Erosion resistant dikes thanks to soil treatment with lime

G. Herrier[1], S. Bonelli[2], F. Cornacchioli[3], N. Nerincx[4], S. Nicaise[2], D. Puiatti[5], J.-M. Richard[1] and P. Tachker[6]

[1] *Lhoist R&D, Rue de l'Industrie 31, 1400 Nivelles – Belgium*

[2] *Irstea, route de Cézanne 3275, F-13282 Aix-en-Provence – France*

[3] *Arcor Technologies, Technopôle Le Moulin, rond-point du Canet, F-13590 Meyreuil – France*

[4] *ISL, Rue du Vieux Faubourg 14, F-59042 Lille – France*

[5] *DPST Consulting, Rue Adèle 6, F-93250 Villemomble – France*

[6] *EDF-CIH, Savoie Technolac, F-73373 Le Bourget du Lac - France*

Abstract

Lime treatment is a well-known technique of earthworks, for soil improvement and stabilization, its applications are mainly roads, railways, airports and platforms construction. In addition, some positive past experiences of lime treatment were related to solve erosion problems of dispersive and non-cohesive soil in hydraulic structures. The interest of the hydraulic works community regarding this technique is currently growing. During the last decade, the benefits of lime treatment and appropriate application technologies were evidenced for earthworks execution, for the improvement of mechanical properties and stability, high internal and external erosion resistance of treated materials and the possibility to maintain low hydraulic conductivity values. These have been shown in the laboratory and for some properties with full scale experiments.

The conferred soil properties can lead to innovative earthfill dams and dikes designs by addressing some of the typical designer's problems, such as stability, watertightness, internal erosion, surface protection and flood control. However, lime treated soil external erosion resistance was still to be quantified in the field for proper designing and dimensioning of lime treated soil external erosion protection or spillways. With this purpose, an experimental earthfill dike was built along the river Vidourle (south of France) in July 2015, in the frame of the French R&D program "DigueELITE". This 50 m long and 3,5 m high dike is made of lime treated silty soil and is provided with sensors (suction, water content and temperature) and piezometer in order to be monitored. It also was tested against surface erosion (JET testing) and real scale overflow testing. The in situ methodology and equipment for assessment of overflow resistance, and the benefits of lime-treatment against overflow are described. Eventually, proposals for dike design perspectives thanks to soil treatment with lime are opened.

1 Introduction

Lime treatment of soils has grown considerably since the mid-1940's for the stabilisation of clayey gravel and sand used in the construction of pavement bases of roads, highways, airfields, railroad, etc. In Europe, since more than 60 years, the technique has also been developed to improve and stabilise silty and clayey soils in earthworks for the same field of applications.

The development in the field of hydraulic structures has been slower. The main benefits of this technique are reported during 70's: preventing softening while underwater, preventing leakage and resisting to erosion from flowing water. The reduction of shrinkage and swelling movements of high plasticity index soils (heavy clays) after lime treatment is also an important benefit for the reduction of the occurrence and development of cracks. Several cases of construction, restoration or reinforcement of hydraulic structures were realised by American and Australian authorities since the 1970's [1-9]. In addition to the very good mechanical and hydraulic performance of lime treated soils, the technique is reported to decrease the overall construction costs, offering the possibility to reuse local soils with poor initial engineering properties, to improve the workability of materials, to take advantage of potential design changes.

In Europe, lime treatment of soils for hydraulic earthen structures was used in the late 19th century. It reappeared 30 years ago (levees and small dams in Czech Republic and France for example), thanks to the initiatives of geotechnical engineers who, aware of the uses in road applications, had the opportunity to transpose them to hydraulic structures.

Important works in laboratory and full-scale, were used to quantify the performance of lime treated soils in hydraulic structures such as stability, watertightness, internal erosion [10-12]. These results are taken into account by the CMD Technical Committee (P) of ICOLD in the ongoing drafting of a bulletin dedicated to Cemented Soil Dams (CSD).

However, the resistance to external erosion needs to be quantified in the field for the proper design of protection against surface erosion. For this purpose, an experimental earthfill dike made of lime treated silt has been built in July 2015 along the river Vidourle (France) in Aimargues, in the frame of the French R&D program "DigueELITE".

