Deltares

Handbook on the use of lime treated clay in dike reconstruction

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Summary

Since 2017 the use of lime treated clay in Dutch dike reinforcement has been an object of study. Lime treated clay is very erosion resistant. After literature research, also of international knowledge and experience, and laboratory research on the behavior of Dutch clays mixed with lime the next step was to scale up and perform experiments on a true scale. In the Hedwigepolder three test sections were built. In each section an object was placed to simulate obstacles (e.g. housing) on the inner slope of a dike. Wave overtopping tests were performed with and without obstacles on the inner slope of the existing dike with a lime treated cover layer.

All the overtopping tests showed similar results. At the start of the overtopping tests a certain amount of erosion took place. However, this was only some loose easy erodible material that was removed from the top of the slope. After that the erosion slowed down. Part of the slope was eroded further but at a slow rate, and part of the slope did not erode at all as well compacted and erosion resistant lime treated materials were reached. In this way a staircased erosion profile was formed, as a result of construction of the slope in horizontal layers of lime treated clay. The hydraulic load was increased from an overtopping discharge of 10 l/s/m’ to 30 l/s/m’ to 50 l/s/m’ to a maximum of 190 l/s/m’, with a simulated significant wave height of 1,0 m. Although some differences in erosion were observed over different places and sections, the lime treated layer of at least 40 cm thick did not fail at any point during the experiments.

Lime treatment of the inner slope of dikes to prevent dike erosion at higher overtopping rates seems a very plausible application for minimalizing costs and environmental load in dike reconstruction. Not having to raise the crest saves clay and land use for dike reconstruction. As lime treatment is applicable on all sorts of clay, it can also enhance the use of local clay instead of having to transport a better quality clay from elsewhere.

This handbook aims to facilitate the use of lime treatment in (Dutch) dike reconstruction on the crest and land side slope of the dike. It does so by providing the current state of the art knowledge on a variety of topics, ranging from very practical tips on construction methods, considerations for design and stability assessment principles, maintenance aspects, and quality control. .

Within the scope of this project it has not been attempted to present an erosion model of a lime treated cover layer. Design of a lime treated cover is a matter of practical considerations, rather than a design of erodibility. Well constructed lime treated clay layers have shown little or no erosion in severe overtopping conditions, which for other reasons (e.g. extreme discharge over the crest, conditions near overflow) will probably not be desirable or even acceptable. The quality of the construction of the lime treated layer was shown to be paramount to reach the observed erosion resistance.

A method for design and safety assessment will have to take further shape in consultation with experts. The best way to do this could be to work out an (alternative) design for a dike reinforcement project, and come to a practical agreement with all parties how to proceed on this topic.

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1 Introduction

1.1 Short history of the investigations

In 2017 the question of the potential of lime treatment of clay for use in Dutch dike reinforcements was raised by two separate parties: Rijkswaterstaat (Corporate Innovation Programme) and Lhoist (a lime production company from Belgium).

This has resulted in several studies, each study provided a step in the development of the concept (see Figure).

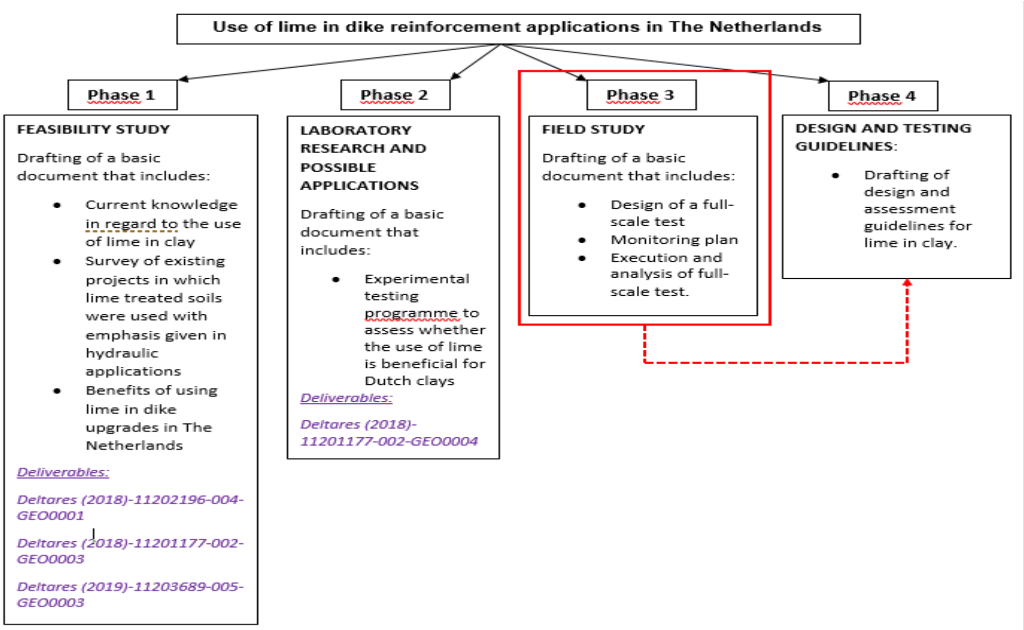

Figure 1-1 Four phases in the development of lime treatment technique in dike reinforcement.

