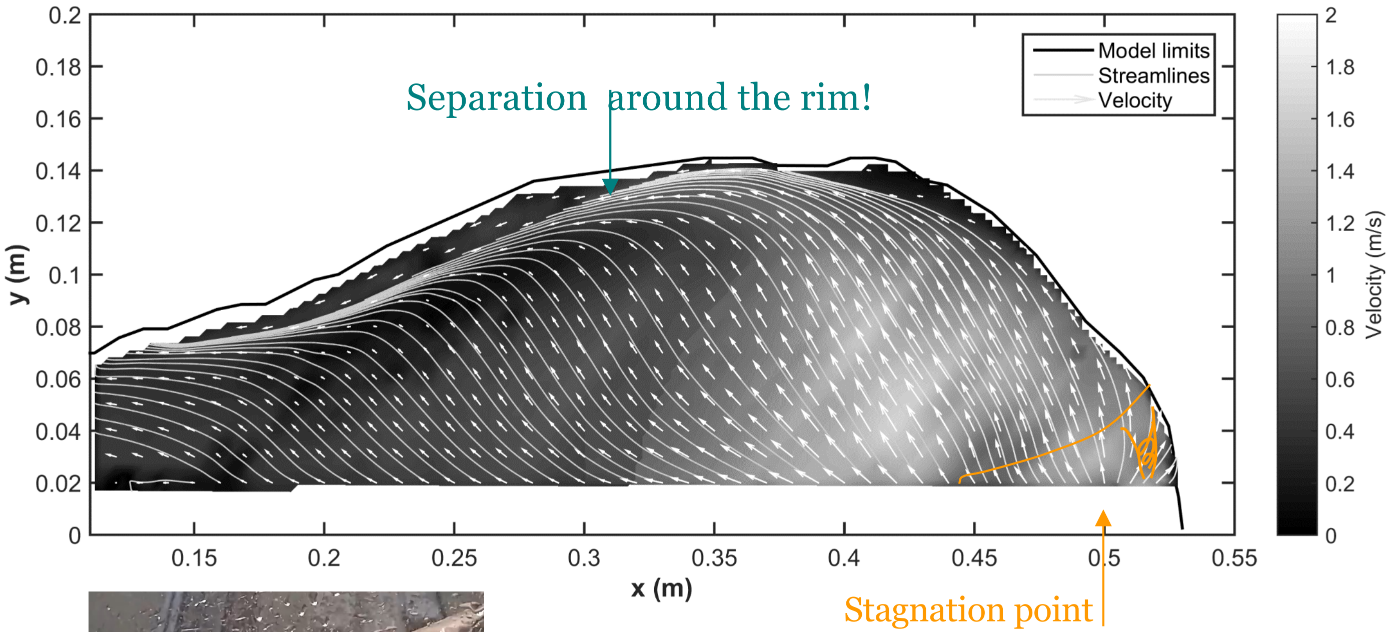
PLUNGING FLOW

Separated flow within the plunging flow



Flow in the plunging pool

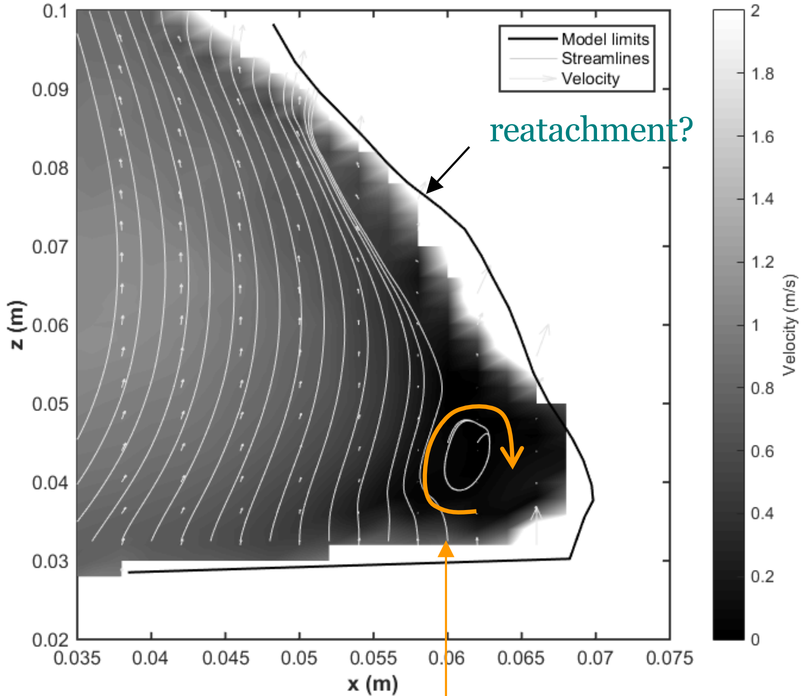
Flow in the horizontal plane



Flow in the horizontal plane – "out" from the plunging flow, turns at the inner walls, leaves as a vortex pair.

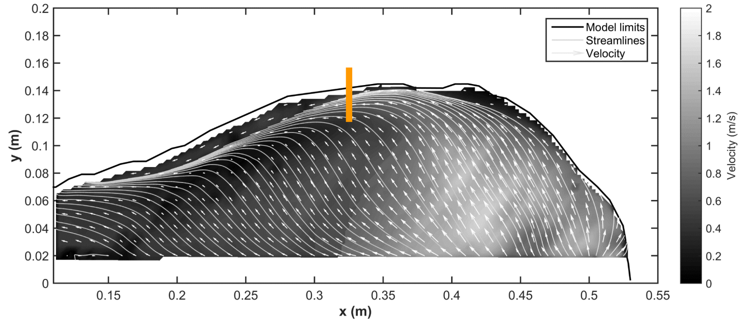
FLOW IN THE PLUNGING POOL

Flow around the rim of the dam inner cavity

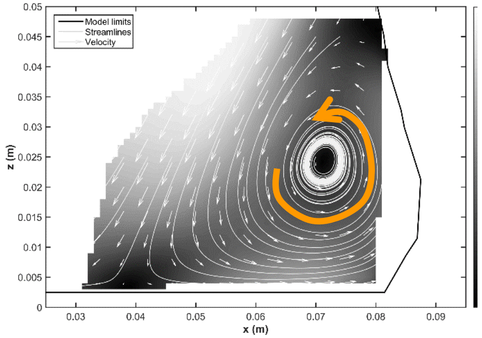


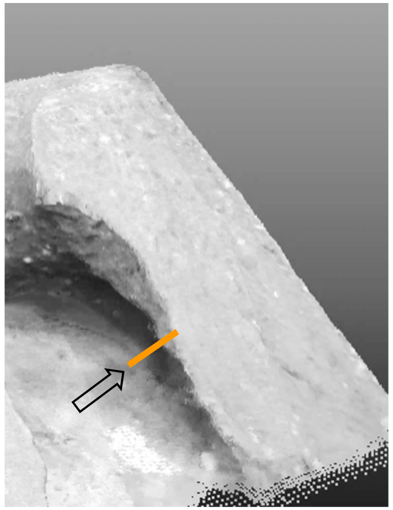
separation point

A separation induced by an adverse pressure gradient as the flow approaches the inner walls of the cavity