2 Performance of lime-treated soils and design requirements

2.1 Lime treatment benefits on mechanical and hydraulic performance of soils

Calcium air lime is a reactant obtained by calcination of pure limestone. It can be in the form of either calcium oxide (CaO) also called quicklime, or in the form of calcium hydroxide [$Ca(OH)_2$] also called hydrated lime. When mixed with a clay containing soil, lime reacts differently than cement. On short term: reduction of the moisture content, particularly when using quicklime, flocculation of the clay minerals, modification of the geotechnical characteristics (Atterberg limits and Proctor curve) and increase of the bearing capacity (immediate CBR). On long term: slow combination with the clay minerals of the soil ("pozzolanic" reaction) and increase of the mechanical performance (CBR after immersion, Unconfined Compressive Strength and shear resistance) [13].

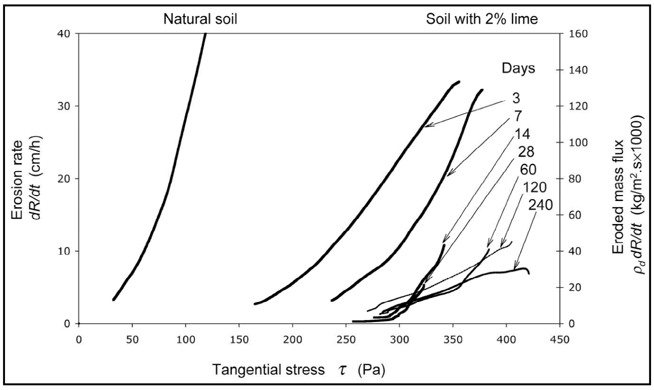
In terms of hydraulic properties, laboratory and full scale tests have shown that the permeability of a lime treated soil was identical to that of the same untreated soil provided it is compacted by kneading (for instance with a vibrating sheep foot roller) on the wet side of the Optimum Moisture Content (OMC).

Lime treatment also increases the resistance to internal erosion. The case illustrated in Figure 1 is illustrative of this benefit: internal erosion resistance (critical shear stress) is multiplied by more than 10 after 2 weeks, thanks to addition of 2 % quicklime.

2.2 Functions and requirements regarding soil-lime component

To optimize the use of the soil lime component and therefore the design of the works, it was conducted an analysis of the requirements related to the lime treated material according to the functions attributed to the component in the hydraulic structure. Table 1 summarizes the results and should be read as follows: a given project may assign one or several functions to the soil lime component. The requirements are described below as well as the parameter(s) to be studied and the treatment process recommended. For instance, if the natural soil is too wet, one may only look for workability and determine the right dosage of lime to reach the necessary bearing capacity and density after compaction.

Figure 1. Hole Erosion Test (HET) curves of a clayey silt from Rhône River (PI=11), untreated and treated with 2% lime, after several curing times [14]



If workability and resistance to erosion are required, the performance to reach will be bearing capacity, density, homogeneity and resistance to internal erosion. The content and procedures of the studies shall be established in order to quantify these parameters.

In the field, the treatment can be done either in place or in a plant. The first method is the most common. The modern equipment (spreaders and mixers) is able to produce high quality mixtures. Mobile plants are in a development phase. Recent models allow a better control of the lime dosage, the water content and the homogeneity of the mixtures.

3 Experimental dike

3.1 Objectives

Table 1 shows that some parameters of lime treated soils are common and may be quantified by laboratory tests or in the field. Feedback from numerous projects is also consistent for some parameters. From this Table, it should be mentioned that resistance to surface erosion has not been qualified nor quantified yet. However surface erosion resistance could be of high interest, especially for low dams and dikes if the designer could consider overflow over the earthfill itself, sparing expensive concrete or grouted rip rap spillways.

Surface erosion resistance cannot be properly analysed in lab test. Scale effect is too high to elaborate relevant and reliable laboratory test. It should be noted as well that lime treated soil should not be tested like other erosion protection devices such as mattresses, geogrid,… The latter are superficial and anchored in the earthfill, while lime treated soil makes the earthfill itself.

Therefore an experimental dike has been built within the French R&D program DigueELITE about lime treated soils in hydraulic works. This dike is tested against external erosion by applying steady artificial overflow. The experimental device itself is innovative and being developed within the DigueELITE program.

This experiment is also the opportunity to validate the construction methodology of lime treated earthfill for hydraulic works, which differs from usual methodology applied in soil treatment for other infrastructure. Methodology applied is shortly described below, and detailed in a companion paper (Bonelli and al. [16]). The experimental dike is integrated in the rehabilitation works of the dike network along the river Vidourle (Gard department, France).

Table 1. Functions and requirements regarding soil lime component.