After the feasibility study and laboratory research into the practical use for lime treatment in dike reinforcements had been concluded with favourable results, Rijkswaterstaat and Lhoist have joined forces and prepared a proposal together with Deltares for the HWBP KIA program (Knowledge and Innovation Agenda of the Hoogwaterbeschermingsprogramma). In the midst of 2021 this proposal was adopted by Waterschap Limburg and incorporated in the POV DGG (Project Overstijgende Verkenning Dijkversterking met Gebiedseigen Grond). Following the positive results of literature study and laboratory research it was decided that large scale wave overtopping tests were the best way to determine the erosion resistance of a real slope under real wave overtopping conditions. As Figure 1-1 shows the large scale overtopping tests are not the end of the road. A further development towards design and testing guidelines is necessary. This Handbook aspires to be a step in that direction, but as the Handbook has no formal status (ENW approved, official part of BOI or otherwise) this development is still underway.

In 2019 it had already been decided that the investigation would focus on the use of lime treated clay on the inner slope of dikes, with the main function of enhancing the erosion resistance of dike covers around objects, e.g. houses. There is a tendency to design dikes with a higher overtopping rate than historically has been the case. This means that a lower crest height for a dike reinforcement is required. This is a logical step in view of research on the erosion resistance of grass covers, which shows that these higher overtopping rates can be resisted by a good grass cover. Around objects however, a grass cover can be hard or impossible to sustain, and the hydraulic load is higher due to concentration of the flow around the object. In that case, enhancing the erosion resistance with lime treatment could be the solution.

Because it was agreed upon that small scale experiments on erosion of lime treated soil could possibly lead to false insights (that is because the question is whether or not the real erosion mechanisms can be simulated on a small scale) the need for large scale experiments became apparent. Besides the scale effect on erosion resistance, also the building of a lime treated clay layer could be tested on true scale. The possibility of performing real scale wave overtopping experiments in the Hedwigepolder was granted by the Polder2C's project (an European project entaminated by the Dutch STOWA and the Belgium Flemish Hydraulic Research).

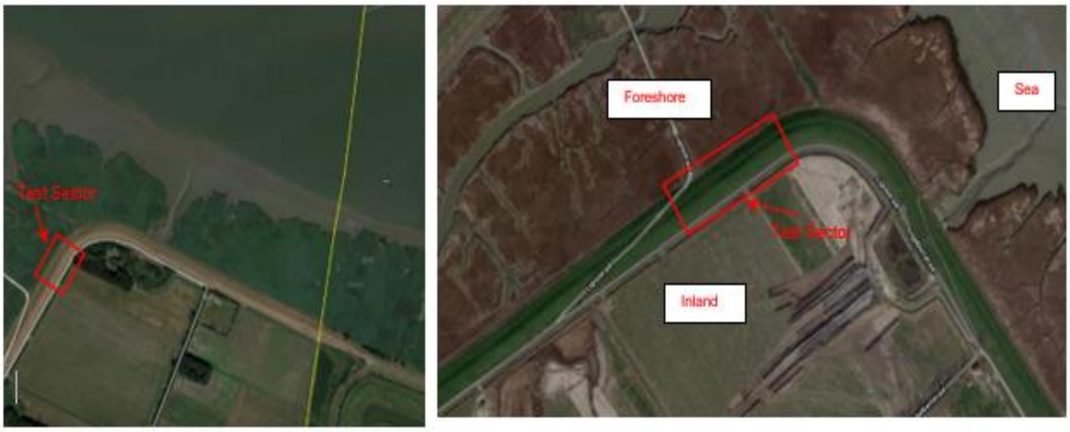

Figure 1-2 Location of the test site in the Hedwigepolder.

In November 2021 the test sections were constructed by Lhoist. Lhoist provided both the know how, the lime and the costs of the contractor. The lay-out of the test sections and the objects within the test sections were provided by Deltares.

The test sections were left alone during the months December 2021 and January and the first half of February 2022. The lime treated material needs a certain curing time during which the chemical reactions between lime and clay take place and the material gains strength. In the second half of February and the first week of March 2022 the overtopping tests were performed by Infram, on direction of Rijkswaterstaat and Deltares. Measurements of the resulting erosion were performed by the University of Louvain.
The tests show that (if the lime treated cover layer is properly constructed) the erosion resistance in regard to wave overtopping is high; a wave overtopping discharge of 190 l/s/m' for H_{m0} is 1 m and 50 l/s/m' for H_{m0} is 2 m were successfully withstood without the cover layer failing. The potential for practical use of lime treatment in dike reinforcement is high. The purpose of this Handbook is to support this practical use, and in doing so make further development of knowledge and experience possible.

1.2 Reading guide

A logical reading guide for this report is:

- Start with defining the scope of application for the lime treatment technique for Dutch dike reconstruction (Chapter 2).
- Give (practical) information on construction of lime treated covers on dikes; experience has been gained in the Vlassenbroekpolder (Belgium) and the Hedwigepolder (Zeeuws-Vlaanderen, the Netherlands); (Chapter 3); including quality control of the works.
- Cover the considerations for design of lime treated clay cover layers and assessment of safety (BOI, or Beoordelings- en Ontwerp Instrumentarium as it is called in Dutch); this should also cover influence of the application on other failure mechanisms; (Chapter 4); including quality control of the material during its lifetime.
- Give implications and guidelines for maintenance aspects; (Chapter 5).
- Concluding remarks (Chapter 6).

2 Scope of application

2.1 Introduction

The starting point for investigations in 2017 was to research possible applications for lime treatment in Dutch dike renovation. Since lime treatment is a known method for soil improvement (especially improvement in bearing capacity) there was literature on the behavior which indicated that lime treatment is suitable for clayey soils, not for sand or peat.

