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Christophe Picault, Fabrice Crampette, Stéphane Bonelli, Sylvie Nicaise, Naïm Chaouch, Faustine Byron, Yves Grémeaux, Alexis Doghmane, Mathys Garoui, Jordan Herbeck, et al.

# FIELD TESTING OF THE OVERFLOW EROSION OF RHONE RIVER LEVEES

**CHRISTOPHE PICAULT[1], FABRICE CRAMPETTE[1], STÉPHANE BONELLI[2], SYLVIE NICAISE[2], NAIM CHAOUCH[2], FAUSTINE BYRON[2], YVES GREMEAUX[2], ALEXIS DOGHMANE[2], MATHYS GAROUI[2], JORDAN HERBECK[2], FRÉDÉRIC GOLAY[3]**

[1]Compagnie Nationale du Rhône (CNR)
4 Rue de Chalon sur Saône, Port E. Herriot
69007 Lyon, France
e-mail: c.picault@cnr.tm.fr

[2] INRAE and Aix-Marseille University
RECOVER Joint Research Unit, 3275 Route de Cézanne - CS 40061
13182 Aix-en-Provence, France
e-mail: stephane.bonelli@inrae.fr

[3] Institute of Mathematics of Toulon (IMATH)
University of Toulon, La Garde, CS 60584
83041 Toulon, France
e-mail: frederic.golay@univ-tln.fr

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**Summary.** It is important to quantify the soil resistance against erosion caused by the overflow of dikes and levees. Small-scale tests are not recommended, as they do not provide a correct representation of the actual soil in place and do not take into account the geometry of the structure. For this reason, the National Research Institute for Agriculture, Food and Environment (INRAE) developed an on-site overflow device in 2015. The procedure followed is based on ASTM-D6460 standard. Two tests were performed in May 2022 on a Compagnie Nationale du Rhône (CNR) dike near Avignon (France). The dike is 6.2 m high; the core is mainly made of sandy silts. The toe is covered by a gravel shoulder which forms a berm. The first test was carried out on the intact soil: the core covered by a natural grass on the upper part, and the gravel fill without grass in the lower part of the slope. The test consisted of carrying out a flow in a channel of 1 m wide and 25 m long, in 12 steps of 30 min (6 hours of flow in total). The second test was carried out on the soil stripped of the vegetation cover in order to study the soil of the upper part of the embankment, made up of compacted sandy silt and sandy gravel. The test consisted of carrying out a flow in a 60 cm wide and 20 m long channel, in 9 steps of 30 min (4.5 hours of flow in total). The test campaigns were carried out with flows ranging from 12 to 140 l/s per linear meter, corresponding to a crest water depth ranging from 4 to 18 cm. On test 1, no significant erosion of the natural grass cover was observed. A small erosion pit 20 cm deep was observed on the compacted gravel berm surface. A scour hole of approximately 1.10 m in depth for a volume of 4.2 $m^3$ was observed in the downstream gravel fill that cover the lower part of the embankment. On test 2, the compacted sandy silt layer was eroded a few centimeters by the surface flow. The sandy gravel layer was eroded from the first flow (5.7 cm of water height at the crest), which led to the beginning of a breach (deepening) over 10 m long, of 1.30 m maximum depth, 1.80 m maximum width and 9 $m^3$ of eroded soil. The first result of these in situ overflow tests is that not all of these observations were predictable from the erosion tests previously performed in the laboratory and in situ (Jet and Het erosion tests). The second result is the remarkable resistance of the natural grass cover.

# 1 INTRODUCTION

The International Levee Handbook (CIRIA, 2013) now clearly present the principles related to flood protection systems. The failure of a river dike following the occurrence of a flood overtopping the crest of the embankment is one of the essential scenarios of risk analysis. To provide resistance to overflow, the practice is to use a surface protection system: asphalt, riprap, calibrated grass or any other type of known surface protection. The resistance of these surface protections is most often estimated from results, obtained by tests in large hydraulic channels in the laboratory (Hewlett et al, 1987). This is for example the case of the hydraulic laboratory of the University of Colorado at Fort Collins (CSU), which makes it possible to simulate overflow (steady overtopping) or wave overtopping (Thornton et al, 2012), according to ASTM D6460 (Standard Test Method for Determination of Rolled Erosion Control Product Performance in Protecting Earthen Channels from Stormwater-Induced Erosion, ASTM, 2012). A similar set of canals was built on the DredgeDike demonstrator to qualify dredging soil on the downstream slope (Olschewski et al, 2014, Cantré et al, 2017). On the other hand, no field equipment nor laboratory equipment is available to correctly qualify the resistance to overflow process of a soil constituting the dike embankment.

Climate projections show a decreasing trend in the average flow of the Rhone, but a variable trend, possibly increasing, in extreme flows (Aubé, 2016; Billy et al, 2018). In the same time, risk analysis on the Rhône river development shown that a medium flood, coupled with problems on gates operations on the regulating dam, can lead to a significant overflowing on embankments. Moreover, the analysis of recent events show that some earth dams and dikes can be overtopped without breach and failure. Finally, the analysis of the state of the art and knowledge shows that progress remains to be made in order to better understand and model the external erosion of the soils constituting embankment structures, especially soils with high granulometry (Courivaud et al, 2018). For all these reasons, it is now necessary to study the external erosion resistance of soils constituting embankment dikes.

The Hole Erosion Test (HET) has been used for several years at the laboratory for internal erosion (Wan and Fell, 2004; Bonelli, 2013). However, the HET internal erosion test does not lead to any conclusion on external erosion resistance. We are not aware of any correlations between these two types of erosion resistance. The EFA laboratory test reproduces surface erosion in the laboratory (Briaud et al, 2008), but it is small scale and requires bringing the soil to the laboratory. The in-situ JET test (Jet Erosion Test) is representative of what happens at the slope toe, or at the bottom of steps for the Head-Cut mechanism (Hanson and Cook, 2004). However, we are not aware of established relationships between test JET results and overflow characteristics, particularly with regard to erosion by tangential flow to the soil.