Function assigned to soil lime component	Workability	Stability	Ability to retain water	Resistance to internal erosion	Surface protection*	Evacuation*
Requirements	Improvement of the use of natural soils	Stability under own weight	Low permeability	Resistance to internal erosion	Resistance to external erosion	Resistance to high speed flow
Parameters to be studied	Bearing capacity Density after compaction	Shear strength Tensile strength Compressive strength	Homogeneity Permeability	Homogeneity Resistance to hole erosion	Homogeneity Resistance to surface erosion	Homogeneity Resistance to surface erosion for spillway
Recommended treatment process	In place or in central plant	In place or in central plant	In place with homogenisation or in central plant	In place with homogenisation or in central plant	In central plant	In central plant

* Resistance to external erosion and resistance to high speed flow are parts of the works of the French "DigueElite" research program

This structure is about 50 m long and 3,5 m high. Upstream and downstream slopes are quite steep but corresponding to operational dikes around (1.5H/1V), the downstream slope length being 5,25 m.

No filter and drain is considered, as for operational dikes. Unlike operational dikes however, no wire netting against burrowing animals is provided, in order to qualify lime treated soils resistance against those animals well present in the area.

Different test zones are foreseen on this experimental dike:

- A first zone is made of natural, untreated soil as reference
- A second zone is made of lime treated soil
- Areas in Zone I and II are dedicated to overflow test
- Other areas in Zone I and II are dedicated to other geotechnical tests
- A stilling basin is foreseen for the overflow test (right part of Figure 2)

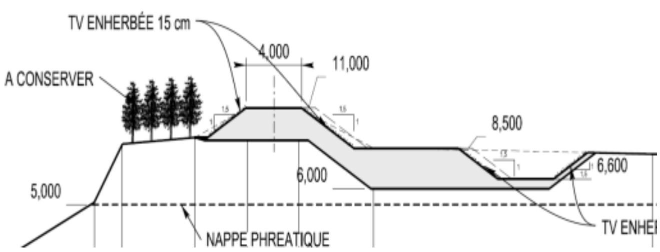
3.2 Design of the experimental dike

The experimental dike design has been set up with the following objectives:

- The dike should receive all the required tests and monitoring devices;
- The dike should be well integrated in its environment of real operational dikes;
- As experimental dike, it should not create any risk in case of failure or undesired behaviour, in the short and long term.

The dike has a typical dike cross section as shown in Figure 2. It should be noted that the dike is set within the Vidourle floodplain, along a meander. The dike has therefore no protection function. Furthermore, in case of flood event, water will raise both sides of the dike.

Figure 2. Experimental dike cross-section.



3.3 Experimental dike construction

The project has foreseen the reuse of excavated soil from the flood control area. This is a silty soil with a low plasticity index, which was treated by lime for the construction of the main part of the dike. The main characteristics of the soil are reported in Table 2.

Table 2. Identification characteristics of excavated and stockpiled soil.

% Clay (<2 µm)	**Passing through 80 µm sieve (%)**	**Moisture content at sampling (%)**
23	82	14 to 17
Plasticity Index (%)	**Plastic Limit (%)**	**Liquid Limit (%)**
5	23	28

The lime used for the soil treatment lab tests is a CL 90-Q quick lime according EN 459-1 standard, containing 92 % of available CaO and a reactivity (t_{60}) of 2 minutes. The lime fixation point of the soil, determined according the Eades and Grim test (ASTM D6276-99a), is 1.5 %. A slightly higher dosage of 2 % was selected to ensure the development of middle to long-term mechanical resistance. Same lime was used during the jobsite operations.

The changes induced by the lime treatment on the compaction behaviour of the soil are the following : the optimal moisture content (according Standard Proctor compaction) of untreated soil is ρ_d=18.1 kN/m³ at OMC=17.0 %. It is known that lime treatment leads to an offset of the OMC towards higher moisture contents and a reduction of the maximal dry density after compaction: the compaction characteristics of the silty soil treated with 2 % quicklime are ρ_d=17.3 kN/m³ at OMC=18.7 %.

After lime and soil mixing, the final materials must be humid, e.g. wet side of optimum conditions, in order to ensure the lowest permeability level (see 2.2). That means that up to 9 % water had to be added because of very dry weather and low initial moisture content. The compaction must be performed with kneading operations (sheepfoot roller) to reach a density level ≥ 95 % of the maximal dry density (17.3 kN/m³). The equipment used for lime treatment was a mobile soil mixing plant with a maximum production capacity of around 150 tons of treated soil per hour. It can precisely control the lime dosage through a continuous weighing of soil passing through the band, and offers a regular addition of water directly in the mixing bell (Figure 3, above). The compaction equipment is a VP5 sheepfoot roller, according the French Standard NF P 98-736 (Figure 3, below).