Laboratory research on Dutch (organic) clays showed that lime treatment for Dutch clay worked. Both in triaxial tests as in K_0 – CRS tests the characteristics changed when there was lime added. The shear strength improved, and the curing effect (further improvement with time) was as expected.

In discussions, the first possible (and most plausible) application was to improve erosion resistance around objects. Under wave overtopping conditions it is common practice to rely on the grass cover on the inner slopes of the dikes. However, around transitions and objects (e.g. houses), there is often no grass cover present or sustainable. If erosion resistance on these weak spots could be guaranteed in an alternative way that would solve the problem.

In literature there is ample evidence that the erosion resistance of clay is improved by adding lime (lit. [10], [11], [18] among others). In those cases most experiments were done using HET, JET or other small scale (surface) erosion tests. Bearing in mind that this is not necessarily the type of erosion one would experience in wave overtopping circumstances the need rose to have a large scale experiment and (if nothing else) observe and model the correct erosion processes. This was the purpose of the large scale overtopping tests perfomed in the Hedwigepolder in February/March 2022 (lit. [21]).

The overtopping tests in the Hedwigepolder may be called a success, thus promoting the lime treatment technique to a very promising innovation. In terms of development stage, the technique has shown it’s added value at a true scale in a field environment. This means that the innovation is ready for acceptance for use in dike renovation in the Netherlands. The next step will be to work out the design for application of a lime treated cover layer in an actual dike renovation project and see if and what issues arise that have not come up yet in the research so far.

2.2 Defining the scope of application

The use of a new technique or materials in dike reconstructions should fall within the scope of experience and within the scope of the studies into its behavior. There has to be a certain level of confidence of the materials and techniques performance over the life time of the construction. Given the current state of knowledge and experience, the lime treatment technique in dike reconstructions should (only) be used for:

1) Overtopping conditions/enhancing the erosion resistance of the crest and inner slope.
2) Enhancement of clay covers: the lime treatment is not suited for sandy soils or peat. It is however possible to use (local) clay of a lesser quality than would normally be used in dikes.

The technique can be used both locally around objects or transitions between cover protections, but also on larger stretches of slopes where crest height is an issue.

When investigations are made to use the lime treatment to build a more erosion resistant clay cover one should take into account the influence this application might have on other dike failure mechanisms. For instance, the geotechnical stability (sliding or uplift) of the lime treated cover layer over the existing dike, if a built up of water pressure underneath the layer is possible. Drainage or thicker layer could be necessary to prevent instability Accepting a high wave overtopping discharge might lead to an unacceptable water level in the polder. A positive effect can be that if the new cover layer is relatively impermeable so there will be less water infiltrating into the dike during overtopping, which is positive for macrostability of the dike (large slip planes going through the subsoil). These design aspects are elaborated on in Chapter 4.

An important factor for use of the lime treatment technique for improving erosion resistance is that experience is based on experiments at a true scale, but the test site in the Hedwigepolder (the largest experiment) was limited to three test sections with a width of approximately 10 meter each, and the construction process was carefully executed and monitored. The quality of the outcome depends on a careful construction process, and lime treated clay is only very erosion resistant when all aspects (testing, dosing, mixing, watering, compaction) are properly executed. Chapter 3 deals with these issues.

The hydraulic loads during the experiments in the Hedwigepolder were chosen to make the results applicable for the river area (when successful). A wave height H_{m0} = 1m was chosen, and overtopping discharges of 10 l/s/m’, 30 l/s/m’, 50 l/s/m’ and 190 l/s/m’ were tested with the Wave Overtopping Simulator. After it was concluded that the cover layer did not fail during these conditions finally a test was done simulating H_{m0} = 2 m and an overtopping rate of 50 l/s/m’, which gives fewer but larger overtopping volumes than the test with 190 l/s/m in combination with H_{m0} = 1 m. It is noted that at this wave overtopping condition the water level will be very close to the crest level and at higher discharges overflow will start to occur. Overflow is at this time outside the scope of testing and conclusions.
The wave overtopping simulator was built to simulate storm conditions with wave overtopping conditions as realistic as possible. The wave overtopping discharge is simulated correct, however, there is a difference in the front velocity of wave overtopping volumes generated by the simulator and predicted by the EurOtop Manual (Ref. [31]) and TAW 2002 (Ref. [32]). The generated front velocities are lower than given by prediction models for wave overtopping conditions. Since erosion models often have the shear stress between the water flow and the slope surface as a load factor and the shear stress is proportional to velocity squared, the erosive load by the wave overtopping simulator is probably somewhat underestimating the erosive load in real wave overtopping conditions. The applicability limits of the test results should therefore be chosen on the safe side relative to the survived test conditions.

For a first estimate the generated front velocity is in the order of 20-25% less than given by the prediction models [EurOtop] [TAW2002] for the largest volumes in a storm condition with a high overtopping discharge. Assuming a squared relation with the erosive load, the erosive load is approximately underestimated by a factor of up to 1,6 (-). The survived loads of 50 and 190 l/s/m for a wave height of 2 and 1 m respectively, could be reduced by this factor to get an idea of the equivalent erosive load in overtopping conditions as predicted by [EurOtop] and [TAW2002]. It was outside the scope of phase 3 to elaborate on erosion modelling. Using a basic erosion model based on shear stress and a critical shear stress (or critical velocity) a more accurate estimate of the survived wave overtopping load can be made.

