Resistance to erosion of lime treated soils and perspectives for coastal dikes

M. De Baecque
IFSTTAR, GERS, Marne-la-vallée & Salon de Provence, France

C. Chevalier[1], S. Palma Lopes[1], M. Le Feuvre[1], P. Reiffsteck[1], I. Charles[2] & G. Herrier[3]
[1]IFSTTAR, Marne-la-vallée, Bouguenais & Salon de Provence, France
[2]Cerema Nord Picardie / BEE – AB, Sequedin,, France
[3]Lhoist R&D, Nivelles, Belgium

Abstract: Fluvial and coastal dikes are the primary protection for human life from natural hazards like flooding or wave action. To build these hydraulic earthworks requires many materials with specific performances in terms of workability, mechanical strength, permeability, resistance to erosion, etc. Very often, local material does not meet requirements imposed by standards, and the transportation of material over long distances is only a short-term solution from an environmental point of view. Lime is used for construction purposes because it decreases the plasticity index and water content of soil, which facilitates compaction and improves its mechanical performance over time. However, the resistance to erosion of lime-treated earthwork remains little known and this is one of the reasons why lime has not been applied to dikes yet.
The engineering behavior of lime-treated dikes depends on the lime-soil interaction and environmental impacts. This study focuses on the comparison between raw and treated material behaviors regarding erosion processes and the effects of water. Erosion tests were carried out on two full-scale experimental dry dikes and laboratory samples for different curing times. Three types of tests were performed: Mobile Jet Erosion Test (an apparatus that can be used either in the laboratory or in the field), Hole Erosion Test (an efficient and convenient laboratory apparatus) and Enhanced Crumb Test (an evolution of the ASTM Crumb Test). In all configurations (soil and apparatus), this study reports a great increase in the resistance to erosion of the treated materials, which leads to a significant reduction in the risk of both internal and surface erosion of earthworks. Last, we discuss the application of these materials for building coastal dikes (characterization of the sustainability of lime treated soil versus saline environment, wetting-drying cycles etc.), and the possible monitoring of such a full-scale coastal dike by geophysical methods.

Keywords: lime treatment, soil, erosion, dike

1 INTRODUCTION

Lime treatment of soil is a widely applied technique throughout the world for improvement and soil stabilization of road works, embankments, railroad beds, etc. Soil workability and mechanical strength are increased for lime treated soil compared to natural compacted soil. Nervertheless the use of lime treated soils in hydraulic earthwork is very restricted, especially at the European level.

In this context Lhoist Group in collaboration with academic research institutes has initiated a project to study lime treated soil behavior with regard to erosion processes. A part of this projet was carried out by IFSTTAR which performed laboratory erosion tests and also erosion test on an experimental full-scale lime treated hydraulic structure (Chevalier et al., 2015). Quicklime CL-90Q with 90.9% available lime content and t60=3.3min reactivity (norm EN 459-1) was used.

Initially, experimental studies were carried out in the lab using compacted samples of natural lime-treated and untreated soils with mastered protocols. Then, in situ tests were performed on two full-scale structures built in the Experimental and Research Center in Rouen (Charles et al., 2012).

2 METHODS

To study the soils resistance to erosion and water sensitivity three devices were used, the Mobile Jet Erosion Test (Reiffsteck et al., 2012) , Hole Erosion Test (Haghighi, 2013) and Enhanced Crumb Test (Haghighi et al., 2012b).

2.1 Mobile Jet Erosion Test (MoJET)

The MoJET is a rotating erosion test apparatus, which can be used both in the lab and in-situ (Reiffsteck et al., 2012; Haghighi, 2013). MoJET results can be compared with other laboratory tests such as the Hole Erosion Test (HET) (Chevalier et al., 2010).

