Quantifying the erosion resistance of dikes with the overflowing simulator

Stéphane Bonelli, Sylvie Nicaise, Guillaume Charrier, N. Chaouch, F. Byron, Y. Gremeaux

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S. Bonelli, S. Nicaise, G. Charrier, N. Chaouch, F. Byron and Y. Grémeaux

Irstea, Aix-en-Provence, France

Abstract

It is important to quantify the soil resistance against erosion cause by to the overflow of dikes and levees. Small-scale tests are excluded, due to the lack of similarity for a free-surface flow phenomenon on stepped slopes, with non-established flow and erosion of a cohesive soil. Moreover, using hydraulic laboratory flumes does not make it possible to have a correct representation of the soil in place, in terms of layer compaction. This is why we have developed an on site overflowing device. The device was deployed as part of the DigueELITE research project on a 3.5 m (9.8 ft.) high experimental dike in channels, 60 cm wide (≈2 ft.) and 15 m long (≈50 ft.), covering the downstream slope (1.5H/1V) and the downstream platform. The procedure followed is based on ASTM-D6460 standard. The test campaigns were carried out with flow rates up to 500 l/s per linear meter (0.5 m^2/s), water velocity up to 5 m/s, and a discharge depth up to 30 cm (≈12 in.) at crest. Two soil types were studied: lime-treated soil, and untreated cohesive soil. The first phase of erosion is that of the surface layer. The second phase is that of the embankment constitutive soil. The erosion shows a stair-steps pattern, due to the layers of compaction. The results obtained show that lime-treated soil has better erosion resistance than untreated soil. Compared to the untreated soil, erosion in the lower part of the slope is 3 times less in lime-treated soil, and the scour depth development process at the downstream toe is 5 to 10 times smaller. This paper presents the experimental setup, the results obtained, and the perspectives. The most important findings are that overflowing experiments are feasible on site with the proposed test set-up.

1 Introduction

The International Levee Handbook (CIRIA, 2013) now clearly present the principles related to flood protection systems. Such a system makes it possible to avoid flooding up to a level called "protection level". Beyond the level of protection, there is overflow. The failure of a river dike following the occurrence of a flood exceeding the crest of the embankment is one of the essential scenarios of risk analysis. For sections resistant to overflow, the practice is to use a surface protection system: asphalt, riprap, grass or any other type of known surface protection. The qualification of the resistance to the overflow is qualitative and is then made by means of expert judgement for a reference flood, by comparing the hydraulic action and the resistance of the surface protection system determined most often in hydraulic laboratory, and available in technical documents. For normal sections, failure by overflow is likely to occur for a small spill over the crest. The probability of occurrence of this failure mechanism is currently estimated from hydrological and hydraulic studies only. It does not include any geotechnical study of the soil resistance to erosion. In France, it is assumed that if there is overflow, there will be embankment breaching.

To qualify a surface protection system, it is necessary to have a specific hydraulic equipment: 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 (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, it is currently impossible to qualitify a soil constituting the dike embankment, with respect to its resistance to overflow, because there is no field equipment nor laboratory equipment for this.

It is crucial to quantify soil resistance to erosion. The Hole Erosion Test (HET) has been deployed for several years at the laboratory for internal erosion (Wan & Fell, 2004), (Bonelli, 2013). However, the HET internal erosion test does not lead to any conclusion on surface 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 interesting. In particular, it is representative of what happens at the toe of slope, or at the bottom of steps for the Head-Cut mechanism, and it gives a quantitative result (Hanson & Cook, 2004), (Robbins & Wibowo, 2012). However, we are not aware of established relationships between test JET results and overflow characteristics.

To quantify the resistance of the soil to surface erosion, it is impossible to use abacuses 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 laboratory tests are excluded due to the lack of similarity for a free-surface flow on a stepped slope with erosion of a cohesive soil. Moreover, bringing the dike soil into a hydraulic laboratory canal does not allow to have a correct representation of the material in place, in terms of particle size and heterogeneity induced by the layered compaction. This is why Irstea has developed a field device to simulate an in situ overflow, and to quantify the erosion resistance of the crest, slope and slope toe.