To quantify the resistance of the soil to surface erosion, it is impossible to use results such as those used for surface protection systems. As is the practice in geotechnics, a test on the soil in question is necessary. Small-scale tests are excluded, as they do not provide a correct representation of the actual soil in place. For this reason, INRAE (Aix-en-Provence) developed an on-site overflow device in 2015. The procedure followed is based on ASTM-D6460 standard. Two types of tests were performed in May 2022 on a CNR 6.2 m high dike near Avignon (France).

# 2 DESCRIPTION OF THE DIKE

## 2.1 Description of the dike

In 1933, the Compagnie Nationale du Rhone (CNR) was created in response to specific needs such as generating electricity, developing navigation and promoting irrigation. The levee systems on the Rhône River include non-overflow levees, overflow-resistant levees (operating under a low hydraulic load), and a gate structure dam (operating under medium and high hydraulic loads). Non-overflow levees are designed to prevent overtopping for flows less than or equal to the 1,000-year flood and maintain freeboard at this level. It is however not excluded that an exceptional hydrological event (or a medium flood coupled with opening gates problems on the downstream regulating dam), leads to an overflow of non-overflow levees. To better understand this phenomenon, a research program has been conducted jointly by CNR and EDF. It is within this framework that the present overflow tests were carried out.

The selected dike section was chosen for its large crest width (more than 60 m), so that the erosion caused by the tests would not be detrimental to the safety of the dike. The site is located in the South of France, near the city of Avignon. The cross section is shown in Figure 1. The dike is 6.20 m high. It is made up of a compacted silt (slope 4H/1V) 3.50 m thick in the upper part. A layer of about 1 m thick and 20 m long, consisting of sandy gravel (0-30 mm with larger blocks of 10 to 20 cm) is located in the downstream part. In the lower part, the soil is a silt in place of 2.70 m thickness (slope 2H/1V). A gravel fill (0-30 mm) 2.70 m thick is placed at the toe of the dike (slope 3H/1V). The crest of this shoulder constitutes a 6.00 m wide berm, which includes a 3.00 m wide road track (compact gravel). The remainder of the berm crest is covered with deposited silt (about 3 m width). Both slopes are covered with a natural grass cover, 3 cm high (approximately) at the time of testing. The first layer of the foundation consists of alluvial gravel. The top of this layer corresponds to the level of the back channel.

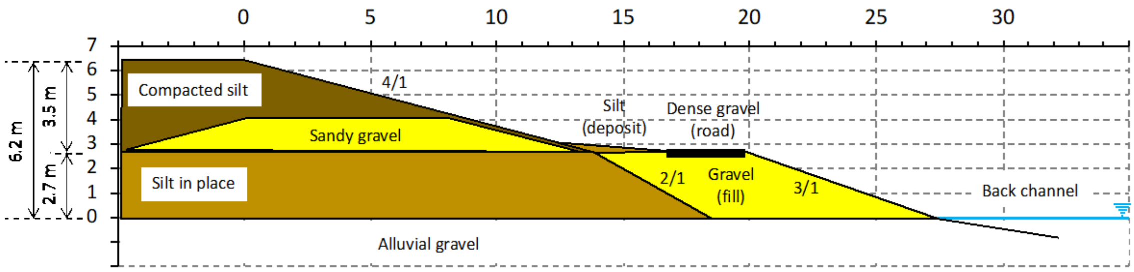


**Figure 1.** Cross-section of the dike.

## 2.2 Soil description and laboratory test results

Table 1 reports the geotechnical characteristics of the different materials constituting the levee, shown in Figure 1. The layers named "Compacted silt" and "silt in place" according to the design cross sections are silty and clayey sand (SM and SC according to USCS classification), respectively; the "sandy gravel" layer at the base of the upper part consists of well-graded gravel (GW) with some very large boulders (200 to 300mm). The gravel fill at the foot of the dike consists of gap graded gravel (GP). The silt's water content, measured just prior to the overflow test at a depth of -0.2m, was 13.4%, meaning that the soil was dry at the surface.

**Table 1.** Geotechnical characteristics of the levee materials.

| Layer (named according to design cross sections) | $D_{max}$ (mm) | $D_{50}$ (mm) | <2mm (%) | <80µm (%) | <2µm (%) | $w_L$ (%) | $I_p$ (-) | $V_{BS}$ (g/100g) |
|---|---|---|---|---|---|---|---|---|
| Compacted silt | 31.5 | 0.4 | 75 | 30 | 4 | 25 | 4 | 0.5 |
| Sandy gravel | 125 | 17 | 26.3 | 4 | - | - | - | - |
| Silt in place | 25 | 0.1 | 90 | 36 | 6.3 | - | - | 0.9 |
| Gravel (fill) | 70 | 20 | 22 | 2 | - | - | - | - |

Several JET erosion tests were performed during the preparation phase of the overflow test according to ASTM D5852, on recompacted and intact samples, as well as directly on the site. The results show that all materials tested by the JET, in situ and in laboratory, are very erodible. The compacted silt's critical shear stress ($\tau_{c,JET}$) is about 30Pa and Hanson coefficient of erosion ($K_{d,JET}$) is about 75cm$^3$.s$^{-1}$.N$^{-1}$, which is high. When covered with grass, the same material has $\tau_{c,JET}$= 60Pa while $K_{d,JET}$=45cm$^3$.s$^{-1}$.N$^{-1}$. The gravel fill's resistance was measured in situ: $\tau_{c,JET}$= 25Pa while $K_{d,JET}$=315cm$^3$.s$^{-1}$.N$^{-1}$, i.e. erosion rate is very fast. In the same way, the dense gravel (road track)'s resistance is low, with $\tau_{c,JET}$= 21Pa and $K_{d,JET}$=54cm$^3$.s$^{-1}$.N$^{-1}$.