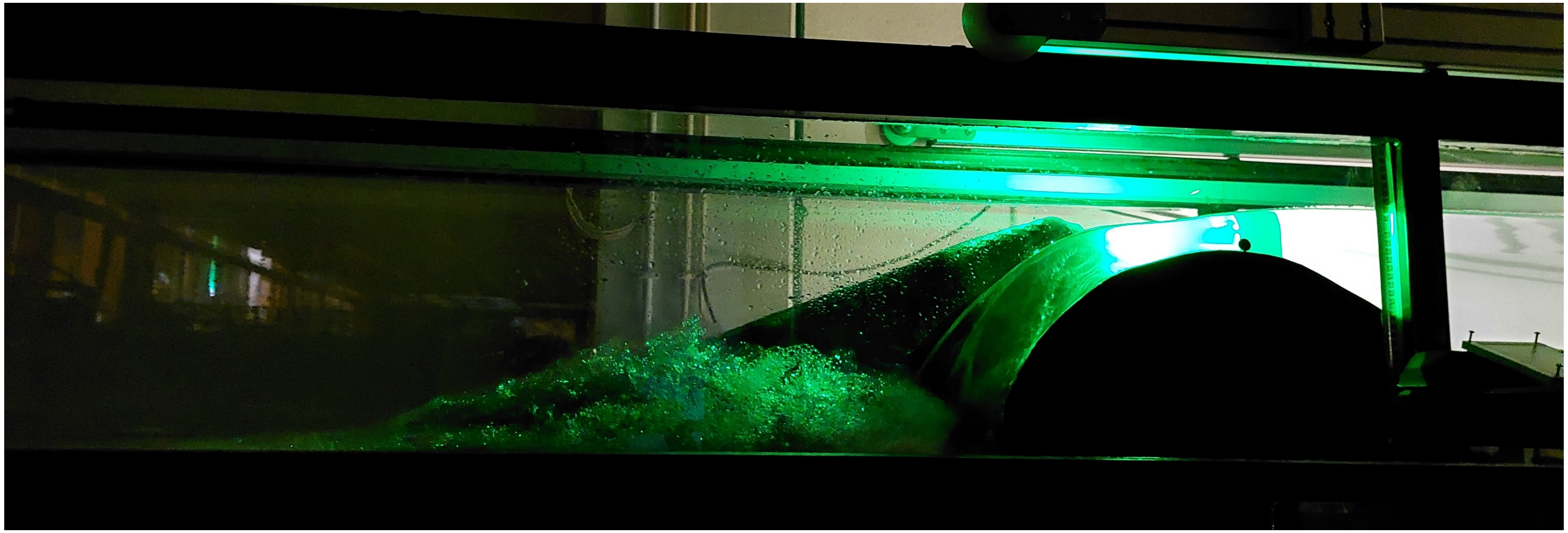
Not the continuation of the separation of the BL





Main Conclusions

- We were able to capture relevant flow structures that help to understand erosion mechanisms
- On the crest we found attached vortex and secondary currents, with no relevant viscous effects
- Erosion rate associated to hydraulic erosion can obey Froude similarity
- As the boundary layer develops and there is erosion along the crest, viscosity and roughness effects will be relevant
- Erosion rates associated to headcutting and underscouring do not obey Froude similarity.



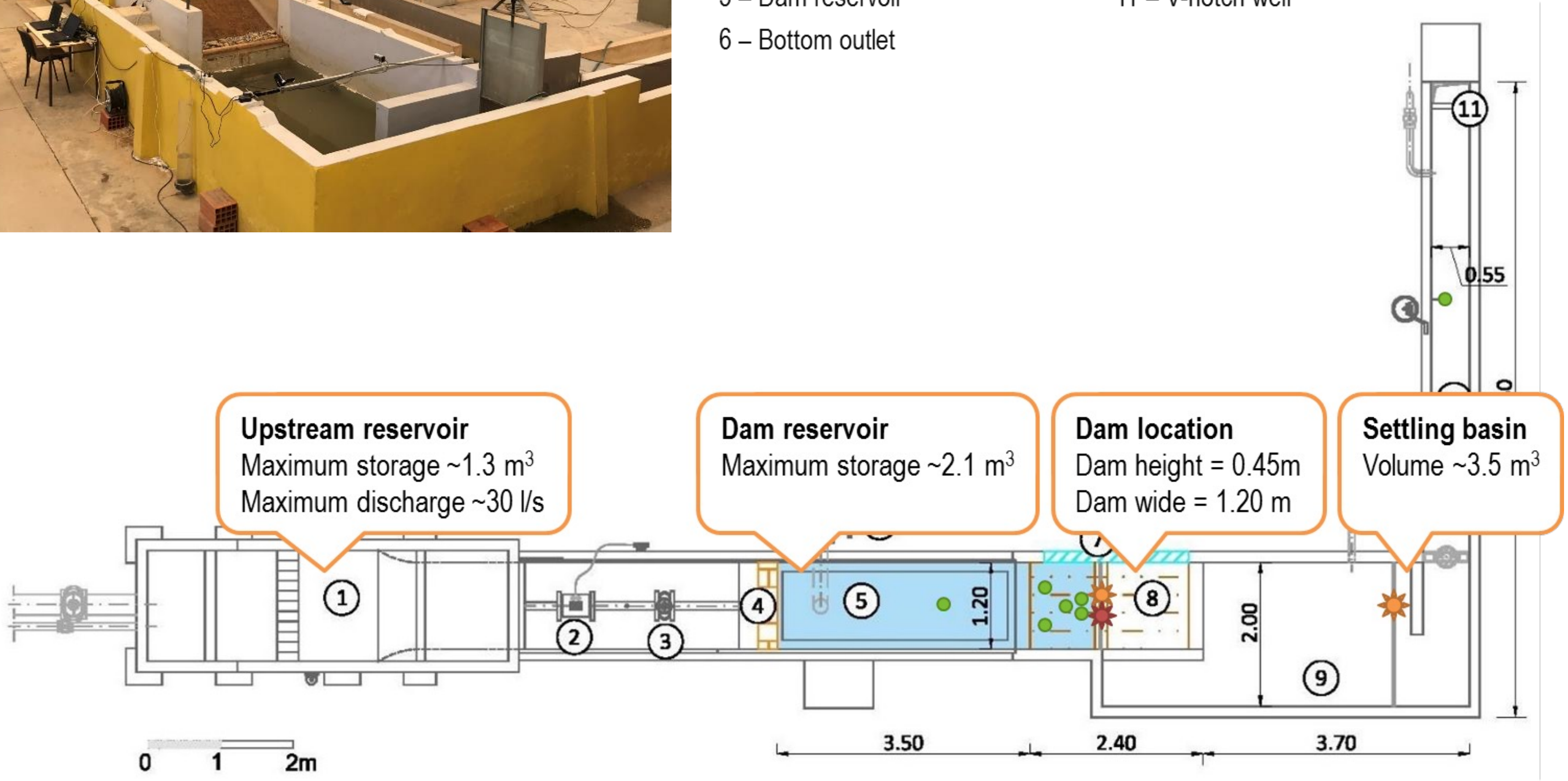
Influence of the dam elements

Experimental Facility

Legend:

1 – Upstream reservoir
2 – Flowmeter
3 – Flow control valve
4 – Brick wall (for flow stabilization)
5 – Dam reservoir
6 – Bottom outlet
7 – Glass wall
8 – Dam site
9 – Settling basin
10 – Outflow channel
11 – V-notch weir

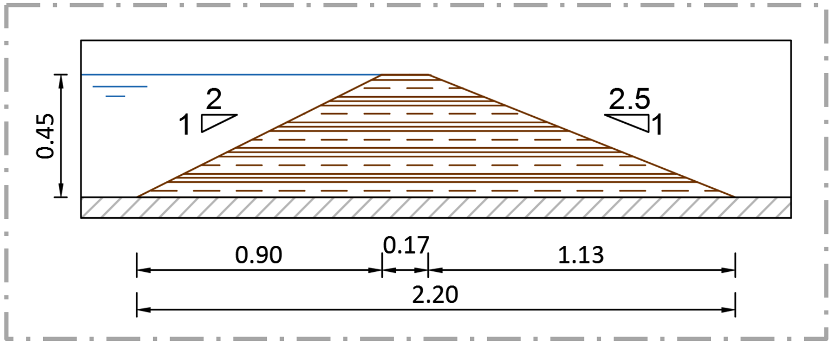
● – Acoustic probe
✸ – Video camera
✸ – Kinect sensor



Experimental Tests

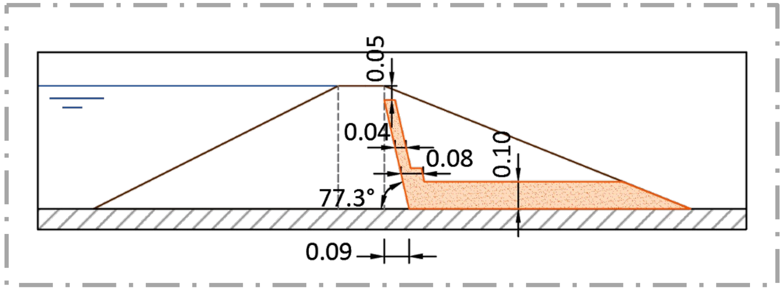
Cohesive embankments

Homogeneous Embankment with toe drain



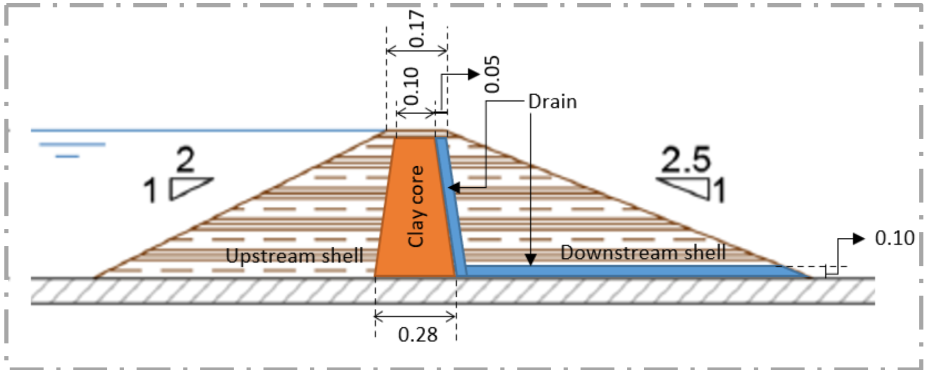
Soil: silty sand with 25% of fines content

Homogeneous Embankment with internal drainage system



Filter and drain detail

Zoned Embankment with clay core and internal drainage system



Impervious core detail

Core soil:
clay with 40% of fines
Downstream and upstream shells soil:
silty sand with 27% of fines

Embankment Construction

Soil homogenization and humidification

Embankment compaction (5 cm layers)

Chimney filter

Sand replacement test

Embankment final cut

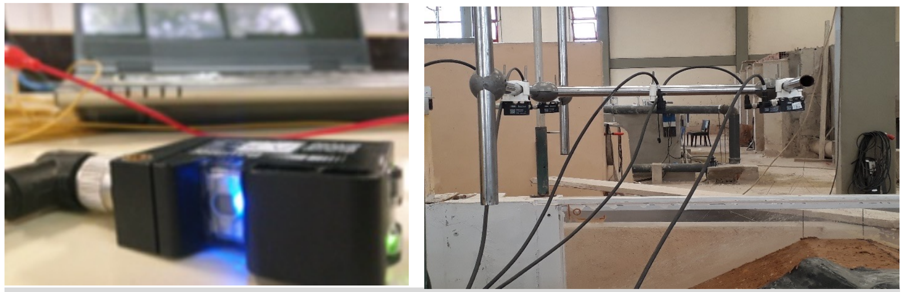
Toe drain

Experimental Procedure

1. Approximately 24 h before the beginning of the test, the reservoir was filled up to 0.38 m;
2. The pilot channel was carved in the center of the crest and blocked, by a plate or soil;
3. The upstream water level was slowly raised up to the crest level (the upper 0.07 m);
4. The block of the pilot channel is instantly removed and the overtopping begins ($t = 0\ s$);
5. The water level inside the reservoir was maintained reasonably constant and equal to the crest level, the inflow discharge was increased whenever the water level in the reservoir became lower than the crest level;
6. The tests were interrupted almost instantly for the breach characterization with the Kinect sensor. To halt the breaching process:
   - the inflow was cut-off, and simultaneously
   - the reservoir bottom valve is opened

Monitored Variables

1. Reservoir inflow
   ⇨ digital flowmeter
2. Reservoir water level
   ⇨ 6 acoustic probes
3. Channel outflow, using water level measurements in the channel
   ⇨ 1 acoustic probe
4. Breach morphologic evolution
   ⇨ 2 HD video cameras
   (above the crest & downstream of the dam)
5. 3D breach morphology
   ⇨ 2 KINECT sensors
   (above the crest & mobile)



Acoustic probes

KINECT sensor and video camera above the crest

Downstream video camera

KINECT sensor

HOMOGENEOUS EMBANKMENT WITH TOE DRAIN

Main Erosion Mechanisms:

homogeneous dams without filter

On the experimental tests, it was possible to fully reproduce the main breaching mechanisms:

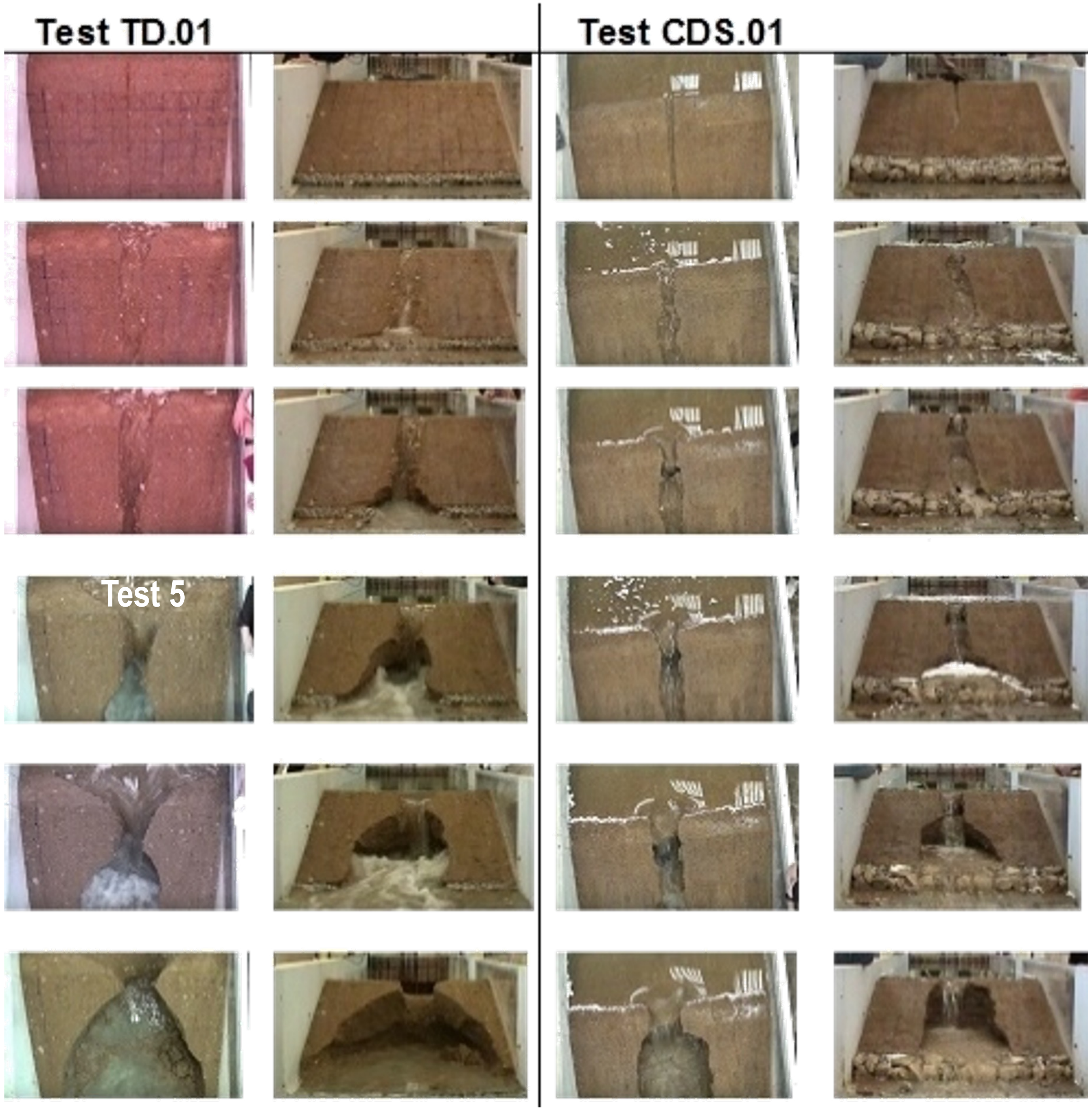
- Hydraulic erosion
- Headcut erosion
- Underscouring

Test 1: Homogeneous dam with toe drain

Test 1 – small pilot channel

Test 3 – large pilot channel

Homogeneous Embankment with Internal Drainage System



Major differences in the breaching mechanisms were observed.

Erosion cavities inside the dam body were observed, as consequence of the filter erosion.

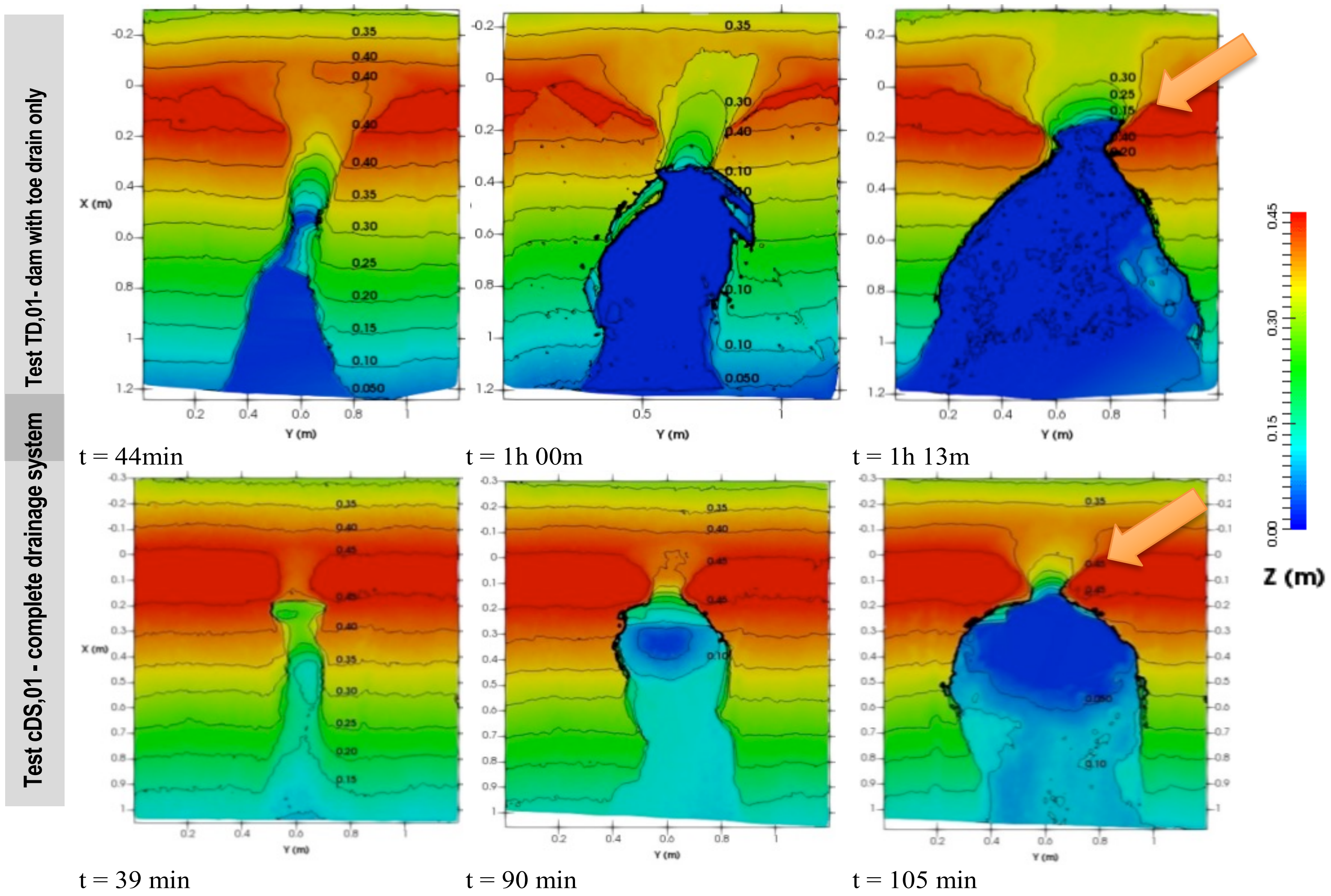
The filter erosion induces a fragility in the downstream slope, that fails mainly by mass detachments episodes.