2 The experimental device

A dike dedicated to the French DigueELITE research program (www.digueelite.fr) was built near Montpellier (France) on the banks of the Vidourle River. It has a height of 3.5 m and a slope of 3H / 2V. The structure consists of a 30 m section treated with lime and a 10 m section of untreated soil (natural soil). The slopes are non-vegetated (Figure 1). The construction techniques and the geotechnical characteristics of the existing soils show that the untreated soil produced corresponds to the "best possible soil" with respect to the rules of the art. The lime-soil has a mechanical resistance and a resistance to internal erosion one to two orders of magnitude higher than that of this untreated soil (Nerincx et al, 2016). The present experimental set-up aims to confirm that the resistance to surface erosion of soil-lime is greater than that of untreated soil.

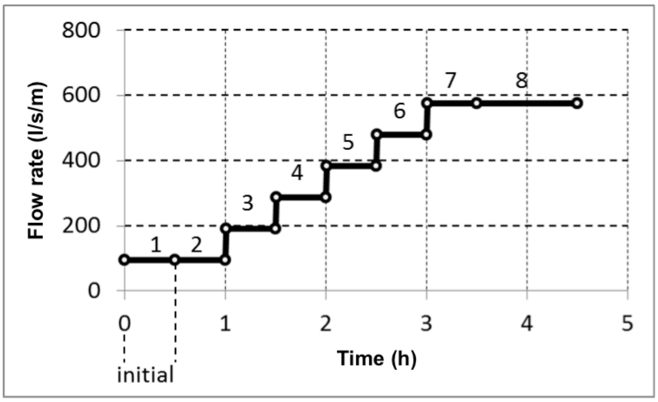
Figure 1. The DigueElite demonstrator, with the two channels before tests, untreated soil on the left, soil-lime on the right.

The experimental set-up consists of two 15 m long and 61 cm wide channels located on the downstream slope of the dike, one in the lime treated zone, the other on the untreated soil, for the purpose to test the erosion resistance at the crest, on the downstream slope and at the foot of the slope (Figure 1). A buffer tank is located on the crest between the arrival of the pumping system and the inlet of the channel. The test channel leads to a bassin that houses the pumps, which makes it possible to operate in a closed circuit (Figure 2).

Figure 2. Overview of the site and overflow simulator. The Vidourle River is on the right.

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. The initial flow rate is 95 l/s/m. This flow rate is gradually increased to 570 l/s/mL (Figure 3). For a flow rate of 570 l/s/m, the water high at the crest is about 30 cm, and maximum flow velocity is close to 6 m/s. The sequence of 8 tests corresponds to 4h30 of flow.

Figure 3. Flow sequence of 8 tests. The initial test No. 1 corresponds to the erosion of the surface layer. It is followed by 6 tests of 30 minutes each with gradual increase of the flow rate, and an 8th test lasting 1 hour. These tests correspond to the erosion of the soil constituting the embankment.



The soil in place, which is not vegetated, has not been deliberately removed, so as not to modify it artificially. The walls of the channels are placed on the ground, and not anchored in it, also not to change the soil in place. It is a question of not creating a reworked zone along the walls, at the base of these, which would have a lower resistance and would have located the erosion in an artificial way. At the beginning of the test, at a small flow rate, the flow is entirely in the channel (Figure 4.a). During the test, at higher flow rates and because of soil erosion, flows under the walls appear (Figure 4.b). This is not unacceptable, since we measure the velocities and the water height along the flow in the channel. Leaks are of the order of 10 to 30% depending on the tests.

The free-surface flow on this slope (angle of 33 °) is super-critical, with a Froude number of about 4 to 5. It is an aerated flow over stepped slope, as shown in Figure 4. The entrance flow rate is measured with a Doppler flowmeter. The velocity of the flow is measured with an electromagnetic current meter and with a radar. The water level and the soil position are measured at graduated scale. Measurements by acoustic sensors and by terrestrial lidar scanner have also been carried out. All these results are being published and can not be included here.

Figure 4. View during test for a flow rate of 95 l/s/mL (minimum flow rate, test No. 1) (left) and a flow rate of 570 l/s/mL (maximum flow rate) (right).

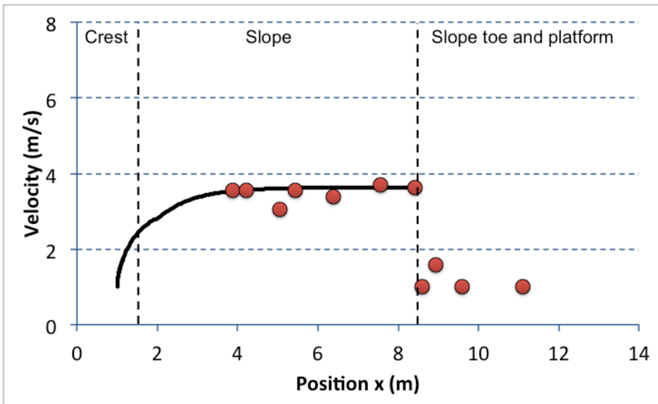
3 Results

The flow accelerates along the slope to reach its maximum velocity at the toe of the slope, between 3.5 and 6 m/s. The flow is established for a flow rate of 0.095 m^2/s but not established for 0.570 m^2/s because the slope is too short (Figure 5). The flow conditions in stepped slopes have been classified into nappe flows, transition flows, and skimming flows: the Chanson model is therefore used for measurement analysis (Chanson, 2001).