Controls during construction were focused on lime addition, water content of materials after placement, layers thickness and materials density after compaction (this last measurement by gamma densimeter). The measured lime and water contents and the calculated standard deviations of the mixture composition showed the high level of homogeneity of the treated soil, and therefore the consistency of the production using the mobile plant. The average layer thickness was 30 cm after compaction, the objectives in terms of water content > OMC and density level were reached (Table 3).

Note that the average water content of the non-treated soil (Zone 1) was determined around 15.7 %, close to its OMC. Note that the untreated soil section of the dike was executed carefully and with respect to the specifications determined according laboratory experiments; it corresponds to the best possible soil material and placement conditions.

A global perspective can be seen in Figure 4, distinguishing the 2 zones (untreated and lime-treated soil).

Figure 3. Mobile lime treatment plant (above) and compaction by a sheepfoot roller (below).

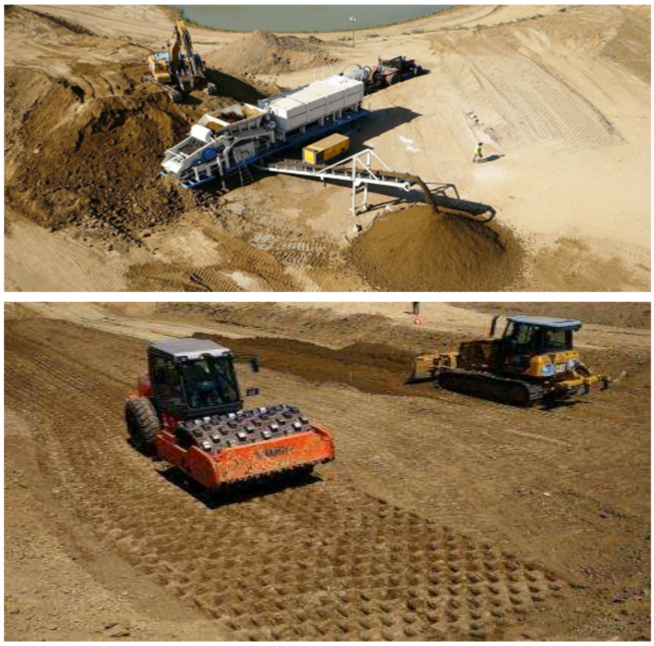


Figure 4. Experimental dike after completion of the construction steps.

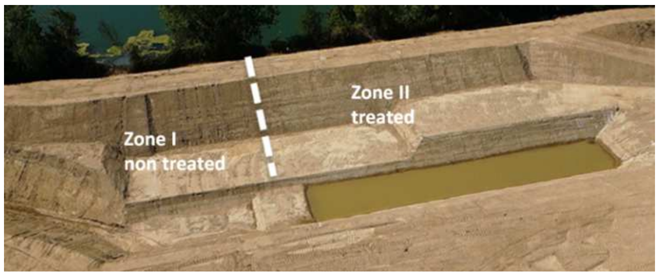


Table 3. Measurements performed on the lime-treated materials and layers after placement.

	Water content (%)	**Lime dosage (%)**
objective	above OMC (19.6 to 21.5%)	2.0
average	19.8 (w-OMC = 1.1 %)	1.9 to 2.2
standard deviation	1.3 (104 measurements)	-

4 Surface erosion experiments

4.1 In situ JET test

The JET erosion test is inspired by methodology and device from Greg Hanson, and described in ASTM 2013 [15]. It allows quantifying the erodibility level of fine and low cohesive soils. Erosion law can be expressed by:

$$\varepsilon_r = \kappa_d.(\tau - \tau_c)$$

Where ε_r represents the erosion rate of the soil (in m/s), τ is the effective hydraulic stress (Pa), τ_c is the erosion critical stress (Pa) and κ_d is the erosion coefficient (cm³/N.s). 5 tests were performed according Greg Hanson's Standard. After an immersion period of about 10 minutes, the hydraulic stress was adjusted in order to obtain a 1.5 m order of magnitude. The obtained erosion parameters are illustrated in Figure 5 in the Hanson's classification diagram. Measurement zones 1 to 3 are related to lime-treated soil, but zone 1 data were rejected due to experimental problems. Other zones 4 and 5 are located in untreated soil zone (without lime addition), which are classified as very erodible and erodible respectively.

Figure 5. Erosion parameters provided from Geophyconsult company, from the tests performed on the experimental dike sections. Zones 4 and 5 are related to untreated soil, Zones 2 and 3 to lime-treated soil. Vertical red lines are estimates of the lowest critical stress values, as no significant erosion was observed on these lime-treated zones.