This shows that the use of lime treated clay for erosion prevention can be promising for at least the river area, and other areas with H_m equal or smaller than 1 m and overtopping rates smaller than 130 l/s/m’, and in other regions where H_m is smaller than 2 m and the overtopping rate is smaller than 30 l/s/m’. The slope angle of the inner slope must not be steeper than the slope in the Hedwigepolder (1 : 2,5). A steeper slope will result in higher velocities and a higher erosive load and might lead to other erosion patterns or behavior than observed in the tests. A prerequisite considering the strength or erosion resistance is that the cover layer is constructed with the same quality as on the test location (or better), including the reached compaction which is also very important for the erodibility. It is recommended to develop a more detailed design method within the first projects were the use of lime treatment in dike reconstruction is considered.

A final remark is that there are more possible applications for the lime treatment technique with regard to dike reinforcement in the Netherlands. The current research has been concentrated on the crest and the inner slope of a dike during overtopping conditions.

It is possible that the same technique can be used for:

- Erosion enhancement in the wave run up area on the outer slope of the dike. This is typically an area where grass and/or asphalt are used. As wave run up is not that different in terms of hydraulic loads compared to water running down a slope it is to be expected that lime treatment can offer a reliable solution to prevent erosion in this area.
- Erosion protection in the wave impact zone. In these zones typically asphalt or stone revetments are used. It could be investigated (starting with lower wave heights that are typical for the river area) to what extent lime treated clay can also resist wave attack.
- Enhancement of macrostability by preventing water infiltrating into the dike during overtopping conditions. In current practice, infiltration of water on the inner slope has a large impact on results of stability analysis. If infiltration is limited by a cover layer with low permeability this would be an improvement of this current practice.
- Future research (with or without lime treated layers) will try to model and quantify the strength of dike bodies after revetment failure or in absence of a revetment. This is part of the development of flood safety standards and regulations in the Netherlands in which the actual risk of flooding is the standard, and instruments to calculate that risk are being developed. This means that apart from the traditional failure modes of a dike (height, piping, erosion, stability) the events leading to that failure mode and the strength of the dike body after an initial failure mode has occurred will become more important. A relatively strong cover layer can also have a positive effect on the strength of a dike body.

All of these possible applications will have to be investigated further before application in actual dike renovations.

3 Practical guidelines on construction aspects

3.1 Introduction

In the use of lime treated clay for erosion protection there is one important condition that must be remembered: the lime treatment works only if the available clay is properly analysed, lime is properly dosed, properly watered, properly mixed and properly compacted. At the end of each work there has to be some form of quality control to check whether or not the required material properties have been achieved. This entire, and crucial, part of the use of lime treatment is the topic of this chapter.

In this chapter use has been made of the knowledge and experience of Lhoist (Vlassenbroekpolder (lit. [27]) and Hedwigepolder (lit. [8])), as well as [lit. 22]. The ICOLD Publication on Cemented Soil Dams (lit. [14]), and lit. [28], [29], [30] provide more information on the issues in this chapter than can be repeated in this report. It is highly recommended for reading.

3.2 Laboratory analysis

3.2.1 Standard classification

Prior to every work lime characteristics for the jobsite should be determined. The lime classification (for instance CL 90) depends on among others the cohesiveness of the original soil. A soil and treatment study prior to construction is essential for the success of operations.

It is recommended to perform a standard qualification of the original soil (water content and proctor density curves, sieve analysis, plastic and liquid limit, plasticity index, content of organic matter, salt content, natural lime content). Part of the data is necessary to determine requirements for compaction and lime content. The purpose of this is also to build up a data base for future reference. For future use it is useful to know whether the soil properties are within or outside of experience with former projects.

Experience in the Hedwigepolder (lit. [21]) suggests that the working of lime treatment in clay depends more on the lime treatment and handling of the composed material than on the classification and quality of the original material. While still in the process of gaining experiences however it is advisable to expand the database of the properties of the original clay soils and know if the properties are inside or outside the ranges of experience. Hydraulic properties, like erosion resistance and permeability are relatively unknown, as opposed to mechanical properties like increase of bearing capacity, which has been extensively researched.

3.2.2 Lime dosage, lime fixation point

In the laboratory the so called Lime Fixation Point must be determined. Lime is added to soils with ‘pozzolanic content’ (i.e. clay content), which means that the soil reacts with the lime. The purpose is to improve properties such as bearing capacity, density and others. When clayey soil is treated with lime in presence of water, the plastic limit increases and thereby the plasticity index decreases. The lime fixation point is defined as the percentage of lime which causes the soil’s plastic limit to reach a stable value. If more lime is added the plastic limit does not change noiticeably. The lime fixation point is also referred to as the amount of lime required to neutralize the clay fraction of the soil. To initiate pozzolanic reactions a higher quantity of lime should be added. Pozzolanic reactions are responsible for the development of mechanical strength. The lime fixation point is usually reached at a lime dosage of 2 to 3,5 %. This depends on the composition of the clay.

The working of lime is dependant on the so called pozzolanic reaction in association with the water content. This is the reason why a lime dosage of 1 or 2 % above the lime fixation point is needed. The required lime dosage (dependant on the lime fixation point) should be determined for each soil. This is dependant on the original soil used.

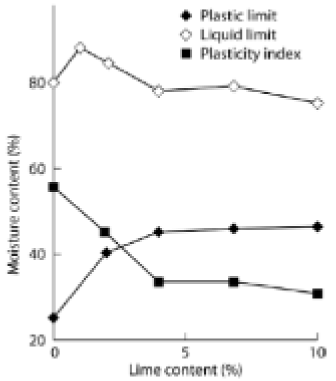

Figure 3-1 Example of the effect of lime on the plastic properties of a clay (image from BRRC guide, lit. [30]).