## 2.3 Description of the experimental device

Two hydraulic channels were built. Channel 1 is laid out on the intact ground. It is 0.60 m high, 1.00 m wide and 25.00 m long (Figure 2a). This channel allows flow to be applied to the vegetal cover and the gravel fill. Channel 2 is laid out on the soil previously stripped of the vegetal cover to a depth of 20 to 25 cm. It is 0.60 m high, 0.60 m wide and 20.00 m long (Figure 2a). This channel allows flow to be applied to the constitutive soil of the dike, especially the compacted silt and the sandy gravel. A buffer tank is located on the crest between the discharge point of the pumping system and the inlet of each channel. The test channels lead to the counter-channel (at the toe of the embankment) that houses the pumps, which makes it possible to operate in a closed circuit.

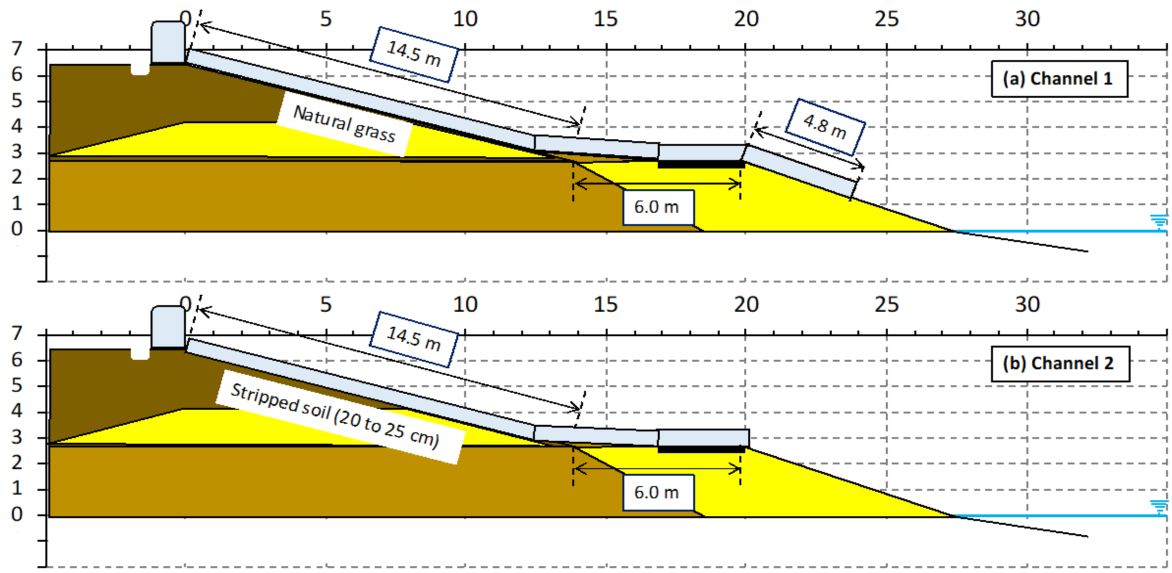


**Figure 2.** Cross-section of the two test channels.

**Figure 3.** View of the two test channels. Channel 1 is in the foreground.

## 2.4 Description of the test procedure

The test protocol incorporates elements of ASTM D6460 (ASTM, 2012). A test campaign consists of carrying out a series of 30-minute flows and measuring erosion between each flow. For channel 1, the initial flow rate was $q$=12.8 l/s/m, corresponding to a water depth on crest $h_0$ = 3.7 cm. This flow rate was gradually increased to $q$=128 l/s/m, corresponding to a water depth on crest $h_0$ = 17.3 cm (Figure 4a). The total flow duration was 6h00 for the sequence of 12 tests. For channel 2, the initial flow rate was $q$=24.0 l/s/m, corresponding to a water depth on crest $h_0$ = 5.7 cm. This flow rate was gradually increased to $q$=141.7 l/s/m, corresponding to a water depth on crest $h_0$ = 18.5 cm (Figure 4b). The flow duration for the 9 tests was a total of 4h30.

During each 30 min flow stage, the following measurements were made: measurement of the flow entering the tank, the flow velocity, the position of the free surface and the position of the soil at several points in the channel. Between each flow stage, a complete measurement of the soil position was also performed.

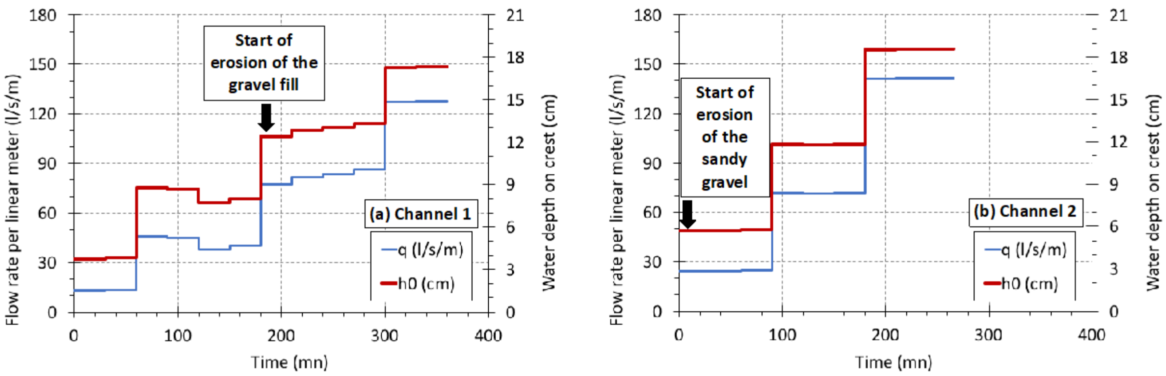


**Figure 4.** Flow sequence of (a) the 12 tests on Channel 1 and (b) of the 9 tests on Channel 2.

## 3 RESULTS

The test campaign was conducted between April 25 and May 10, 2022. As of the date of this communication, the measurements were not yet analyzed and interpreted. The present results are only preliminary and qualitative with regard to erosion.