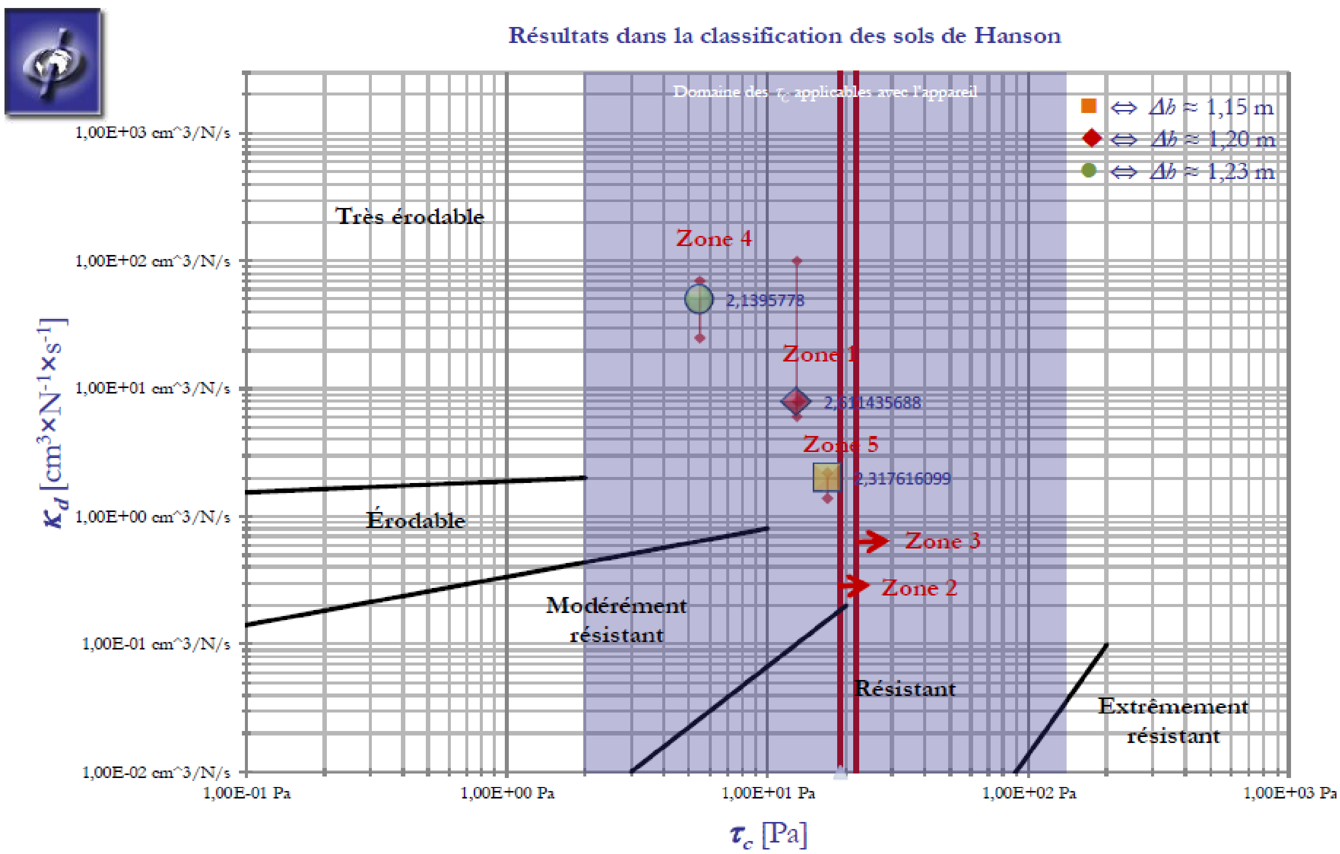
On lime-treated soil zones (# 2 and 3 in Figure 5), no significant erosion was observed. In this case, the test can only provide and underestimated (minimal) value of the critical stress, directly linked to the hydraulic stress applied on the soil surface at the beginning of the test. According this method, "minimal"erosion critical stress values registered are 19 Pa and 22 Pa respectively, positioning the lime-treated soil as "at least" resistant to erosion. It was not possible to determine an erosion coefficient for lime treated soil, due to lack of significant erosion because of the limits of test device.

The JET test can be considered as representative of the erosion and scour phenomenon which could occur at the toe of the embankment slope, provided in this case a quantitative result. However, JET parameters are not sufficient to assess overflow characteristics of a full scale structure, because of the specific construction methodology (stair-shaped), the dike profile and dimensions, the free-surface flow phenomenon on the slopes, etc.