Various factors affecting lime-soil stabilization are soil type, lime type, lime content used, compaction and curing period.

3.2.3 Optimum Moisture Content for densification

To obtain greater strength of the lime-soil mix the compaction of the mix should be as large as possible. In the laboratory the Optimum Moisture Content (OMC) of the proposed mix should be determined. This is an important steering factor for the field operations. The density is usually referred to the Standard Proctor Density test for these applications. An example of the results of these tests are shown in the next figure.

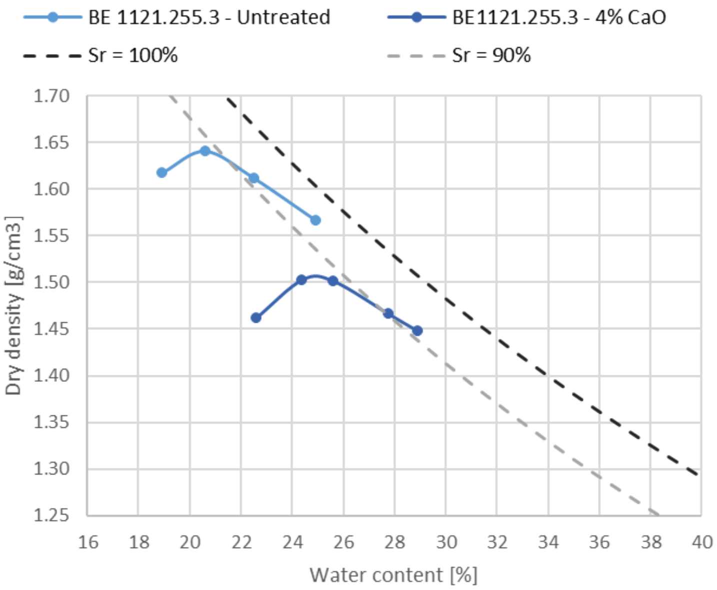

Figure 3-2 Dry density curves for "Poor quality clay B" natural soil and "Poor quality clay B" soil treated with 4% Proviacal® DD lime (Figure courtesy of Lhoist). *Sr stands for degree of saturation.*

3.3 Influences on the result of field operations

Curing is faster in warmer conditions. Perhaps the term hardening is more accurate than curing. It means to say that the kinetics of pozzolanic reactions is faster in warmer conditions. Construction during the summer period (between spring and fall) is to be preferred.
Lime treated soil is suitable for soils like clay, silty clay, clayey silt or even silt and is not suitable for sand.
Clayey soil can have large lumps (clogs or aggregates) of clay. These should be pulverized before treatment. Maximum lump size is preferably below 1 to 3 cm of size.
If lime powder is used it should be spread evenly over the clayey soil. Water content of the soil should correspond with the Optimum Moisture Content, but should preferably not be higher than that (lower water content is less of a problem for densification).

A very important aspect of the implementation of lime-treated soils for hydraulic works (as experience of the last few years shows) is that:

- Soils should be processed with a water content between 1,05 and 1,15 times their optimum moisture content. Reference is the treated material density curve at the desired energy of compaction. In this way the density of the material is at it's lowest. This is also the reason why kneading compaction is required. The treated material forms new micropores which give the treated soil a permeability that is comparable or even lower than the original material.
- The density versus water content curve of the treated material is flat compared to that of the natural soil, which means it is not detrimental to work slightly above the optimum moisture content.

It is possible that several rounds of watering and mixing are required to get the best results. The final result can be checked in a field laboratory to see if the result are satisfactory. Lump size is also diminished by mixing rounds.

Factors affecting the effectiveness of lime-soil stabilization are as follows:

1. Soil type.
2. Lime type.
3. Lime content.
4. Compaction.
5. Curing.

3.3.1 Soil type

- The type of soil used in stabilization should be of reactive type soil. Which means the soil should react with lime content when added. This can best be tested in the laboratory.
- To react with lime, the soil should contain pozzolan content (reactive clay content) in good amounts.
- When lime is added to pozzolanic soil in presence of water, calcium hydroxide from lime reacts with siliceous and aluminous materials of soil and form a mix with cementitious properties. This reaction is called pozzolanic reaction.
- This reaction will increase the strength of lime-soil mix and strength gain is gradually increased with age since pozzolanic reaction continues for very long periods.
- Soils shall not content in excess components that could prevent or disrupt the pozzolanic reactions, like organic matter, sulfate, nitrates, chlorides, micas. In case of doubt, specific analysis and tests should be carried out.
- The reactivity of Dutch organic clay has been tested in the laboratory (ref. [1] and [2]). The clays proved to be suited for treatment with lime.

3.3.2 Lime type

- Quicklime should be carefully operated as a considerable amount of heat can be caused by operations and reactions.
- There can be differences in lime types and lime mix used. Given the quality of results and execution sought in hydraulic structures the best available quality of lime for soil treatment should be used (CL 90). No past experiences in this field have been gained using lower quality limes. The provider of the lime can help determine the most effective product.

3.3.3 Lime content

- When lime content is added to soil in presence of water, the plastic limit increases and thereby the plasticity index decreases.
- When lime content is added further, after a certain point the plastic limit stops decreasing. More lime has to be added to obtain the desired improvement of mechanical properties (pozzolanic reaction).
- To obtain the desired stability, plasticity index should be very low which means to make the clay or soil as non-plastic as possible.
- Adding a proper quantity of lime also increases shrinkage limit.
- Swelling can also be minimized by increasing the lime content in the soil.