The MoJET is made up of one mechanical part, named "eroding unit" with 6 rotating water jets, a water supply tank with the possibility of pressurization, and a few additional parts (pump, flowmeter etc.). The eroding unit projects water jets with 0.5 mm diameter nozzles (Fig. 1a) perpendicular to the soil. The mould is placed on a 10% slope (6 degrees) (Fig. 1.a and 1.b). The outfall ring is inserted around the mould while directing the outfall towards the downstream side of the slope into the top of the measurement container. The ground is then subjected to the action of the water jets with the following test parameters:

- imposed flow rate of 600 ml/min (standard, jet pressure is approximately 36kPa) or 2 000 ml/min (modified, jet pressure is approximately 400 kPa),
- duration of the experiment: 15 minutes (standard, with sampling of the whole effluent at 1, 3, 5, 8, 11 and 15 minutes) or 5 minutes (modified, with sampling at 0.5, 1, 2, 3, 4 and 5 minutes).

After the test, the soil sample generally shows gullies located where the water jets impact its surface (Fig. 1c).

Effluent collected at the different times are placed in the drying oven and measured to determine the mass of dry material eroded (Pham, 2008, Reiffsteck et al., 2012). This solid load (i.e. eroded mass as a function of time) can be used to perform qualitative evaluations of erosion, to establish correlations between the amount of eroded soil and geotechnical properties, or to compare between various soil behaviors.

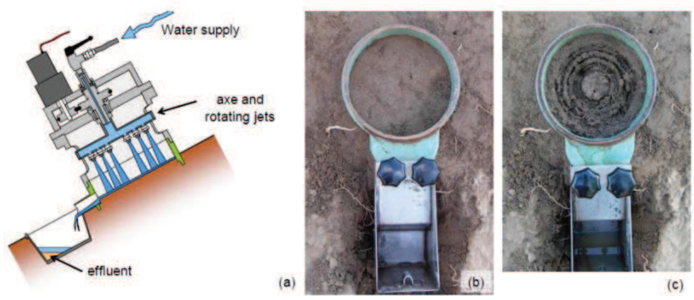


Figure 1. Mobile jets erosion (MoJET) test set-up: (a) Schematic diagram of eroding unit. Image of eroding unit in field (b) before and (c) after test

2.2 Hole Erosion Test

In order to quantitatively characterize piping erosion, the Hole Erosion Test recently developed by Wan and Fell (2004) was a great step forward.

We recently designed and developed our own HET device (Pham, 2008; Haghighi et al., 2012a). Similar to the one developed by Wan and Fell, it presents a number of improvements designed to make it easier to use and more comprehensive for measuring erosion parameters on process.

The HET device has three parts: an upstream water tank, an eroding unit where the sample is located and a downstream water exit. The erosion unit is depicted in figure 2 along with the measuring instruments. The soil sample is prepared in a cylindrical Plexiglas mold. The dimensions are 7cm in diameter and 15cm in length (volume: 500 cm^3), and vertically drilled. The diameter of the initial hole is 3 or 5mm. After bringing water to the system and especially in the sample, the air pressure in the upstream water reservoir is raised gradually until the desired pressure difference is reached. This pressure difference is kept constant after the erosion occurred. During the test, from the increase of head charge to the decrease, the data collected by flow meter (flow rate Q), pressure transducers (pressure drop ΔP) and turbidimeter (turbidity T) are stored on a computer using a data-logger. The acquisition frequency is generally 1 Hz. These measurements and data on initial and final radii allow us to calculate erosion curves (interpretation method detailed in Pham (2008) and Haghighi et al. (2012a)) i.e. the relationship between the two following physical quantities:

- the shear stress τ , applied to the interface by the flowing liquid applies (SI unit: Pa),
- the erosion rate $\dot{\varepsilon}$, defined as the mass of soil eroded per unit area and time (SI unit: $kg.m^{-2}\cdot s^{-1}$).

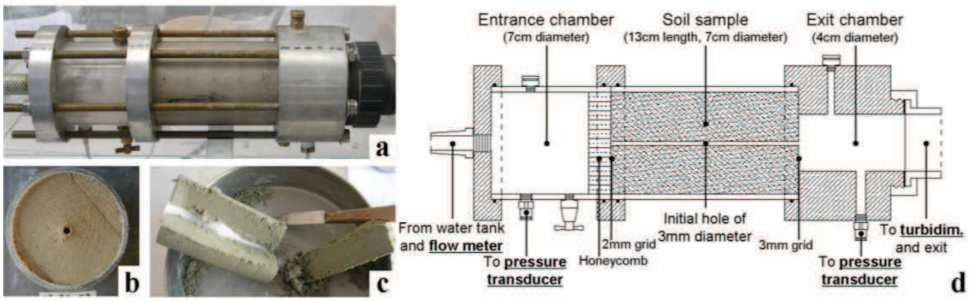


Figure 2. Experimental set-up and soil sample treatment. (a) Image of eroding unit. (b) Sample before test with 3mm diameter hole. (c) Cut sample after test with wax mold. (d) Drawing of eroding unit. Sensor are indicated in bold and underlined characters.