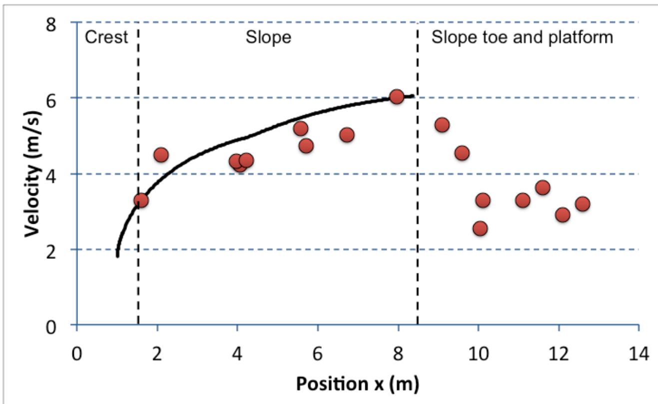
The eroded volume per square meter, the unitary erosion (m^3/m^2), represents an average thickness of eroded soil. This average thickness is to be considered taking into account the heterogeneity of the erosion profile, whether with the steps of the slope, or the erosion pit at the toe of the slope. The ratio between average thickness and maximum depth is of the order of 2 to 3. This unitary erosion is comparable to the Clopper Soil Loss Index (CSLI) of the ASTM D6460.

Erosion is not uniform, and the spatial distribution is different for the two soils tested. To better analyze this, the analysis is done in four areas: the crest, the upper part of the slope, the lower part of the slope and the slope toe (Figure 6). The time evolution of the unitary erosion for these 4 zones is given in Figure 7.

Figure 5. Flow velocity for a flow rate of 0.095 m^2/s (minimum flow rate, test No. 1) (a) and a flow rate of 0.570 m^2/s (maximum flow rate) (b). Symbols represent the measurements. Solid lines represent the Chanson model.



(a) q=0.095 m^2/s



(b) q=0.570 m^2/s

Overall, soil-lime erosion is less than that of untreated soil. It even appears that the erosion of the soil-lime in the 4 zones, lower than 0.05 m^3/m^2 for the 4h30 of test, is lower than the only initial erosion of the untreated soil (test No. 1, 30 mn). In addition, the first initial test causes soil-lime erosion that is about half that of the untreated soil. These curves obtained from measurements with the graduated ruler are comparable, albeit somewhat higher, than those obtained with the high accuracy measurements made by terrestrial lidar scanner (Nerincx et al., 2017), (Herrier et al., 2018).

Figure 6. The four zones of erosion analysis.

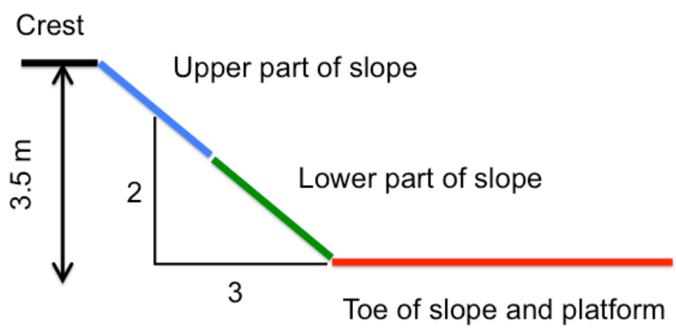
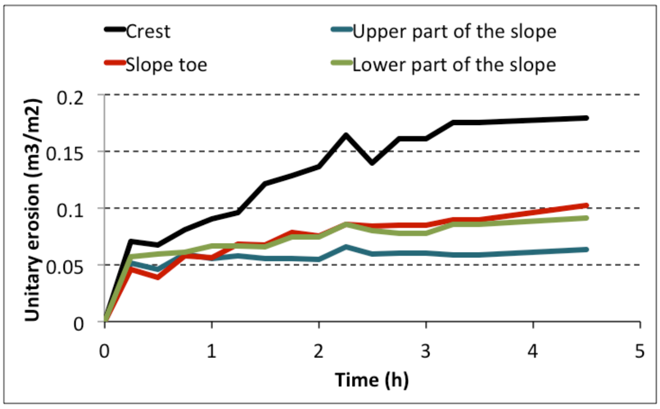
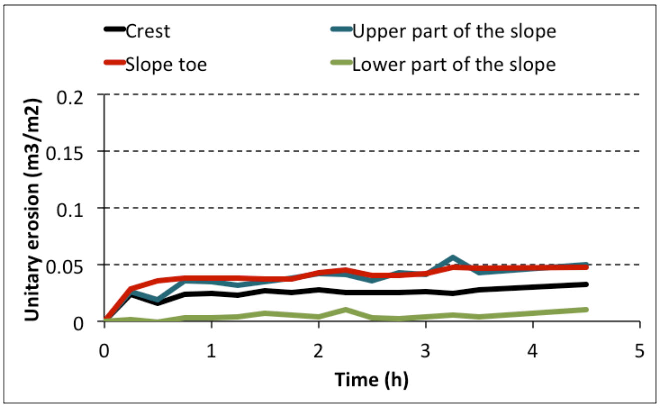