4.2 In situ overflow tests

In the framework of the French DigueELITE project, Irstea institute developed an in situ testing device and procedure in order to quantify the erosion resistance of the levee, also allowing the differentiation between the crest, the embankment slope and the toe. The dike surface was not covered, neither by vegetation nor by topsoil.

A companion paper by Bonelli and al.[16] explains in details the experimental set-up and protocols applied



for the overflow tests. The 2 testing flumes, inspired by ASTM D6460, can be seen on Figure 6. We propose in the present paper to emphasize the materials behavior and compared performance.

Figure 6. Overview of the experimental set-up: 2 overflow flumes, placed on each zone (untreated soil and lime-treated soil); pumping units are located in the basin, bringing water to a buffer tank on the crest, starting point of the water flow.

During the last overflow test series, the following parameters were registered:

- Maximum flow rate inside the flume: 570 l/s/mL
- Highest water speed at the toe of the slope: 6 m/s
- Highest water height at the crest: 32 cm.

The analyses of the data recovered by several method (see Bonelli and al. .[16]) supports the following conclusions on the erosion behavior of the dike profile parts, and related to constitutive materials:

• The first test executed at a water flow rate of 0.095 m²/s (which was the minimal value) acts as a "washing" operation of the surface. The erosion is in this case representative of the surface layer affected by exposure of the embankment in atmosphere (effects of rain, heat, sun…) after construction. The following increase of flow rates and duration of tests have better highlighted the differences between zone I and II:

• On the crest, erosion of lime-treated soil is 6 to 7 times lower than of untreated soil (but of high homogeneity and execution levels);
• On the slope toe, the erosion of lime treated soil is 5 to 10 times lower than untreated soil; a significant pit is created on the untreated section (see Figure 8);
• In the upper part of the slope, erosion magnitude is similar for both zones;
• In the lower part of the slope, erosion of lime treated soil is 3 times lower than untreated soil.

Graphs presented at Figure 7 illustrate those differences in erosion resistance. It is possible to have a visual overview of erosion resistance measured inside the 2 flumes (after 4h30 testing), thanks to terrestrial lidar scanner methodology developed by Arcor Technologies company (Figure 8).

Figure 7. Erosion depths after first ("washing") step and last step (17h testing duration) on lime-treated soil (blue curves) and untreated soil (red curves).

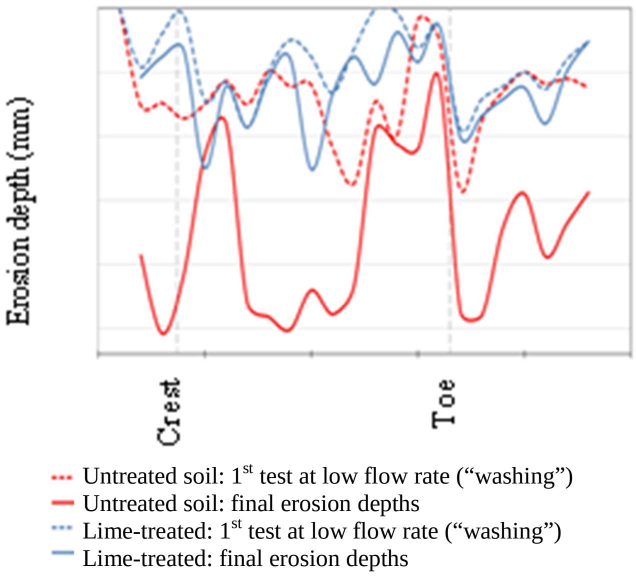
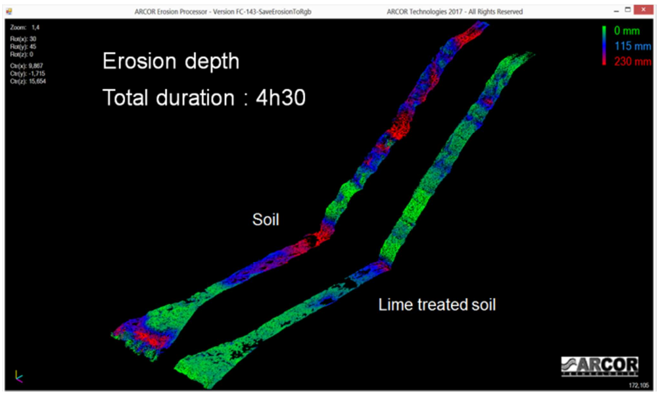


Figure 8. Interpretation of terrestrial lidar scanner data, giving a visual perspective of erosion depths along the flumes (Arcor Technologies).