### 3.1 Erosion of natural grass cover

This analysis concerns channel 1. The natural grass cover was cut to a length of 3 cm two weeks before the trials. The site had a few days of rain and mainly sunshine during this period. Several plant species are present. Vegetation grew heterogeneously, depending on the species present. The cover on the high slope was overall homogeneous in density and did not have any significant uncovered soil surface. At the beginning of the trials, the length of the grass blades was variable and could reach up to 5 cm. After the 6h of flow, the grass blades remained lying in the direction of the flow (Figure 5). As for the gravel shoulder, which contains little fines, the vegetation cover is not significant. This is also true for the berm.

The flow rate was gradually increased from q=12.8 l/s/m to $q$=128 l/s/m. The flow corresponding to $q$=85.1 l/s/m and $h_0$ = 13.3 cm is shown in Figure 6a. The slope after the 6 h of flow is visible in Figure 6b. No significant erosion, in the sense of the Clopper index (ASTM, 2012), was observed.

It is remarkable that the silt deposit at the slope toe, also grassed over, was not eroded either.

It is not compacted silt, as it is constituted of deposited soil that comes from the surface erosion of the slope during rainy periods. This shows that the natural vegetation cover also protected this area. Therefore, no scouring of the slope toe was observed.

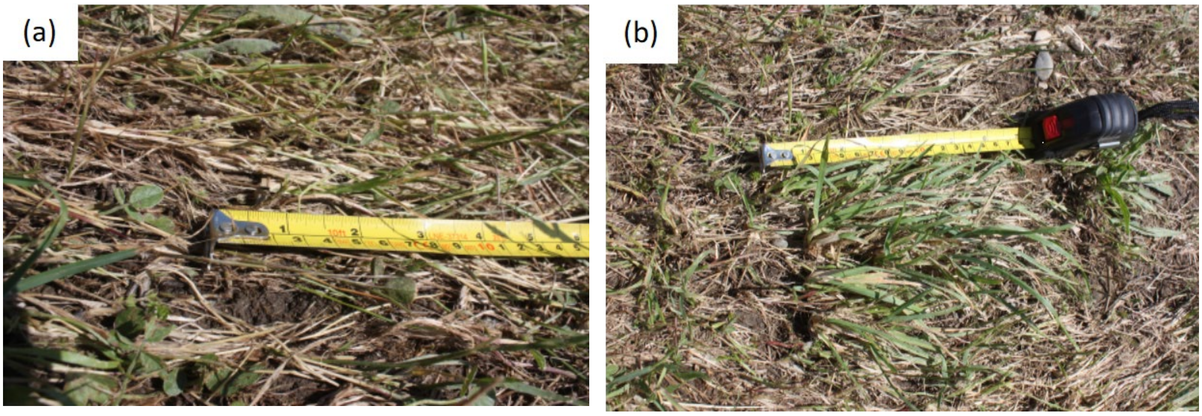


**Figure 5.** Natural vegetation cover after 6 hours of flow.

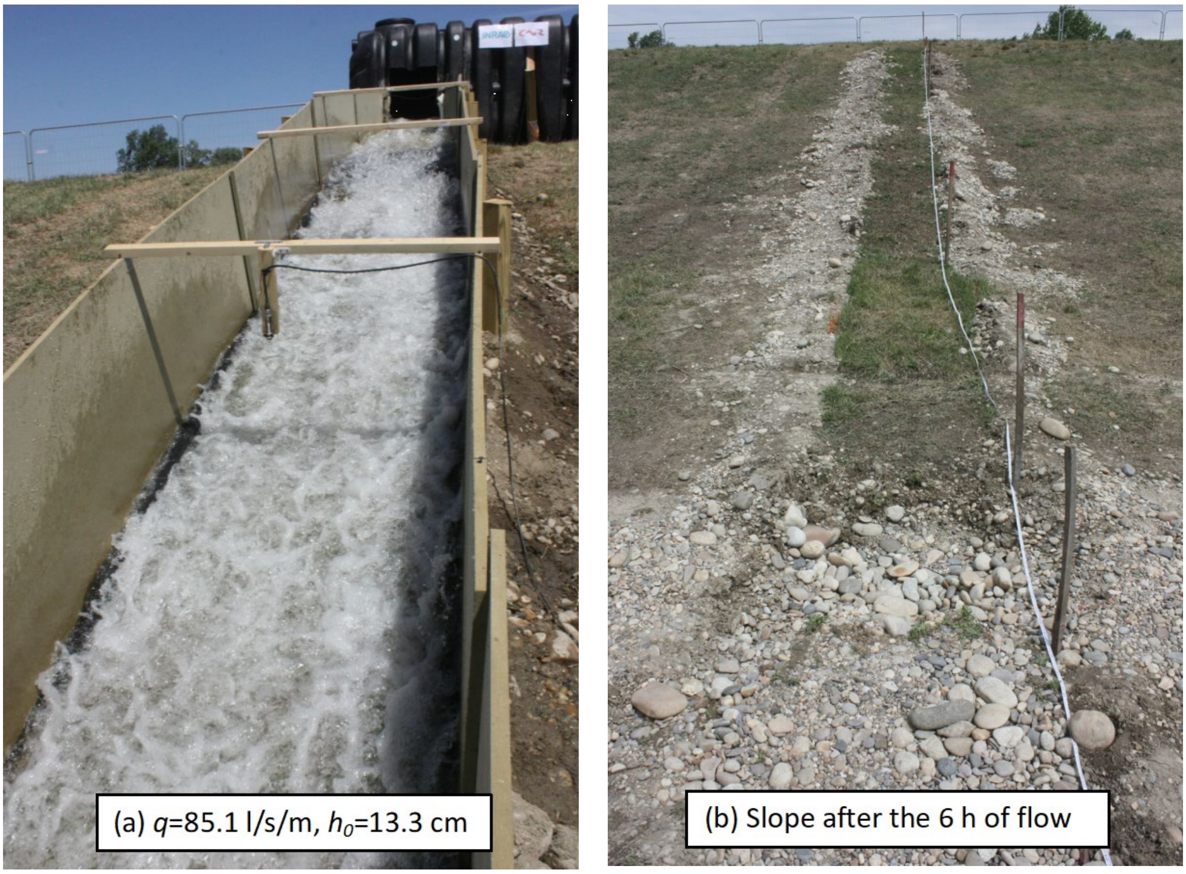


**Figure 6.** (a) Flow corresponding to $q$=85.1 l/s/m and $h_0$ = 13.3 cm. (b) Slope after the 6 h of flow.

### 3.2 Scouring on the berm (top of the gravel shoulder).

This analysis concerns channel 1. The scour on the berm is visible in Figure 5b: it is the gravel square between the two wooden posts. It is about 1 m wide, 1 m long and 20 cm deep after 6h00 of flow (Figure 6). This scour occurs about 2 m from the slope toe, just before the road, which is made of hard, compacted gravel.