However, this is not accompanied by an upstream progression of the breach, through hydraulic erosion.

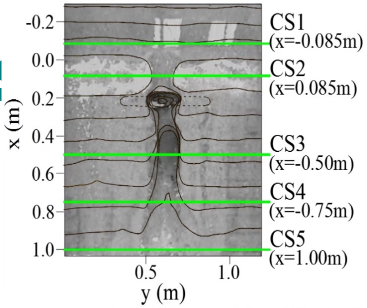
The breach discharge increases slowly while large amounts of body material are removed from the downstream dam slope due to the fragility induced by the filter.

HOMOGENEOUS EMBANKMENT WITH INTERNAL DRAINAGE SYSTEM

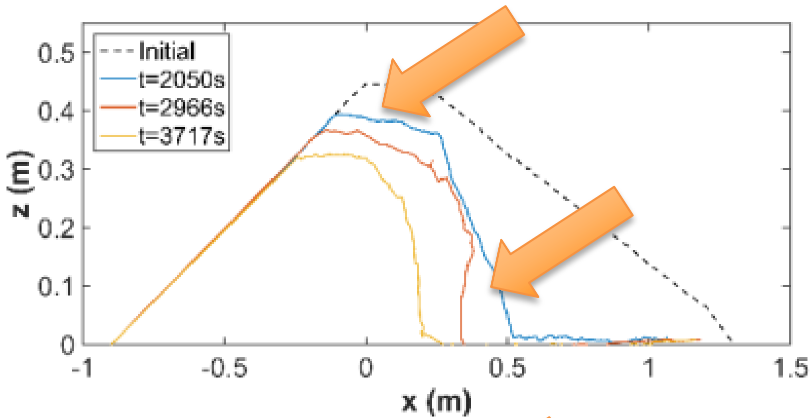
HOMOGENEOUS EMBANKMENT WITH INTERNAL DRAINAGE SYSTEM

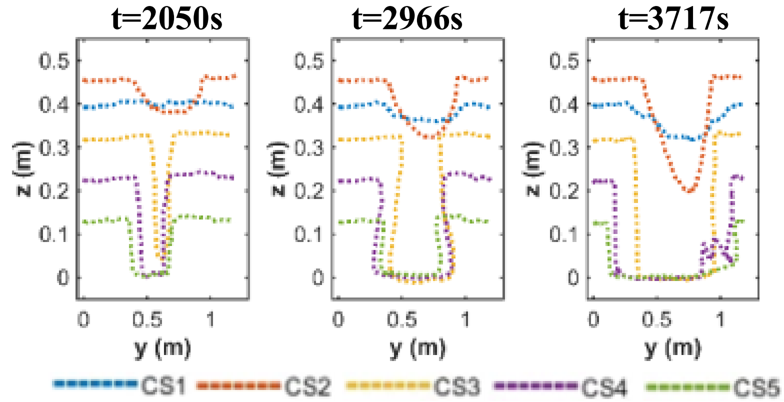


HOMOGENEOUS EMBANKMENT WITH INTERNAL DRAINAGE S

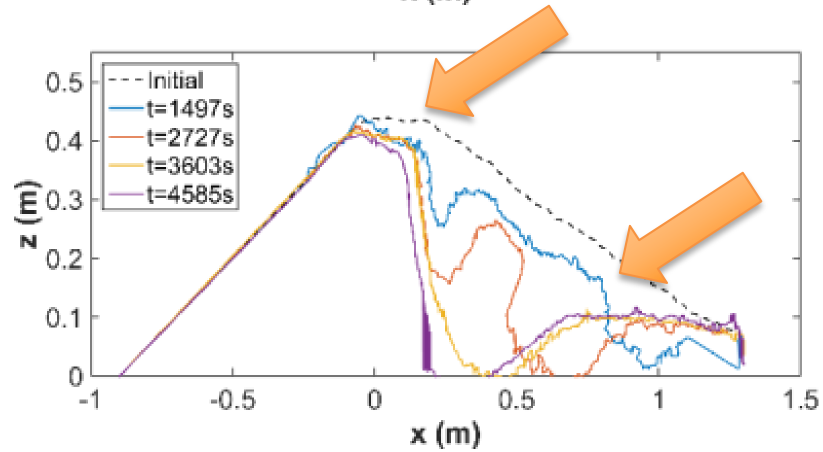


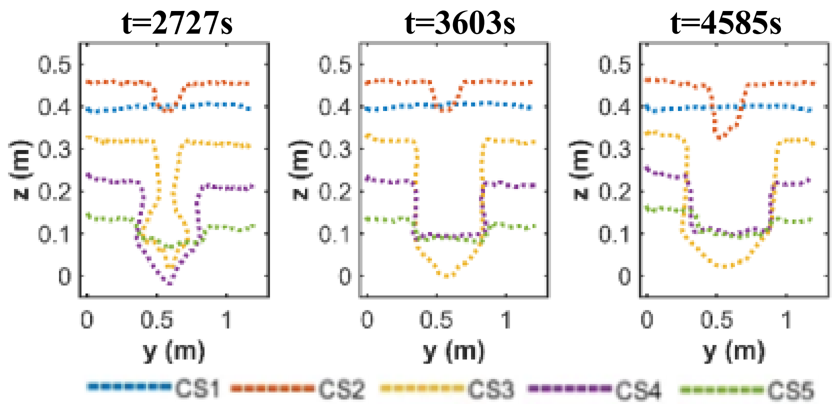
Test TD.01 - toe drain



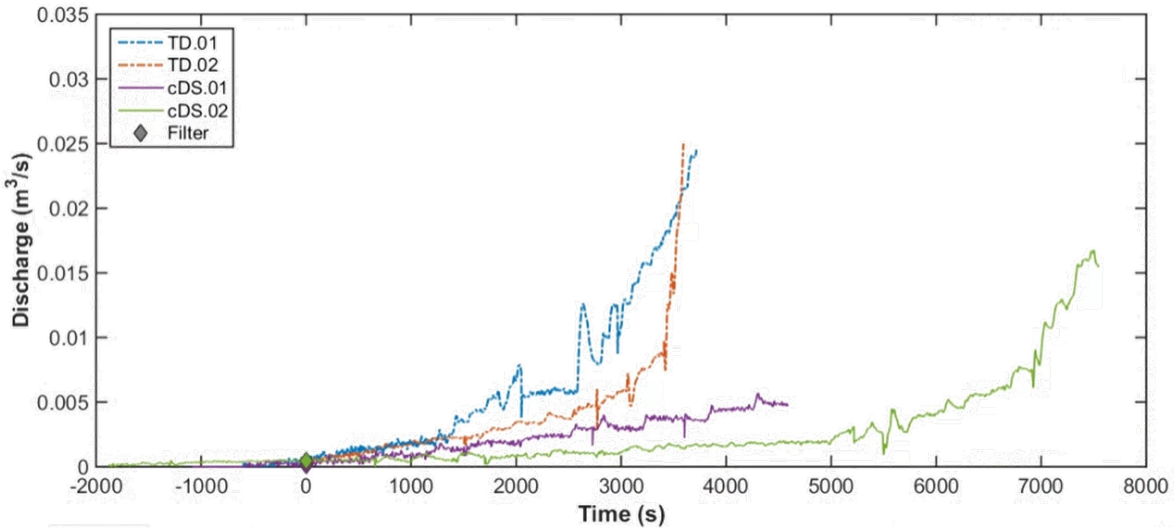


Test CDS.01 – Internal drainage system





HOMOGENEOUS EMBANKMENT WITH INTERNAL DRAINAGE SYSTEM



Breach outflow hydrographs were computed from mass balance in the reservoir:

$$Q_{out}^{n+1} = \frac{1}{2}\left(Q_{in}^{n} + Q_{in}^{n+1}\right) - A_r \frac{z_w^{n+1} - z_w^{n}}{dt}$$

where Q_{out} is the estimate of the breach outflow, Q_{in} is the inflow at the channel entrance, A_r is the reservoir surface area and z_w is a weighted average of water levels in the reservoir.

In the dams equipped with an internal drainage system (Tests CDS.01 and CDS.02) the **breach discharge has a much longer initial stage** as the erosion of the filter controls the upstream erosion progression.

When the filter has mostly disappeared, the breach discharge increases at a higher rate.

Homogeneous Embankment with Internal Drainage System

1) For t < 0 s: the dams have similar behavior

Erosion in the crest region during the initial phase, is hydraulic erosion, hence susceptible to be described by the Exner equation

$$(1-p)\frac{\partial z_b}{\partial t} = -\frac{\partial q_s}{\partial x}$$

2) At t = 0 s: the chimney filter is uncovered

3) Very soon after t = 0 s: erosion cavity across the breach channel in the dam with chimney filter

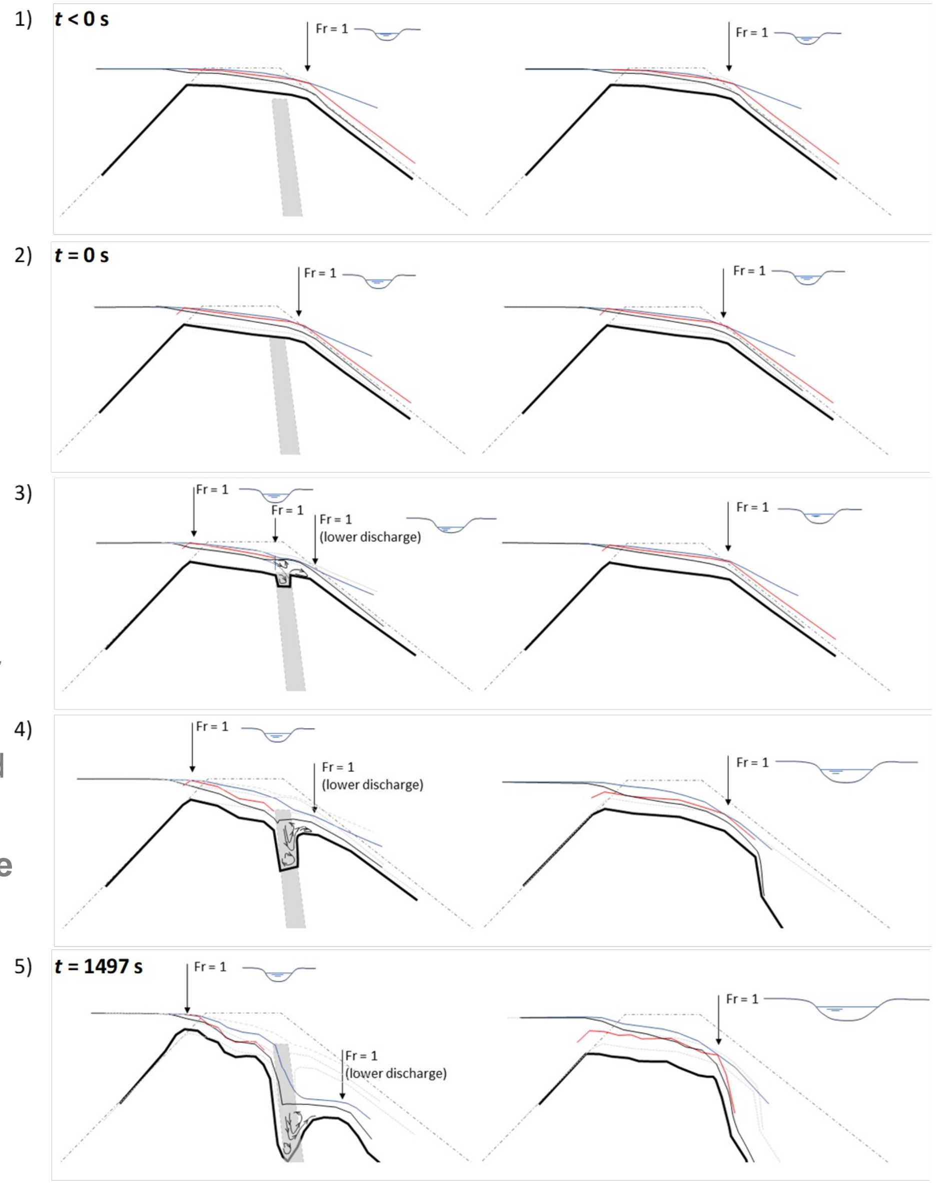
The filter is now able to convey a part of the breach discharge, estimated in less than 10%.
There are two possibilities for a new control section, a new knickpoint soon to be developed just upstream the filter or the initial cross-section of the channel over the dam crest

4) The knickpoint has been clearly formed upstream the filter

We hypothesize that the slope of the reach up to the filter cross-section is mild. This means that the breach discharge is controlled at this knickpoint, as the flow is likely to be subcritical up to it.

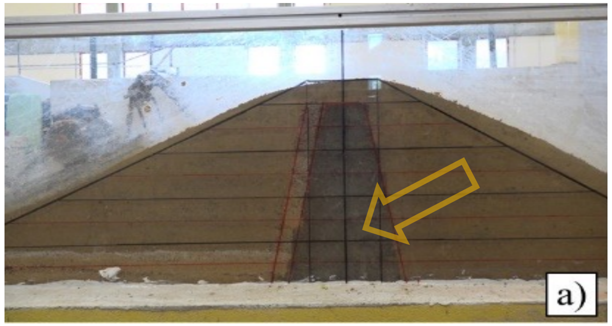
5) Morphology measurements allow for a quantification of the channel slope

Dam with toe drain: the channel is mild and the flow should be subcritical
Dam with internal drainage system: the channel is steep, which justifies channel deepening and not widening. The control section suffers few changes and the flow discharge does not increase substantially.