Figure 7. Unitary erosion (eroded volumes per square meter) as a function of time. Comparison of erosion of untreated soil and lime-soil for each zone.



(a) Untreated soil



(b) Lime treated soil

More precisely, the observations made in Figure 7 are as follows:

- Untreated soil
  - the first test caused relatively uniform initial erosion in the 4 zones of the order of 0.05 m^3/m^2, ie an average of 5 cm;
  - the erosion was the largest at crest, reaching 0.17 m^3/m^2, with an average kinetics of 3 cm/h after test No. 1;
  - along the slope, erosion kinetics averaged 0.4 cm/h in the upper part and 0.8 cm/h in the lower part after the first initial test;
  - the erosion of the slope toe is of the same order of magnitude as in the lower part of the slope, but it is more localized and deeper.
- Lime-soil
  - the first test causes an initial erosion of the order of 0.02 to 0.04 m^3/m^2, except on the lower part of the slope, where this initial erosion is negligible;
  - the area with the lowest erosion is the lower part of the slope;

- along the slope, erosion kinetics averaged 0.8 cm/h in the upper part and 0.3 cm/h in the lower part after the first test;
  - erosion at crest and erosion at the upper part of the slope are of the same order of magnitude (0.8 cm/h);
  - after test No. 1, the erosion kinetics of the slope toe and the lower part of the slope are of same order of magnitude (0.3 cm/h).

The first test at 0.095 m^2/s caused significant erosion of both soils. It is representative of the surface layer, altered by thermal, water and chemical exchanges with the external environment for 10 months, since the construction. In order to better highlight the resistance of the embankment soil itself, which appears to be superior to that of the surface layer, the evolutions over time of the unitary erosion are plotted from the end of the test No. 1, Figure 8.

The data in Figure 8 are used to evaluate the average ratios of eroded unit volume, and average ratios of erosion kinetics. These two ratios are of the same order of magnitude:

- on the crest, the erosion of untreated soil is 6 to 7 times greater than that of soil-lime;
- on the slope toe, where the erosion pit is developing, the erosion of untreated soil is 5 to 10 times greater than that of soil-lime;
- in the lower part of the slope, the erosion of untreated soil is 3 times greater than that of soil-lime;
- in the upper part of the slope, the erosion of untreated soil is of the same order of magnitude as that of soil-lime.

The embankment was built in successive compacted layers of 30 cm thick. Compaction induces a density gradient within each layer. The lower part of each layer is less dense, and therefore less resistant to erosion.The mechanism is known as headcut, which determines a re-shape of the embankment downstream face in forms of steps.

Leaks under the sidewalls caused soil erosion on both sides of the canals. This is seen in Figure 9. Untreated soil being more erodible, erosion on both sides of the channel is more localized and deeper (left channel in Figure 9). On the contrary, the lime-soil is less erodible, and the leakage flows spread more widely on both sides of the channel (right channel in Figure 9). On both soils, the erosion of the surface layer highlights the layers of compaction.