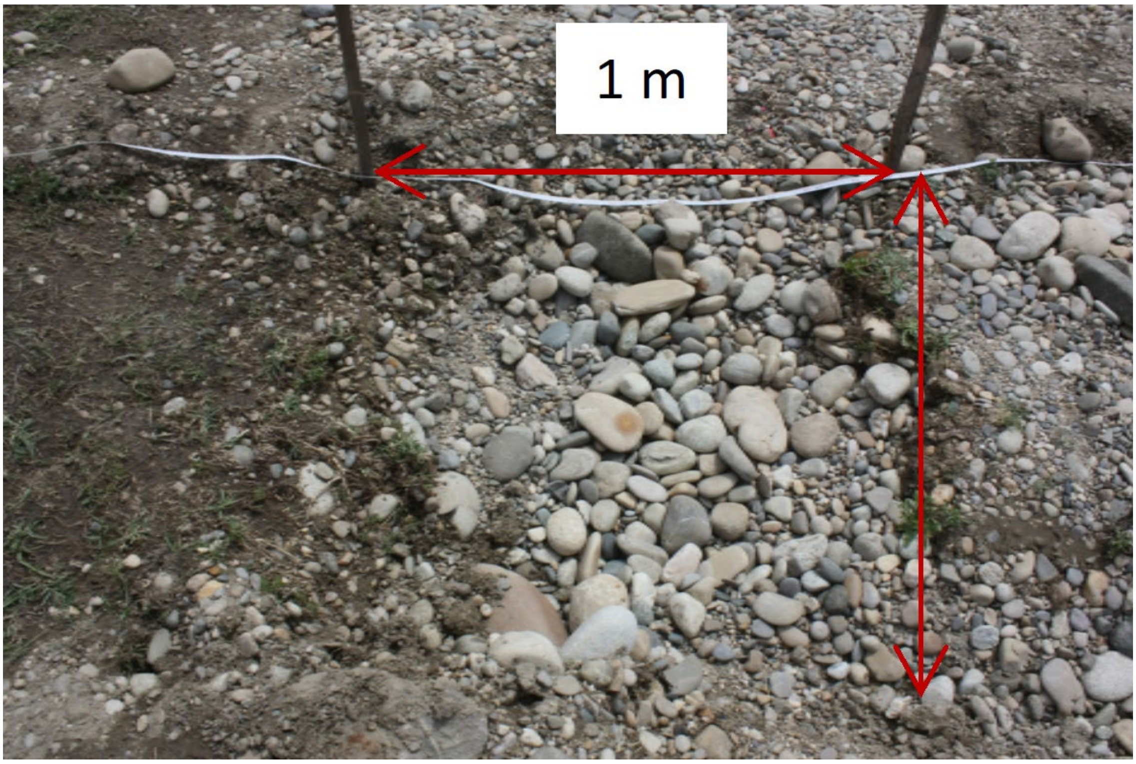


**Figure 7.** Scouring at the slope toe after the 6 h of flow (channel 1), depth is 20 cm. The flow goes from the left to the right.

### 3.3 Erosion of the gravel fill.

This analysis is for channel 1. The erosion of the gravel fill was initiated just below the road track, at the flow level $q$ = 77.5 l/s/m and $h_0$ = 12.4 cm (Figure 4a). This flow is visible in Figure 8a. The situation one hour later is visible in Figure 8b for a similar flow ($q$ = 88.6 l/s/m, $h_0$ = 13.0 cm), showing significant erosion of the gravel fill. The erosion between $t$=210 min (initiation) and $t$=300 min, for a little variable flow ($q \approx 82$ l/s/m and $h_0 \approx 13$ cm) is visible in Figure 9. After 6 hours of flow, the eroded area is 4 m long, maximum width of 2 m, maximum depth of 1.10 m, and corresponds to about 4 $m^3$ of eroded material (Figure 10).

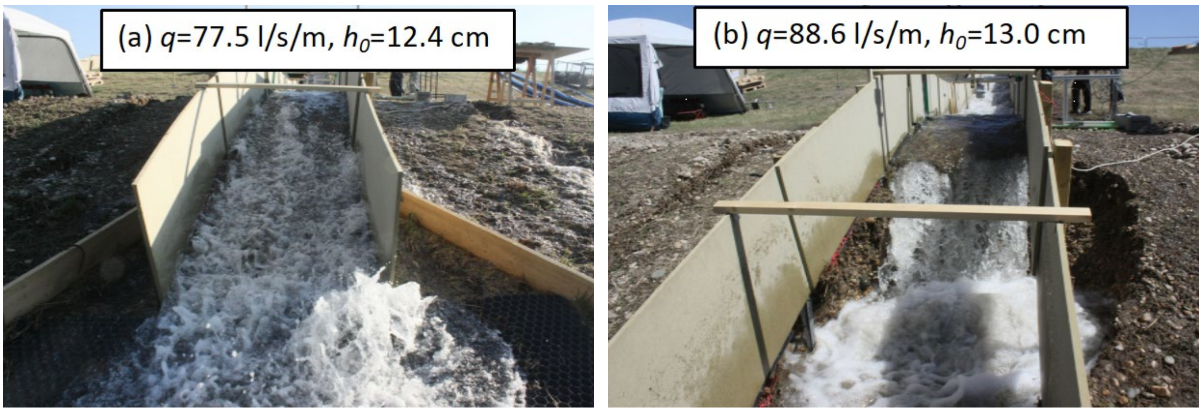


**Figure 8.** (a) Flow corresponding to $q$=77.5 l/s/m and $h_0$ = 12.4 cm at the time of erosion initiation of the gravel fill. (b) Flow corresponding to $q$=88.6 l/s/m and $h_0$ = 13.0 cm one hour later, showing significant erosion of the gravel fill.