3.3.4 Compaction

- The higher the energy of compaction the greater the strength of the lime-soil mix. Kneading compaction is required to obtain the lowest permeability and the highest strength. The method of compaction is primarily of four types, namely kneading, static, dynamic or impact and vibratory compaction. Different type of action is effective in different types of soil such as cohesive soils. Sheepfoot rollers or pneumatic rollers provide the kneading action.
- Lime-Soil mix should be compacted at 1,05 to 1,15 times optimum moisture content (OMC), at which soil gets maximum compacted density given a certain amount of compaction effort.

3.3.5 Curing

- Curing (or hardening) is also an important factor in achieving good stabilized lime-soil mix.
- Proper curing (mainly: prevention of evaporation) must be provided for the mix especially during initial stages where the rate of strength gain is rapid. During warm seasons this means periodical spraying of the surface of the exposed treated layers.
- The strength gain is dependent on temperature of that area, for low temperature conditions the rate of strength gain will be low. For freezing conditions the strength gain rate is almost zero. This applies to the velocity of curing, but the end result can still be the same.

3.4 Experiences of construction of test sites in Vlassenbroekpolder and Hedwigepolder

In the following text use has been made of experience gained in constructing the test sites on dikes in Belgium (Vlassenbroekpolder) and the Netherlands (Hedwigepolder). Both test sites have been constructed by contractors under supervision of Lhoist.

In both cases it was decided to use a production platform (for instance of size in the order of 40 x 40 meter) to have a (more) controlled working environment. In Vlassenbroek the platform was constructed with the available silty soil treated with 2 % of Proviacal DD. In the Hedwigepolder the used soil was sandy. The thickness of the platform is around 40 cm. Upon the working platform all operations for preparing the material (spreading, dozing, watering, mixing) took place.

Figure 3-3 View of production platform at Vlassenbroek polder.

Also in both cases a field laboratory was present for lime characterization of new stock at reception, pH, lime availability tests on treated material, water content prior and after treatment and checking spreader calibration. Operations were first performed on the production platform, then the result was checked with the simple laboratory tests and only when satisfactory was the mixed material transported to the dike.

The material was mixed and prepared on the production platform and then transported with trucks to the dike. There it was spread out in layers of approximately 38 cm to 50 cm thickness and compacted to layers of about 30 cm to 40 cm thickness. This is somewhat in contrast with the usual operating modus when compacting clay. It is recommended to apply layers of maximum 25 cm which are compacted to 20 cm to get optimum density results.

The compaction machines are shown in Figure 3-5. Compaction was done by dynamic kneading using a vibrating pad roller. It appears that for dynamic compaction of these layers the subsoil needs to have a reasonable bearing capacity. Operations and compaction under wet weather conditions are problematic. At one point at the Hedwigepolder water was observed flowing out of the dike on the slope near the berm of the dike. Dynamic compaction was not possible. At a different point the heavier compaction equipment was not available and weather was unfavorable during compaction. At these two points extra erosion was observed during the overtopping tests. This underlines the importance of careful and controlled work while constructing a lime treated cover layer on a dike.

There was a distinct difference in applying and densifying the material on the dike. In the Vlassenbroekpolder the material was spread out and compacted along the slope (see figure 3-4).

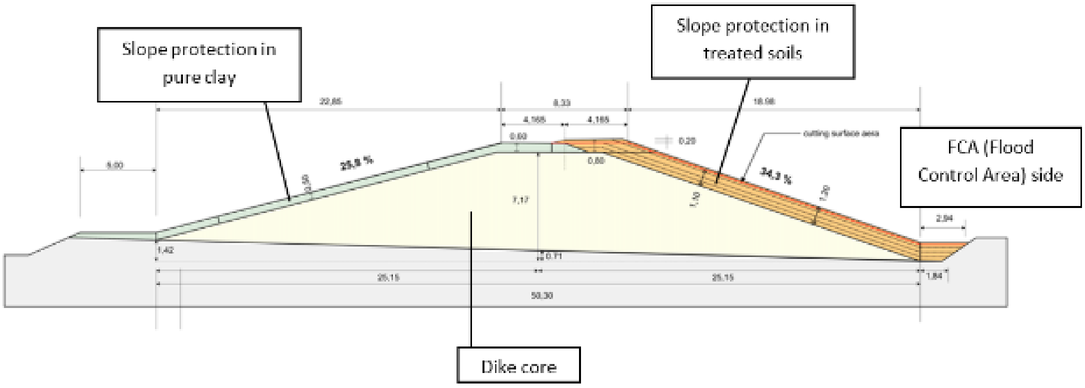

Figure 3-4 Cross-section of the FCA (Flood Control Area) levee network at the Vlassenbroek polder
The project involving lime-treated soils consists in building some sections of the slope protection on the FCA side (orange layer).

The cover of 1,2 m thick was constructed of 4 compacted layers of 30 cm thickness (after compaction, that is about 38 cm thick before compaction).

Figure 3-5 Compaction of the treated soil along the slope (Vlassenbroekpolder).

In the Hedwigepolder a different construction method was used. First the grass cover from the original dike was removed. Then a staircased profile was dug. On the staircased profile one layer of 40 cm (after compaction) was applied and compacted on each step of the stair case. Construction and compaction were done horizontally, not parallel to the slope.