2.3 Enhanced Crumb Test (ETC)

The aim of this experimental method is to quantify the disaggregating geometry of an immersed unsaturated soil specimen as a function of time (Haghighi et al., 2012b). With this purpose in mind, a soil specimen of 15 mm in diameter and 20 mm high is placed in a large water container and monitored by two digital cameras (Figure 2).

The general behavior of the soil specimens, after being placed in water, is almost the same but with different characteristics for different soil textures. This behavior can be divided into two different phases: (a) hydration and (b-c) dispersion. Nevertheless detailed characteristics (height of swelling, disaggregation time, etc.) vary between different soil textures.

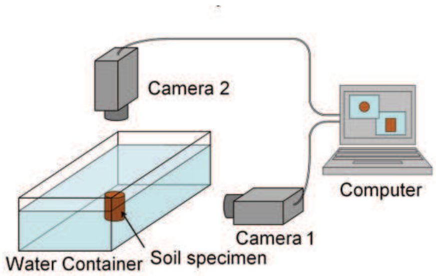


Figure 3. General layout of the experimental setup

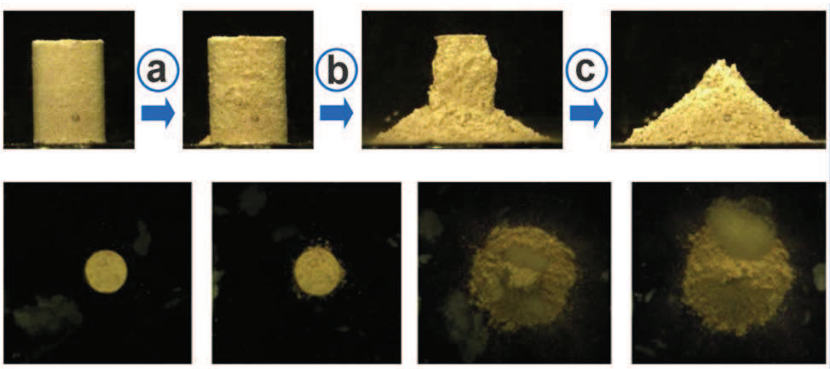


Figure 4. General behavior of a specimen

3 RESULTS AND INTERPRETATIONS

3.1 Erosion test on laboratory rebuilt sample

Two different fine graded soils, a silty and a clayey soils, from Héricourt (Haute-Saône, France) were used to perform the tests. Test results on both the silty and the clayey soils showed a considerable increase in all aspects of erosion resistance for treated soils. Results are detailed in Chevalier et al (2012) and Haghighi (2013).

Regarding HET tests, the critical shear stress cannot be measured for treated soil: for the silty treated soil it is higher than 800Pa, being at least 2 times greater than shear stress for untreated silt.

Images of an example of an untreated silt sample and a treated one are given on figure 5.

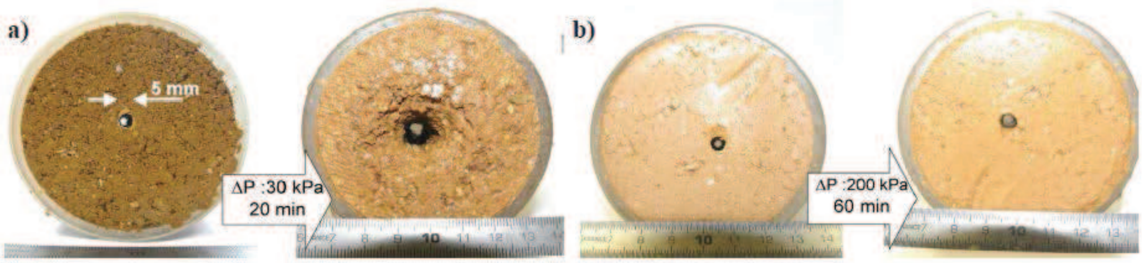


Figure 5: Typical HET results on materials. (a) Untreated silt before and after test (pressure difference of 30KPa during 20 minutes), (b) treated silt before and after test (pressure difference of 200KPa during 60 minutes).