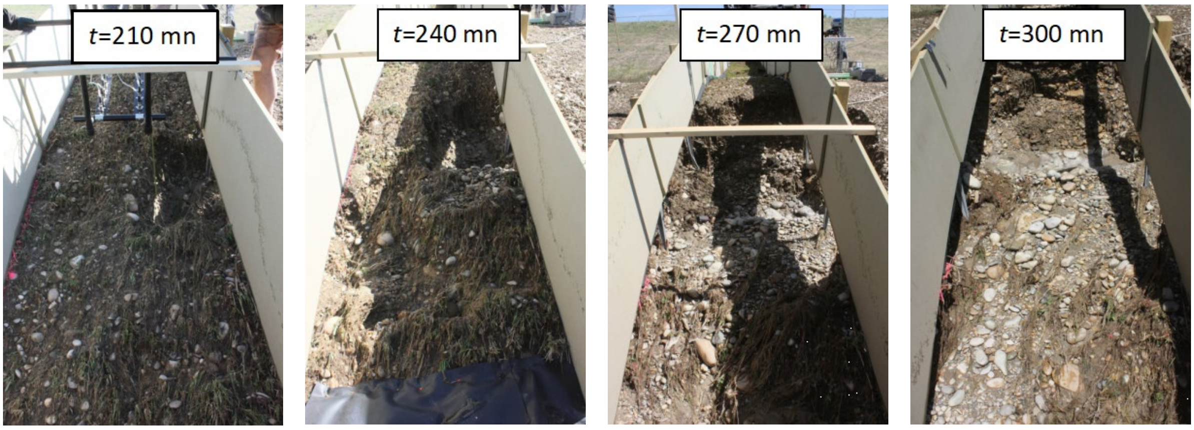


**Figure 9.** Erosion of gravel fill, between $t$ = 210 min (initiation) and $t$ = 300 min, for a little variable flow ($q \approx 82$ l/s/m and $h_0 \approx 13$ cm).

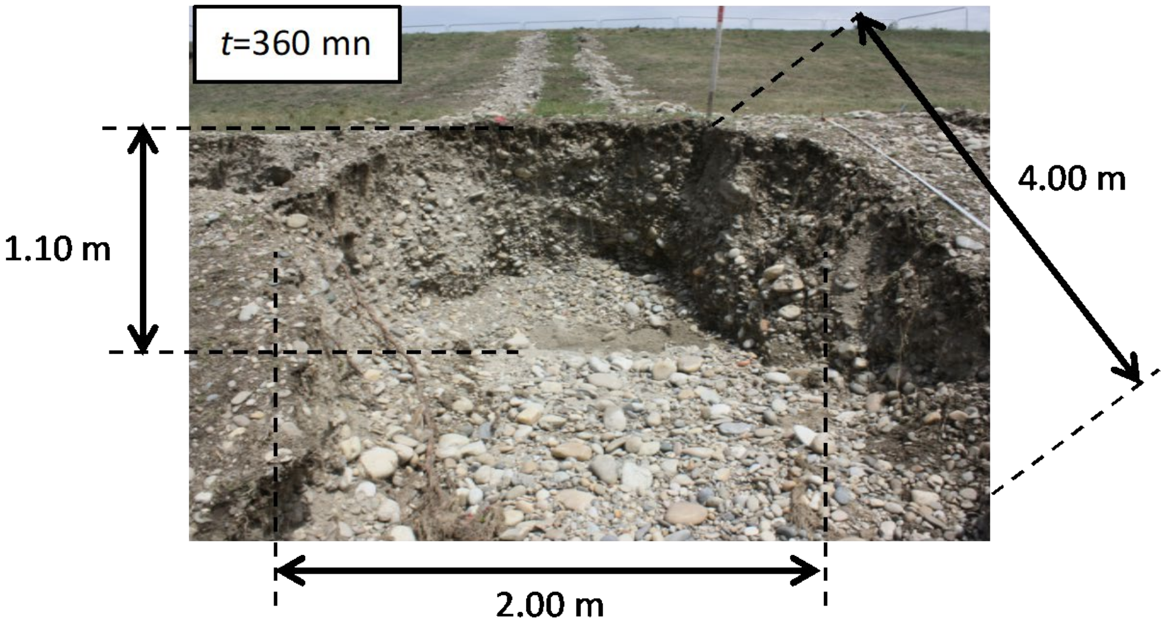


**Figure 10.** Erosion of gravel fill after 6 h of flow (channel 1).

### 3.4 Erosion of compacted sandy silt

This analysis concerns channel 2. The initial flow rate was $q$=24.0 l/s/m, corresponding to a water depth on crest $h_0$ = 5.7 cm. This flow rate was gradually increased to $q$=141.6 l/s/m, corresponding to a water depth on crest $h_0$ = 18.6 cm (Figure 4b). The sequence of 9 tests corresponds to 4h30 of flow.

The soil before testing is visible in Figure 11. After 30 minutes of flow at $q$=24.0 l/s/m and $h_0$ = 5.7 cm, the visible erosion corresponds to that of the surface soil, which is not significant. The initiation of a scouring (Figure 11) is probably due to the fact that the flow has a locally high velocity at the outlet of the geomembrane. This result will allow to quantify the erosion threshold from the velocity measurements at this location. After 90 min of flow at $q$=24.0 l/s/m and $h_0$ = 5.7 cm, and 60 min of flow at $q$=43 l/s/m and $h_0$ = 11.8 cm, surface erosion is a few cm and scouring is more significant (Figure 11).