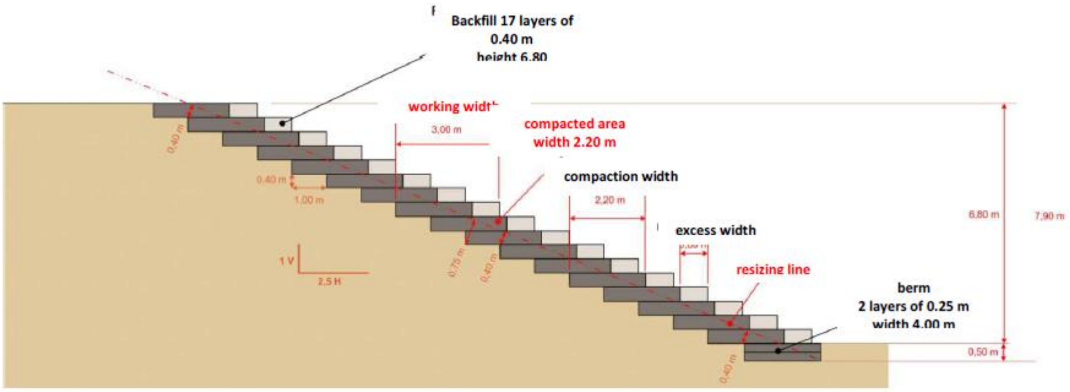

Figure 3-6 Construction of the lime treated cover layer at the Hedwigepolder.

After the steps were competed the slope was recut to a slope of 1 : 2.6 by scraping off the excess material making the slope smooth again.

Figure 3-7 Densification in horizontal layers in the Hedwigepolder.

On the advantages and disadvantages of these different ways of construction reference is made to Chapter 4.

3.5 Construction of test pad

The entire process of construction of the test sites was very thorough. The following points were examined:

- Verification of actual soil treatment conditions, and monitoring of the results obtained in terms of:
  - Moisture content of the natural soil before treatment.
  - Thickness of the natural soil layer before treatment.
  - Dry density of the natural soil before treatment.
  - Amount of water if moistening is needed.
  - Spreading of binding agent (mass per unit area).
  - Milling of the soil binding agent.
  - Mixer speed.
  - Mixing depth.
  - Moisture content of the treated soil.
- Verification of actual conditions under which work is done with treated soil, including compaction, and monitoring of the results obtained in terms of:
  - Provisioning methodology for leveling and adjustment.
  - Thickness of the bulk layers before compaction to reach the required compacted thickness.
  - Moisture content before compaction.
  - Compaction energy (compactor speed, number of passes).
  - Layer thickness after compaction.
  - Density obtained after compaction.
  - Peak resistance depending on the depth after compaction.

Depending on the observations made on the test pad, and the results of the checks carried out, the actual treatment and earthwork methods were confirmed or modified where necessary.

3.6 Quality control and monitoring procedures

Throughout the earthwork operations, the following factors were monitored on an ongoing basis.

- Conditions for placing natural soil onto the stockpile:
  - Shoveling over the entire height of the stock (visual monitoring).
  - Stirring, if necessary (visual monitoring).
- Work Area for Treatment (Sequential):
  - Thickness of natural soil conveyed onto the treatment platform prior to compaction (using surveyor data or on-board guidance system).
  - Moisture content of the natural soil prior to treatment (random sampling and rapid measurement by microwave drying).
  - Humidification of the natural soil if needed (visual monitoring, grading equipment, bin weighing if necessary).
  - Surveyor data of the soil layer before treatment.
  - Spreading of binding agent (bin weighing if necessary).
  - Amount of binding agent spread (spreader weight scale tickets).
  - Covering of the spreading strips (visual monitoring).
  - Mixing depth (visual monitoring, measurement with a soil auger).
  - Mixing speed (visual monitoring, timing).
  - Covering of mixing bands (visual monitoring).
  - Moisture content of the treated soil (random sampling and rapid measurement by microwave drying).
  - Milling of the treated soil (visual monitoring, random checks with sieving if necessary).
  - Thickness of the placed treated soil (surveyor data and visual monitoring).

- Work Site for Earthwork:
  - Interval between the end of treatment and compaction (time elapsed time).
  - Thickness leveled soil prior to compaction (using surveyor data or on-board guidance system).
  - Moisture content prior to compaction (random sampling and rapid measurement by microwave drying).
  - Compaction methods: number of passes, speed, sweep-plane (visual monitoring, timing, tachograph).

The moisture content was measured on the experimental pads immediately after leveling is completed, and prior to compaction. This was done by taking in situ soil samples, the moisture content of which was determined by weighing and immediate microwave drying (or after weighing and packing in a leakproof bag by laboratory drying). At least 2 samples per layer were taken per pad, distributed over the surface of the layer.

Data analysis was carried out for each working day or half-day.

The densification level was also monitored with in-place density and peak resistance measurements with a dynamic variable energy penetrometer. The results were analyzed with reference to the peak resistances corresponding to the typical case concerned (soil class - hydrological status) and by comparison with the peak resistances obtained on the compaction test pad. These measurements were carried out after the first two layers had been applied, at mid-fill, and on the last two layers applied.

A site logbook was kept and updated on a daily basis:

- Weather conditions (temperature, rainfall, wind).
- The schedule for the various jobs (start time, end time, metrics; cubatures):
  - Conveyance of natural soil onto the treatment platform.
  - Preparation of the natural soil before treatment.
  - Moistening.
  - Binder spreading.
  - Mixing.
  - Movement of treated soil.
  - Compaction.
- Surfaces and volumes applied layer by layer.
- Observations noted during routine monitoring (visual observations).
- Incidents encountered.
- List of checks carried out (type, location), with all associated information and data.