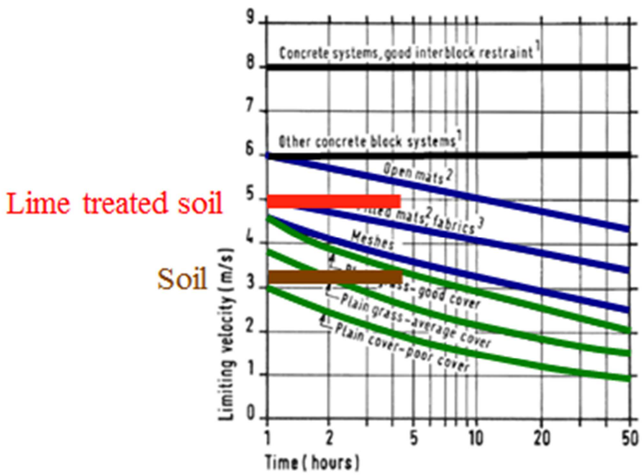
On Figure 9, a stair-shape profile can be observed along the slopes. The compaction procedure of successive layers has induced a density gradient, the bottom of the layers being somewhat less dense. During overflow tests, this part is more erosion sensitive and leads to a re-shape of the embankment. Note that the untreated zone is visually more damaged; the irregularity of the surface is due to the departure of materials by entire blocks.

Figure 9. Pit created at the toe of the downstream slope after overflow testing on the untreated soils (left) and comparison with limited erosion on the lime-treated soil (right); picture taken after 17 hours testing.

4.3 Lime treated soil as erosion-resistant material: classification tentative

From the results acquired during the overflow test series, it could be possible to classify the materials excavated from the Vidourle River surroundings and used, with and without lime addition, for the construction of the experimental dike. Thanks to interpretation of laser scanner (Arcor Technologies) in terms of Clopper Soil Loss Index, as described in ASTM D6460 Standard, the threshold lines corresponding to acceptable erosion (CSLI < 0.5 inch) are reported in Figure 10. Even only the materials used for this experiment are evidenced, one can appreciate the erosion improvement due to lime treatment and the assessment of lime-treated soil, placing it among other recognized techniques like filled mats or fabrics.

Figure 10. Positioning of untreated and lime-treated soil in CIRIA classification, according acceptable erosion (according water flow rate and duration). From Hewlett and al. [17]



5 Perspectives and typical development cases

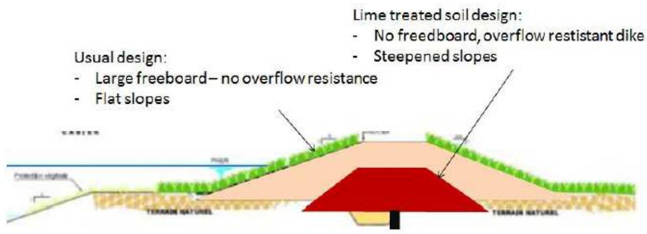
Special attention should be paid to overflow resistant dikes in the frame of climate change: climate change will most probably lead to higher peak flows and more frequent floods than observed today. In most cases, it will be impossible to build dikes protecting against 100 or 1000 year floods, even for very high stakes. With current dike design, the probability of failure is high. In fact, the practice is to consider that overflow will always cause a failure, and possibly many fatalities and damages, unless in specific zones protected against overflow. With lime-treated soils and DigueELITE type design, erosion tests show that the erosion resistance is at least an order of magnitude higher, which greatly reduces the probability of breaching, even for floods higher than the project flood. Such a design is then a very promising part of the answer to climate change in the context of flood defense system.

Using the results of the DigueELITE projects, some projects have been studied, and may be built in the near future.

First case is a flood controlled area embankment. Soils to be used in the project are of poor quality. Furthermore, even if the Maximum Water level is relatively low (< 5 m), flood controlled areas dimensions lead to large fetch, and consequently large freeboard. The site suffers from soil scarcity; therefore reducing the embankment volume is critical for the Owner.

Comparison has been made between usual design and lime treated soil design, taking advantage of increased geomechanical characteristics (function S as per Table 1) and overflow resistance (function ES as per Table 1), as shown in Figure 11. Result is a very significant decrease of the embankment volume.

Figure 11: Typical profile for a flood controlled area embankment. Comparison between usual design and lime treated soil design.