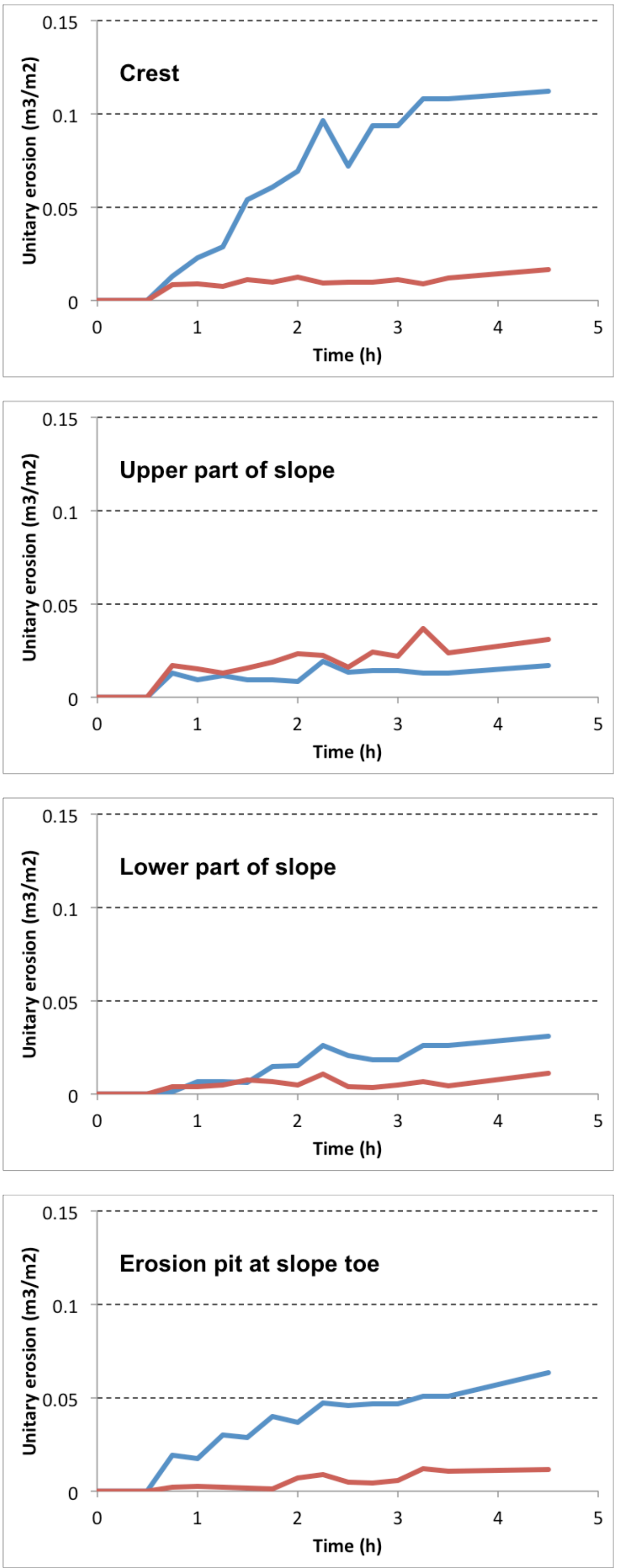


Figure 8. Unitary erosion (eroded volumes per square meter) as a function of time from the end of test No. 1, after the surface layer erosion. Erosion of untreated soil (blue) and lime-soil (red) for each zone.

Figure 9. View after the tests campaign. Leaks caused soil erosion on both sides of the canals. Untreated soil being more erodible, erosion on both sides of the canal is more localized and deeper (left). On the contrary, the lime-soil is less erodible, and the leakage flows spread more widely on both sides of the channel (right). On both soils, the erosion of the surface layer highlights the layers of compaction.

4 Conclusion

The in situ overflow simulator presented in this paper allows to quantifie the resistance of dike soil to erosion. The crucial point is to hydraulically load the soil of the embankment in place. This allows to consider the whole soil granulometry in place. This also makes it possible to reproduce the mechanism of formation of the steps on the slope due to the construction in layers. The present overflow tests were carried out with flow rates up to 0.570 m^2/s, and led to a 30 cm water high on crest and 6 m/s velocity at the slope toe. These values are representative of an overflow of a dike or a small earth dam. The erosion profile of the talus in stair steps, due to compacting layers, is highlighted. Erosion is quantified on the crest, on the slope, and at the slope toe where the erosion pit appears. The simple analysis of the raw measurements obtained, without modeling hypothesis, already allows to bring elements of conclusion. To go further on the evaluation of the critical stress or the critical velocity, and the coefficient of erosion, it is necessary to set up numerical modelings to interpret the results obtained, because of the complexity of the aerated flow on stepped slope.

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