**Figure 11.** Erosion of compacted sandy silt, between $t$ = 0 and $t$ = 150 min (channel 1).

### 3.5 Erosion of the sandy gravel

This analysis concerns channel 2. The soil before testing is visible in Figure 12. Significant surface erosion was observed from the first flow stage, corresponding to $q$=24.0 l/s/m, and $h_0$ = 5.7 cm (Figure 12). After 90 min of flow at $q$=24.0 l/s/m and $h_0$ = 5.7 cm, and 60 min of flow at $q$=43 l/s/m and $h_0$ = 11.8 cm, surface erosion reaches 20 to 30 cm (Figure 12). The visible soil corresponds to the coarse fraction, the fines having been washed away.

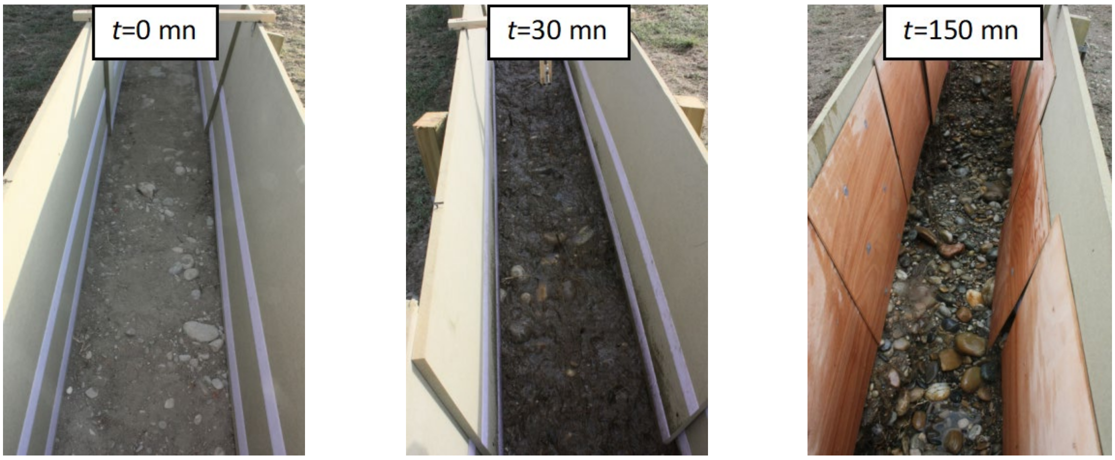


**Figure 12.** Erosion sandy gravel, between $t$ = 0 and $t$ = 150 min (channel 1).

Erosion of the sandy gravel formed a step with the sandy silt, located 8.70 m from the crest at t=30 min. This step then regressed to 3.20 m from the crest. This evolution is probably more responsible for the departure of the sandy silt (by mechanical instability), than the surface erosion of the silt itself.

After 4h30 hours of flow, the eroded area is 10 m long, maximum width of 1.80 m, maximum depth of 1.50 m, and corresponds to about 9 $m^3$ of eroded material (Figure 13).

Part of the coarse fraction of the eroded soils was deposited in the downstream part of the eroded areas, especially on the berm. This probably explains why the silt deposited at the foot of the slope, covered by these gravels, was not eroded. These deposits are visible in Figure 13.



**Figure 13.** Erosion of compacted sandy silt and sandy gravel after 4h30 of flow (channel 2).

**Table 2**. Summary of hydraulic conditions on channels 1 and 2.

| Channel 1 | | | Channel 2 | | |
|---|---|---|---|---|---|
| Duration (mn) | $q$ (l/s/m) | $h_0$ (cm) | Duration (mn) | $q$ (l/s/m) | $h_0$ (cm) |
| 60 | 13.1 | 3.8 | 90 | 24.2 | 5.7 |
| 120 | 42.3 | 8.3 | 90 | 71.6 | 11.8 |
| 120 | 82.2 | 12.9 | 90 | 141.5 | 18.5 |
| 60 | 127.5 | 17.3 | | | |

### 3.6 Summary of erosion observations

The summary of hydraulic conditions on channels 1 and 2 is given in Table 2. The set of observations is grouped in Figure 14 for channel 1, and Figure 15 for channel 2.

- No significant erosion of the natural vegetation cover, in the sense of the Clopper index (ASTM, 2012), was observed; this vegetation appears to be resistant to a flow of the type described in Table 2 (channel 1), i.e. 6 h in duration, with a water depth at the crest that starts at $h_0 = 3.8$ cm and increases in stages to $h_0 = 17.3$ cm; it constituted a protection for all types of soils concerned: compacted sandy silt, sandy gravel, and deposited sandy silt;
- No scouring of the slope toe was observed on channel 1; this is probably due to the protection by the vegetation cover;
- A small erosion scour formed on the berm, of 1mx1m and 20 cm deep; it was located between the slope toe and the road track, where vegetation cover is not significant;