The MoJET tests using the standard protocol do not cause erosion on treated soil. Using the modified protocol, eroded masses are at least 80 times lower for treated soil compared to untreated soil.

Treated soils therefore are virtually water insensitive according to ECT tests. The swelling is very low and crumbling almost nonexistent (Figure 6).

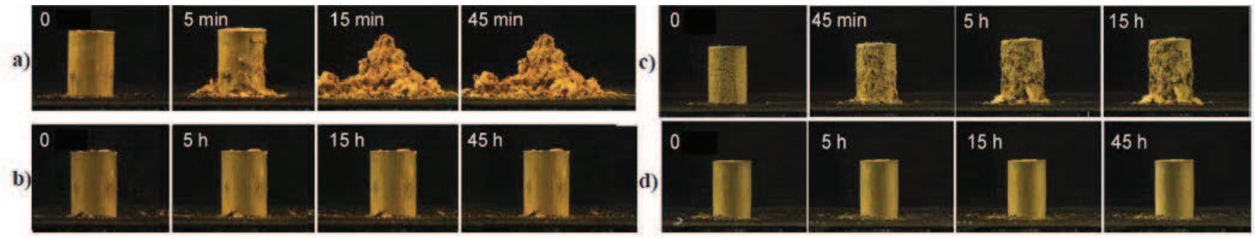


Figure 6: Evolution of the geometry of ECT soil specimen during test. (a) Untreated silty soil, (b) treated silty soil, (c) untreated clayey soil, (d) treated clayey soil.

To make an assessment, lime treated fine soils present a considerable increase in erosion resistance compared to untreated clay and silty soil. Nevertheless, samples were built in the laboratory under strictly controlled conditions especially regarding homogeneity and compaction. In practice, on the building site and under industrial conditions of construction, parameter states of soil and special homogeneity are less controlled and can vary significantly. Therefore, a study on a full-scale dike was performed and is presented below.

3.2 Tests on experimental full scale structures

In this section, in situ and laboratory tests performed with soil from two full-scale experimental hydraulic structures built in the Rouen CER (Experimentation and Research Center) are presented (Charles et al. 2012). The structures were two dry dikes built with silty soil from "Marche-les-Dames"(Belgium), one had been treated with 2.5% lime and the other was untreated. The treatment was performed using a mobile mixing plant. Materials were compacted in the wet state, at 17% water content (wOPN+2%) in the case of the untreated silt structure, and at 19.4% (wOPN+1.6%) in the case of the treated soil structure. Pictures of the two dikes are presented in figure 7. The treated soil homogenization was guaranteed throughout the production using the mixing plant, and its compaction was performed by a sheepfoot roller (kneading compaction). Consequently, laboratory conditions of preparation are well reproduced in situ.


Figure 7. View of the experimental dry dikes built at the Rouen Experimentation and Research Center: on left the lime treated dike and on right the untreated dike.

To compare natural soil and lime treated soil behavior regarding erosion, specimens were sampled from the two dikes to perform the Hole Erosion Test (HET) and the Crumb test (ECT). MoJET tests were directly performed on the dikes (treated and natural).

3.2.1 Mobile Jet Erosion Test (MoJET)

Tests were performed in situ 28, 180 and 368 days after the building. In most cases, two repeatability tests were carried out for each configuration (soil constitution, protocol and curing time). Tests were performed under temperate climate (15°C mean at 28 days, 20°C mean at 180 days and 15°C mean after 365 days) and without intense rainfalls. Nevertheless, dikes spent winter without superficial protection and at 180 days, a few millimeters of flaky crust had appeared on the free surface of the lime treated dike (Figure 8). That crust was not there after 28 days curing. The two erosion protocols were used on each dike (classic: 600mL/min during 12min; and modified: 2L/min during 5min).