Second case is a real dike with an overflow stretch in lime treated soil. Lime treated soil replaces stone mattresses. The proposed design requires functions EI and ES, as per Table 1. The main progresses are, after validation under the precise project circumstances:

- No stone mattress is required anymore nor on the slope or at the toe
- Slope and toe can be cover with grass, that is far more acceptable on a landscape point of view than stone mattresses
- The river slope is protected only by a grass cover, as there is no burrowing animal threat anymore,
- Limited concrete foundation of the spillway beam is required, as lime treated soil makes a strong foundation
- Fill watertightness is sufficient as for non-treated soil.

6 Conclusions

Lime treated soils are not commonly used in water retaining structures (earth dams and dikes), and in any case barely used to take advantage of the whole range of their properties. As for now, on top of reuse of poor soil available at site, a designer could consider performance such as mechanical stability, low permeability and resistance to internal erosion, to optimize a dike project and decrease construction costs.

The experimental dike along river Vidourle has confirmed assumptions related to resistance to surface erosion, based on previous research programs. Thanks to overflow experiments, assessment and quantification of surface erosion resistance of soil treated with lime has been performed. These results may greatly impact the design of dikes: steady overflow could be organized on the earthfill itself and the need for concrete or other "hard" spillways may be drastically reduced.

Acknowledgements

Authors gratefully acknowledge all the members of the consortium "DigueELITE" (ISL, Irstea, Arcor Technologies, EDF, Lhoist) as well as EPTB Vidourle for their support and contributions. Authors also gratefully acknowledge Contractor, Berthouly TP and Geophyconsult. The French DigueELITE project was funded by BPI, the Region PACA and the CD13 through FUI (AAP 15).

References

1. Perry J.P. (1977) Lime treatment of dams constructed with dispersive clay soil, *Transactions of the ASAE*, vol. 20, 99, 1093-1099.
2. ANCOLD (1978) *Bulletin of the Australian National Committee On Large Dams*, p. 51.
3. Gutschick K.A. (1978) Lime stabilization under hydraulic conditions, *4th lime congress*, Hershey (PA), pp1-20.
4. Gutschick K.A. (1985) Canal lining stabilization proves successful. *Pit & Quarry*, pp.58-60.
5. Knodel P.C. (1987) Lime in canal and dam stabilization, *US Bureau of Reclamation, Report No GR-87-10*, 21p.
6. Fleming R.L., Sills G.L. & Stewart E.S. (1992) Lime stabilization of levee slope, *2nd Interagency Symposium on Stabilization of soils and other Materials, Metairie, Louisiana*, pp 79-87.
7. USBR, U.S. Bureau of Reclamation (1998) *Earth Manual, Denver CO*, 349p.
8. Stapledon D, MacGregor P, Bell G & Fell R. (2005) Geotechnical Engineering of Dams, *Transactions of the ASAE*, vol. 20, 99, 1093-1099
9. US Army Corps of Engineers (2010) *Revised Final Independent External Peer Review Report Alton to Gale Organized Levee Districts, Illinois and Missouri, Letter Report*, go to: http://www.usace.army.mil/Portals/2/docs/civilworks/Project20Planning/alton2gale.pdf
10. Chevalier C, Haghighi I & Herrier G (2012) Resistance to erosion of lime treated soils: a complete parametric study in laboratory, *Proceedings of the 6th International Conference on Scour and Erosion*, Paris, France, pp 161-168.
11. Herrier G. & Bonelli S. (2014) Internal erosion resistance of soils treated with lime: An evolutive benefit, *Proceedings of the 7th International Conference on Scour and Erosion, Perth, Australia*.
12. Makki-Szymkiewicz L, Fleureau J.M., Hibouche A, Taibi S, Herrier G, Lesueur D (2015) Evolution of the properties of lime-treated silty soil in a small experimental embankment, *Engineering Geology*, 191, pp 8-22.
13. Little D.L. (1995) *Handbook for Stabilization of Pavement Subgrades and Base Courses with Lime*, Dubuque (Iowa), Published by Kendall/Hunt Publishing Company.
14. Bonelli S. (2013) *Erosion in Geomechanics Applied to Dams and Levees*, Wiley/ISTE , 388 p.
15. Hanson G. & Cook K.R. (2004). Apparatus, test procedures and analytical methods to measure soil erodibility in situ. *Applied engineering in agriculture*, 20 (4): pp. 455-462.
16. Bonelli S., Nicaise S., Charrier G., Chaouch N., Byron F. &Grémeaux Y. (2018) Quantifying the erosion resistance of dikes with the overflowing simulator, *3rd International Conference on Protection against Overtopping*, 6-8 June 2018, Grange-over-Sands, UK .
17. Hewlett H.W.M., Boorman, L.A. & Bramley, M.E. (1987) Design of reinforced grass waterways. *CIRIA Report 116, Construction and Industry Research and Information Association*, London.