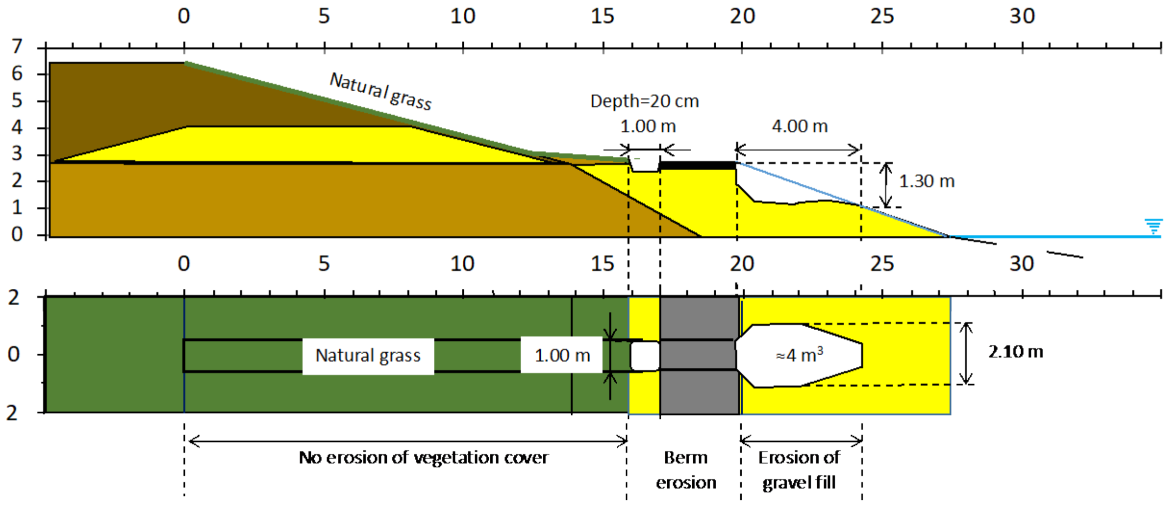


**Figure 14.** Summary of erosion observations on channel 1 after 6 h of flow.

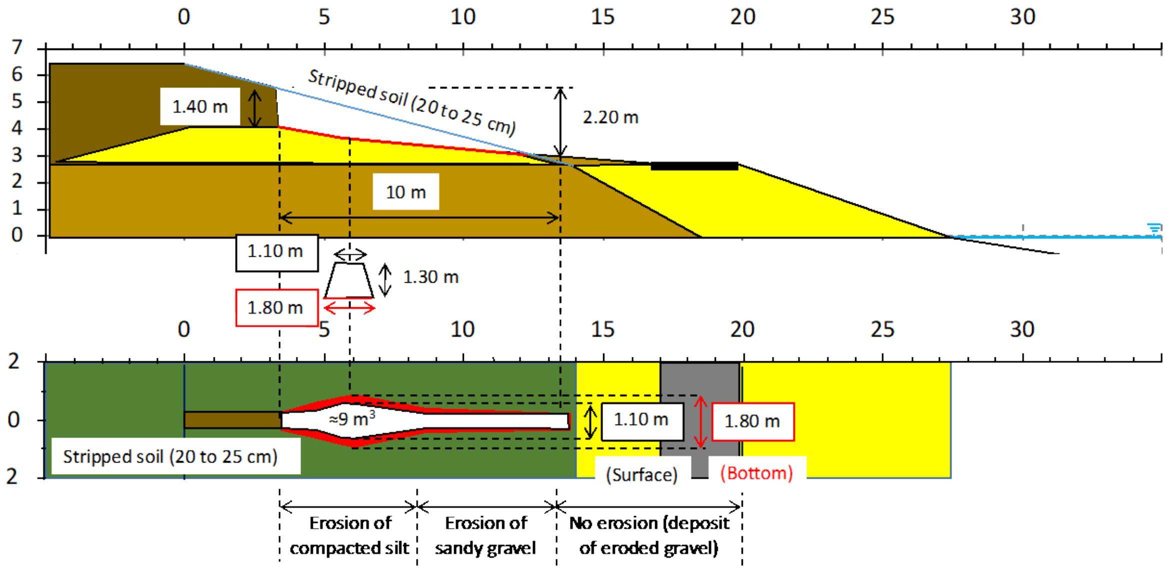


**Figure 15.** Summary of erosion observations on channel 2 after 4h30 of flow.

- No erosion of the gravel fill was observed during the 60 min of flow at $h_0 = 3.8$ cm, and the 120 min at $h_0 = 8.3$ cm; erosion was initiated by the flow at $h_0 = 12.9$ cm (approximately); the area eroded by 120 min of flow at $h_0 = 12.9$ cm and 60 min at $h_0 = 17.3$ cm is 4 m long, maximum width of 2 m, maximum depth of 1.10 m, and corresponds to about 4 $m^3$ of eroded material;
- Surface erosion of the sandy silt during the hydraulic conditions of Table 2 (channel 2) was only a few centimeters; this observation is surprising because laboratory and in situ erosion tests showed very little resistance to erosion; possible explanations include: (i) the role of the intertwined roots of the vegetation, (ii) the importance of the presence of the coarse fraction (gravel) in the silt, removed for the erosion tests; (iii) the importance of the intactness of the soil, compared to a laboratory specimen;
- Erosion of the sandy gravel began at the first flow corresponding to $h_0 = 5.7$ cm; the area eroded by 90 min of flow at $h_0 = 5.7$ cm, and 90 min at $h_0 = 11.8$ cm and 90 min at $h_0 = 18.5$ cm is 10 m long, maximum width of 1.8 m, maximum depth of 1.5 m,

and corresponds to about 9 $m^3$ of eroded material;
- The removal of the compacted sandy silt is mainly due to the erosion of the sandy gravel layer; this erosion formed a step whose height increased as it regressed towards the crest; it resulted in mechanical instabilities which caused the removal of the silt by clods;
- No scouring of the slope toe was observed on channel 2; this is probably due to the deposit of the coarse fraction of the eroded soils that protected the soil.

## 4 CONCLUSIONS

Two overflow tests were carried out on a CNR dike with the device developed by INRAE. They made it possible to study the resistance to erosion of the intact soil, and that of the soil constituting the dike, with and without the natural vegetation cover. The test campaign was conducted between April 25 and May 10, 2022. As of the date of this communication, the measurements were not yet fully analyzed and interpreted. The present results are only preliminary and qualitative with regard to erosion. The first result of these in situ overflow tests is that not all of these observations were predictable from the erosion tests previously performed in the laboratory and in situ (Jet and Het erosion tests) with similar conditions in terms of hydraulic loads and shear stresses. The second result is the remarkable resistance of the natural grass cover. The conclusion is that in situ investigations are essential to quantify the resistance of a dike to overflow, in addition to conventional erosion tests (HET, JET).

These in-situ overflow tests highlight that many gaps need to be filled by research on this topic to provide predictive modeling tools for the behavior of dikes in the event of an overflow.

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