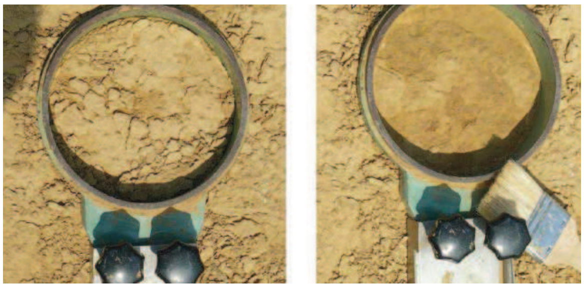


Figure 8: On left the flaky crust which appeared between 28 and 180 days after the construction. On right, this crust is removed using a brush.

Figure 9 shows treated and untreated dike surfaces after tests using the normal protocol. First, we note a large difference in erosion depth and water penetration between tests performed on the treated and untreated dike. Because of the very low permeability of treated dikes, the water stream around the mould and the infiltration depth were only a few millimeters. Removing the superficial layer, the soil water content below was still the same as before solicitation.

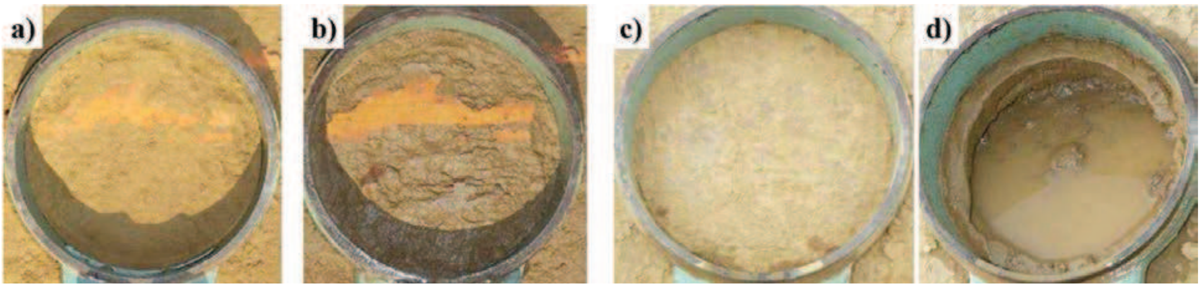


Figure 9. Soil surfaces before and after normal protocol MoJET tests, 28 days after the construction. Soil treated before test (a) and after test (b); untreated soil before test (c) and after test (d).

Results from the 28 curing days test program are shown in figure 10. The repeatability tests are also plotted. The total eroded mass with the classical protocol is on average 900g for the natural soil, against 35g for the lime treated soil. With the modified protocol these values reach 1000 and 80g.

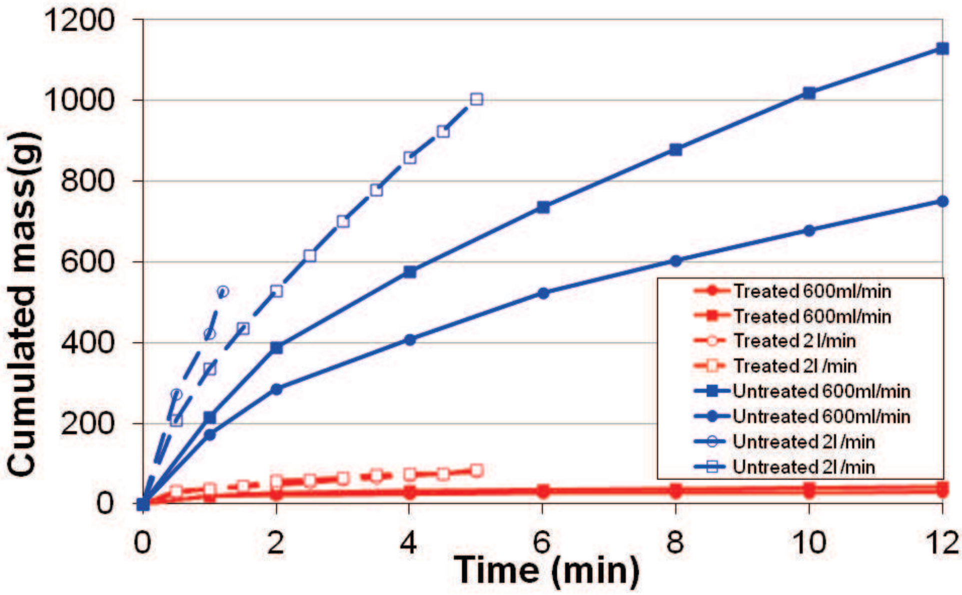


Figure 10. Cumulated mass versus time for the tests 28 day after the construction