Zoned Embankment

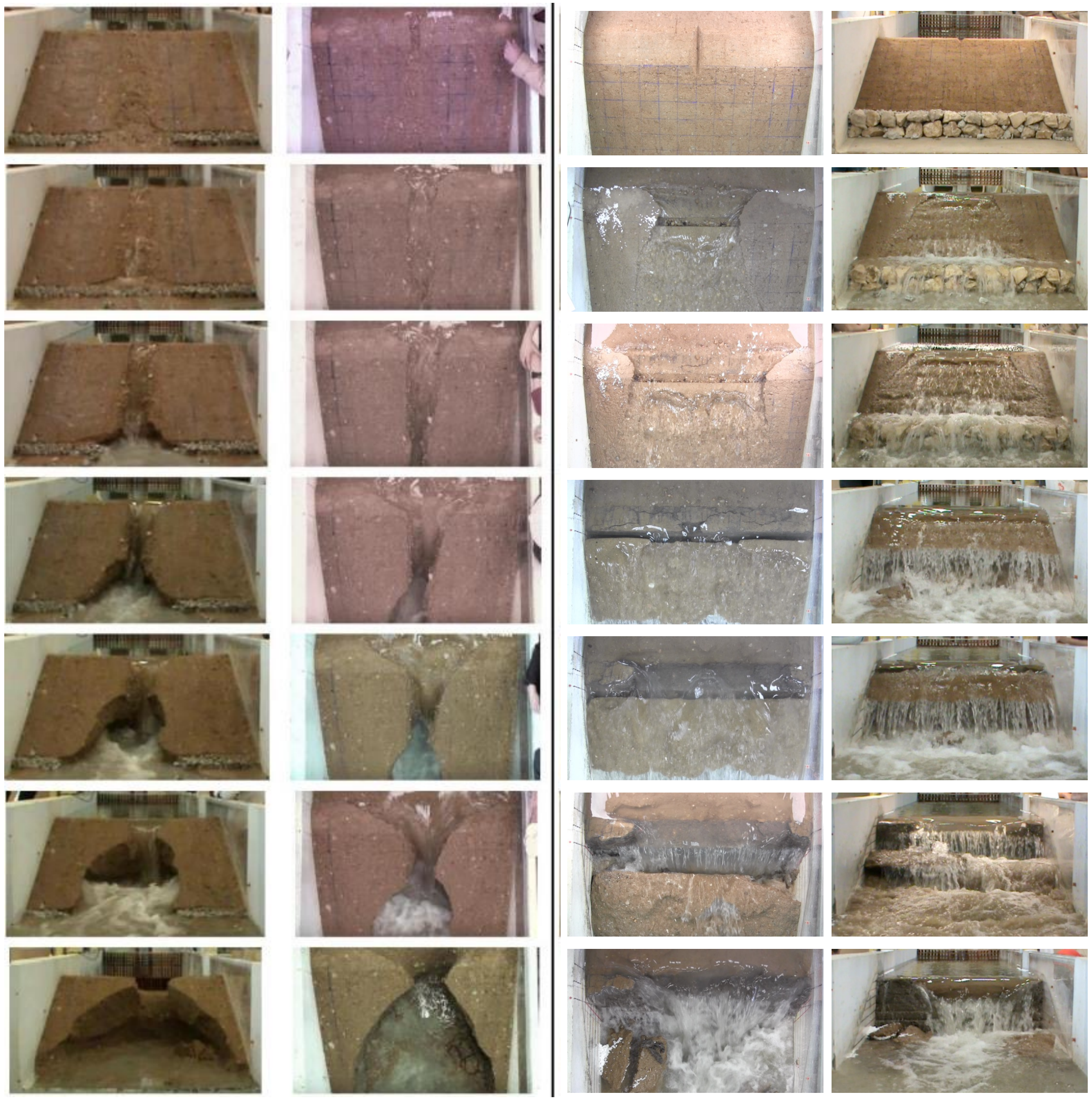
With Impervious Clay Core



Major differences in the breaching mechanisms were observed.

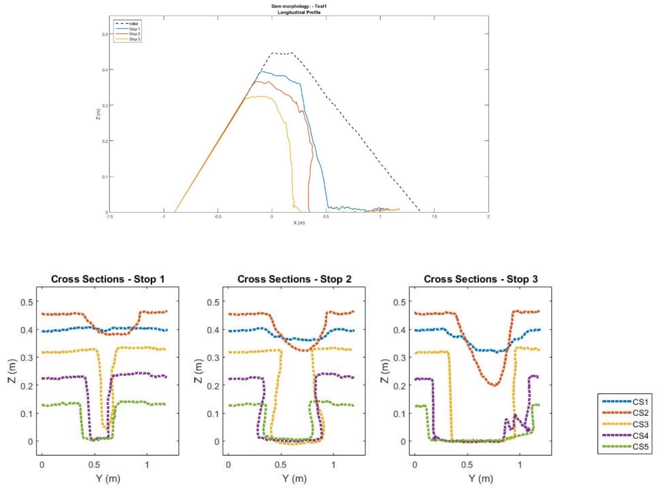
Clay core erodes by hydraulic erosion, with a much lower erosion rate than the downstream slope.

The erosion is essentially planar until the flow destabilizes a layer of clay material, causing the downstream shell collapse.