The test performed on the natural soil dike gave the same results at 28 and 180 curing days. For the soil treated dike, systematical differences were observed in the eroded masses with and without the flaky crust (Figure 11). The crust showed a low resistance to erosion and was eroded during the 2 first minutes of the test. After the crust was removed the erosion rate from the two layers became similar. Apart from this difference, the results followed similar trends between 28 and 180 days: 1130g natural soil eroded and 40g treated soil eroded in the configuration without the flaky layer, using the classical protocol (600mL/min).

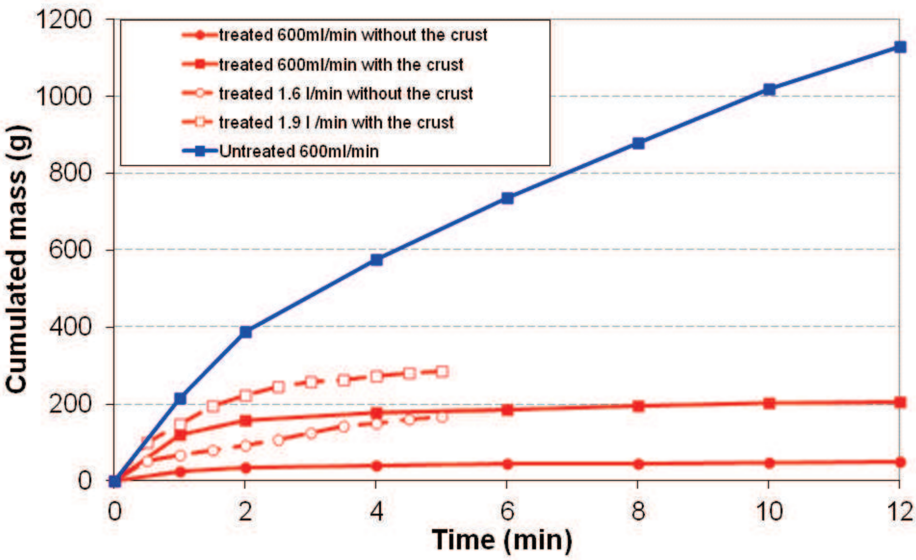


Figure 11 : Effect of the flaky crust on the eroded mass for the tests 180 day after the construction.

After 365 days of curing, tests were only performed on the soil treated embankment, at different depths (surface, 2 and 5cm deep), and on one surface covered by a vegetated layer. The classical protocol was used.

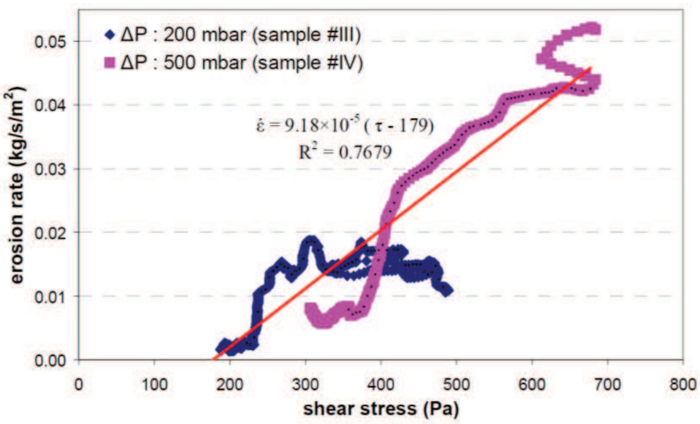
As for the 180 day tests, we note a difference between the uncleaned surface (crust not removed) and the other configurations (surface cleaned, 2 and 5cm deep), especially during the 2 first minutes, the time needed to totally erode the superficial crust. After that the erosion rates remained similar. The results follow trends close to the 28 and 180 days tests. At 2 and 5cm deep the cumulated eroded masses are respectively 80 and 15g. Under the vegetated surface, the cumulated eroded mass is 50g.

Plants seem to protect treated soil from surface degradation, often caused by hydric and temperature variations.

Erosion resistance is therefore higher on the construction using lime treated soil than on the one using natural soil: whatever the protocol, the finale eroded mass is at least 10 times lower. This resistance is obtained after 28 days and is maintained over time**,** except for the superficial crust observed after the winter. Nevertheless this crust does not appear if the embankment is protected by plants, which is a current esthetic technique to integrate embankments into their environment.

3.2.2 Hole Erosion Test (HET)

For this test, soil was sampled from the two dikes 28, 180 and 365 days after the construction, using a PVC cutting edge in the case of the natural construction (500mm long and 80mm external diameter), and a double envelope core drill on the treated embankment. Samples were cut (diameter 68mm, height 150mm) and sealed in a mould using silicone gel to avoid parasitic erosion between the sample and the mould. Two tests were performed using untreated 28 days curing soil, of which one with 20kPa hydraulic solicitation and the other with 50kPa hydraulic solicitation. Experimental curves are given in Figure 12. The critical shear stress for natural soil is about 180Pa.



$$\tau_C = 179\,Pa \qquad k_{er} = 9.18\times10^{-5}\,s/m$$

Figure 12 Tests result performed with core sampling from the untreated dike, with 20 and 50 mbar hydraulic solicitations

Regarding the lime treated embankment, tests show a very high erosion resistance at 28, 180 and 365 curing days. Note that 180 and 365 days old samples are ductile. Therefore, during sampling and preparation, these samples have more risk of being disturbed or cracked.

Among the 8 tests carried out on treated soil, only two may have shown weak initiation of erosion for a critical shear stress lower than 800Pa.

Results again reveal that treated and untreated soils have very different behaviors. There is at least a factor 4 increasing in critical erosion shear stress values between treated and untreated embankments.

3.2.3 Enhanced Crumb Test (ECT)

For the test after 28 days of curing, the typical visual aspect of the sample geometrical evolution is presented in figure 14. Final morphology is reached after 10 minutes of immersion. Contrary to lab rebuilt soil, samples taken from the treated dike present very low water sensitivity. They crumble slowly and less intensively than the untreated samples. Moreover, the aggregates which come off are bigger than those from the untreated soil.

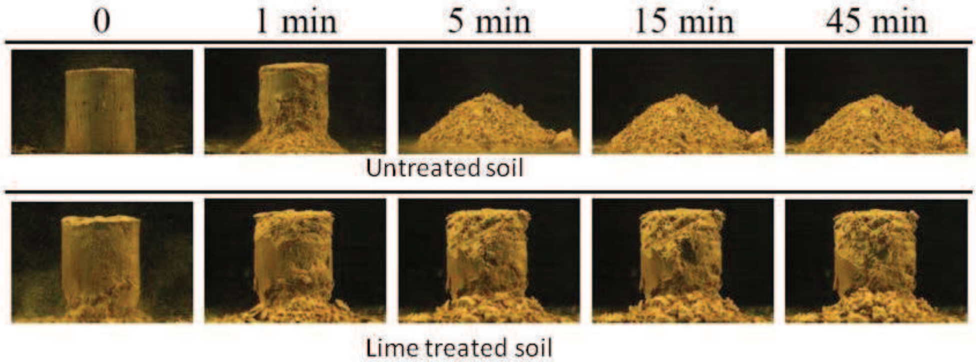


Figure 13. Representative tests results for cores sampled in the treated dike (down), and untreated (above) after 28 days of curing. No evolution observed beyond 45 minutes.

Tests performed at 6 months and 1 year curing times on samples removed from the treated embankment gave similar results to those at 28 days of curing.

In the case of soil treated samples, surface and volume behavior must be differentiated. Surface behavior is largely impacted by the way of sampling. Because of the material high mechanical strength, the cutting edge has a strong effect on the soil structure. It impacts the short-term behavior (i.e. 1 to 5 min) but not the long term behavior. On the other hand, volume behavior does not show any water sensitivity.