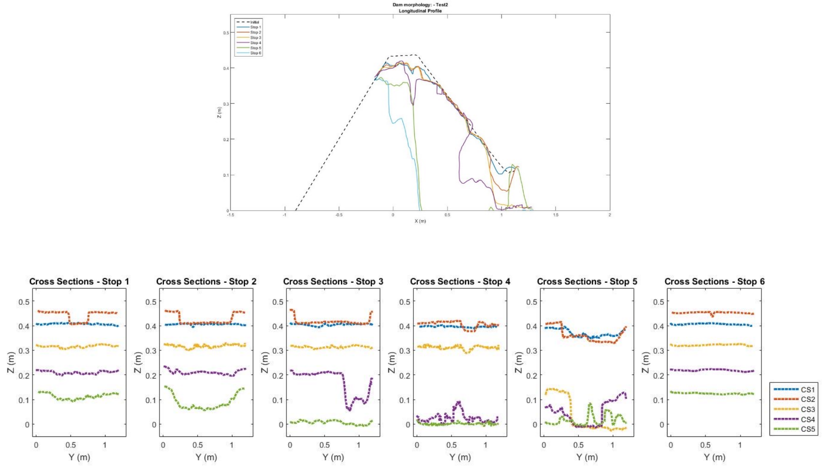


ZONED EMBANKMENT

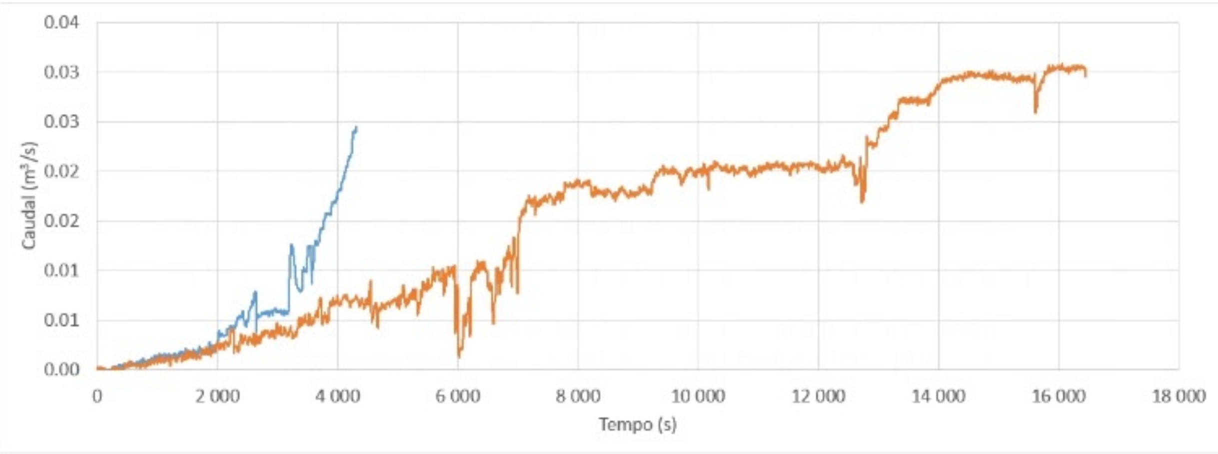
WITH IMPERVIOUS CLAY CORE



HOMOGENEOUS DAM

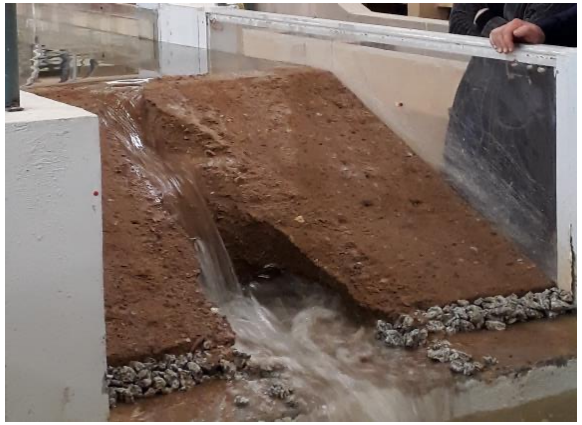


ZONED DAM



Main Conclusions

- Major differences in the breaching mechanisms were observed due to the heterogeneity and complexity created by the introduction of the internal filters and clay core.
- For homogeneous dams, the filter erosion causes a delay in the discharge increase that needs to be accounted in the dam emergency plans
- This is especially relevant for the flood warnings systems for the communities located in the inundation area, that may have more time for a proper evacuation than what is estimated with the current models.



PUBLICATIONS

Publications

These results have been presented in conferences as oral communications (14) and poster presentations (1)

1. Alvarez, T., Aleixo, A., Valente, S., Amaral, S., Viseu, T., Ferreira, R.M.L. (2023). Hydraulics and Morphodynamics of Overtopped Dams with Chimney Filter. M.S. Yalin Memorial Colloquium 2023. Palermo, Italy. 26-27 January 2023.
2. Alvarez, T., Aleixo, A., Valente, S., Amaral, S., Viseu, T., Ferreira, R.M.L. (2022). Frozen in time: continuous measurements in a dam-breach flow. River Flow 2020 - 11th Conference on Fluvial Hydraulics. IAHR. Conference online. 8-10 November 2022.
3. Alvarez, T., Valente, S., Aleixo, A., Amaral, S., Caldeira, L., Viseu, T., Ferreira, R.M.L. (2022). Hydraulics and morphodynamics of overtopped dams with chimney filter. 39th IAHR World Conference – From Snow to Sea. Granada, Spain. 19-24 June 2022
4. Aleixo, R. Amaral, S., Mendes, S.V., Viseu, M.T., Alvarez, T., Fraga Filho, C.A. & Ferreira, R.M.L. (2022). Challenges of Surface Image Velocimetry - The dam-breach example. 39th IAHR World Conference – From Snow to Sea. IAHR. Granada, Spain. 19-24 June 2022
5. Mendes, S., Amaral, S., Alvarez, T., Aleixo, R., Muralha, A., Viseu, T. & Ferreira, R.M.L. (2022). Image analysis techniques to characterize scaled embankment failures. TEST&E 2022 - Tecnologias Inteligentes. 3º Congresso de Ensaios e Experimentação em Engenharia Civil. NOVA / IST / RELACRE. Caparica. 21-23 June 2022
6. Alvarez, T., Valente, S., Amaral, S., Viseu, T., Ferreira, R.M.L. (2020). Dam breach hydraulics and morphodynamics in overtopped earth dams with chimney filter. River Flow 2020 - 10th Conference on Fluvial Hydraulics. IAHR. Conference online. 6-17 July 2020.
7. Amaral, S., Alvarez, T., Caldeira, L., Viseu, T., Ferreira, R.M.L. (2019). Recent advances on experimental dam breach studies. Mecânica Experimental, 31:11-25

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8. Alvarez, T., Valente, S., Amaral, S., Viseu, T., Ferreira, R.M.L. (2019). Influência do teor de humidade na rotura de barragens de aterro por galgamento. 14º SILUSBA. Praia, Cabo Verde, 19-20 September 2019
9. Alvarez, T., Valente, S., Amaral, S., Viseu, T., Ferreira, R.M.L. (2019). Sensitivity analysis to the pilot channel geometry in dam breach by overtopping. 38th IARH World Congess – Water Connecting the World. Panamá City, Panamá, 1-6 September 2019 (poster)
10. Amaral, S., Alvarez, T., Caldeira, L., Viseu, T., Ferreira, R.M.L. (2018). Recent advances on experimental dam breach studies. Proceedings of the 1st Iberic Conference on Theoretical and Experimental Mechanics and Materials / 11th National Congress on Experimental Mechanics. Porto, Portugal, 4-7 November 2018
11. Alvarez, T., Valente, S., Amaral, S., Viseu, T., Ferreira, R.M.L. (2019). Análise de sensibilidade à geometria do canal piloto na rotura de barragens por galgamento. TESTE&E 2019 – Monitorizar e Preservar. 2º Congresso de Ensaios e Experimentação em Engenharia Civil. Porto, Portugal, 19-21 February 2019
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15. Amaral, S., Alvarez, T., Viseu, T., Ferreira, R. (2018). Modelação Física da rotura de barragens de terra. Instrumentação e métodos de monitorização. 14º Congresso da Água, Évora, 7-9 March 2018

Expected Publications

Breaching of Homogeneous Dams with Internal Drainage Systems

Submited to Water Resources Research

Alvarez, T.; Ferreira, R.M.L.; Mendes, S.; Aleixo, R.; Amaral, S.; Caldeira, L. & Viseu, T.

Hydrodynamics of overtopped breaching dams

To be submitted to Jornal of Fluid Mechanics

Alvarez, T.; Aleixo, R.; Viseu, T. & Ferreira, R.M.L.

Failure of homogeneous and zoned dams subjected to overtopping. Timescales and fundamental morphological processes

To be submitted to Journal of Hydraulic Engeeniring

Alvarez, T.; Aleixo, R.; Mendes, S.; Amaral, S.; Caldeira, L.; Viseu, T. & Ferreira, R.M.L.

THANK YOU!