To conclude, sampled materials from the treated embankment have a very low water sensitivity compared to those from the untreated dike. In particular, there is less swelling and the sample does not totally collapse after the hydratation phase.

4 CONCLUSION

After a lab parametric study (Chevalier et al. 2012), sensitivity to erosion was studied in two full scale flood protection dikes in order to characterize and to compare behaviors of lime treated and untreated soils.

Test results on treated and untreated dikes proved a considerable increase in all aspects of erosion resistance for treated soils. Treated soil properties seem to be maintained over time and during long loading periods which is not the case for the untreated soil. Results obtained are in line with tests performed on lab-reconstituted soil. The increase in resistance to erosion is lower in situ than in the lab sample. Among possible explanations, we can cite: differences in soil preparation, weathering due to climate and material damage caused by in situ sampling. Nevertheless, in any case, differences between lime treated and untreated soils are significant.

In this study, soil sensitivity to erosion is described for materials, which have not suffered strong degradations. Future studies will focus on the durability of the lime treated soil in coastal environments. The first tests will be performed using lab-reconstituted samples. We will stimulate the aging of the materials by imposing wetting-drying cycles. These cycles will be chosen to reproduce as closely as possible the real-life climatic effects of a marine environment. The impact of sea water will be studied.

Erosion tests will be completed by geophysical characterization at the lab-scale, in order to yield existing correlations to the resistance to erosion (e.g. critical shear stress, erosion rate). Then, erosion tests and geophysical measurements will be performed on a full scale experimental lime-treated coastal dike which will be built on the Mediterranean coast (*Digue 2020* project). The soils used for the coastal dike and for the lab study will be the same. First lab results are expected in the autumn 2017.

ACKNOWLEDGMENTS

Digue 2020 is financed as a part of CPER 2015-2020, with the participation of the French State, PACA region and French department council 13.

Digue 2020 is financed with the participation of the European Union. The Europe commit in Provence-Alpes-Côte d'Azur with the European Found for Regional Development (FEDER)

REFERENCES

Charles, I., Herrier G., Chevalier C., and Durand E. (2012). An experimental full-scale hydraulic earthen structure in lime treated soil . *Proceedings of the Sixth International Conference on Scour and Erosion (ICSE)*, 181–188.

Chevalier, C., Haghighi I., Pham T.L., and Reiffsteck P., (2010). Two complementary tests for characterizing the soil erosion. *Scour and Erosion*, 152-161.

Chevalier, C., Haghighi I., and Herrier G. (2012). Resistance to erosion of lime treated soils: a complete parametric study in laboratory. *Proceedings of the Sixth International Conference on Scour and Erosion (VI ICSE)*, 161-168.

Chevalier, C., Herrier, G. and Charles, I. (2015) Resistance to erosion of lime treated soils. *Proceedings of the 16th European Conference on Soil Mechanics and Geotechnical Engineering* (XVI ECSMGE), 2773-2779

Haghighi, I. (2013). *Caractérisation des phénomenes d'érosion et de dispersion : développement d'essais et applications pratiques*. PhD-thesis Université Paris-Est.

Haghighi, I., Chevalier C., Duc M., Guédon S., and Reiffsteck P. (2012a). Improvement of hole erosion test and results on reference soils. *Journal of Geotechnical and Geoenvironmental Engineering* 139 (2): 330-39.

Haghighi, I., Martin T., Reiffsteck P., and Chevalier C., (2012b). An "Enhanced Crumb Test" for better characterizing water sensitivity of soils. *6th International Conference on Scour and Erosion (VI ICSE)*, 1049-1056.

Pham, T.L. (2008). *Erosion et dispersion des sols argileux par un fluide*. PhD-thesis Ecole des Ponts ParisTech.

Reiffsteck, P., Haghighi I., and Chevalier C., (2012). Erodibility diagnostic of existing hydraulic earthworks by Mobile Jets Erosion Test. *6th International Conference on Scour and Erosion (IV ICSE)*, 1105-1112.

Wan, C.F., Fell, R., (2004). Investigation of rate of erosion of soils in embankment dams. *Journal of geotechnical and geoenvironmental engineering* 130 (4): 373-80.