3.7 Required equipment

For operations some specific equipment is required. Experience shows that there were several (Dutch and Belgium) contractors with both the required equipment and with experience in Dutch dike reconstruction.

A view of the required equipment is shown in the next figures. From the figures an impression can be obtained about the entire operation chain.

Figure 3-8 Machine for dozing and levelling (Figure courtesy Lhoist).

Figure 3-9 Storage silo, Watering unit, lime spreader and mixer (Figures courtesy Lhoist).

Figure 3-10 Excavator and transport truck on the production platform.

Figure 3-11 Long armed excavator crane and compactor on the slope of the dike.

Figure 3-12 Compactor machine.

3.8 Concluding remarks

Both the Vlassenbroek site as the Hedwigepolder site were constructed with great care. The production of lime treated soil and the construction of the cover layer were carefully thought out, executed and monitored.

Operating with the proper water content for densification is one important aspect, but dosing and mixing and avoiding to large clogs of clay are also important. In practice several rounds of dosing, watering, mixing were required to get a good quality of material. Testing whether or not the material could be compacted to a required level before applying it on the slope of the dike is an essential step.

Both at the Vlassenbroek site and in the Hedwigepolder tests were done on the material on the slope to monitor the result. Especially the compaction was measured by nuclear density measurement and by Panda technique (energy probing). On the one hand this was done to test whether or not the results satisfied compaction requirements. The Panda measurement was also repeated after some time (three months for the Hedwigepolder, one and a half year for the Vlassenbroekpolder). In the case of the Hedwigepolder it was clear that the energy required to drive the probe into the slope had increased substantially. In the case of the Vlassenbroekpolder it was even almost impossible to drive the probing rod more than 20 or 40 cm into the slope. This is not to say that the density of the lime treated cover layer has necessarily increased, but curing (hardening thanks to the chemical reaction forming bonds between clay parts and lime) does seem to have increased the strength of the material.

Although density (or Panda results) is no direct measure for erosion resistance this gives some confidence that erosion resistance increases in time due to hardening of the lime treated clay. The overtopping test results in the Hedwigepolder suggest a strong relationship between compaction and erosion resistance. Therefore (even though it is expected that hardening in time enhances the properties of the material) great emphasis has to be made to the quality of the construction process to get optimal compaction and working of the soil mix to ensure reliable results.

4 Considerations on design and assessment of safety

4.1 Introduction

The experiments in the Hedwigepolder have shown that the parts of the slope where densification has been successful are very erosion resistant. The top of the compacted layers showed no significant erosion up to a simulated wave overtopping discharge of 190 l/s/m. There has been erosion of lesser compacted or not compacted material, but the erosion pattern shows that only the material between the well compacted steps of the staircase profile are eroded when the hydraulic load (coupled to the overtopping rate) is increased. This follows more or less the course as shown below.

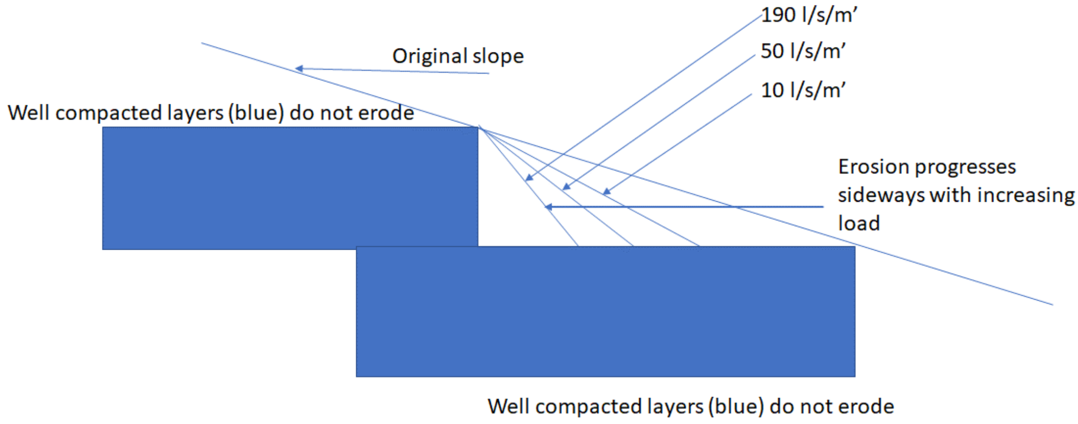

Figure 4-1 Schematic presentation of erosion as observed in overtopping tests Hedwigepolder.

Figure 4-2 Footprint of the compacting machine (well compacted layer does not erode) and steep clif in between (material erodes with increasing hydraulic load).

An important notion is that the steep cliffs did not erode significantly further in time during a specific wave overtopping condition. They form as a result of increasing hydraulic load, take their form and remain stable after that. Each higher load step (higher simulated wave overtopping discharge) steepens the cliff a little bit, but then does not erode any further during that condition.

The entire cover layer in this configuration did not fail, nor was there any indication that it would fail even at a higher load, because the erosion rate slowed or even stopped with increasing the load up to the maximum. Given the rate of erosion observed in the overtopping tests a thin cover layer would be sufficient to provide a small probability of failure of the cover layer due to erosion. As it appears there are practical reasons to use thicker layers in construction (for instance layers of 20 cm) and to use at least two layers of lime treated material above each other to give the construction a larger robustness.

In this chapter all the considerations to come to rules for design and safety assessment are given.

4.2 Design principle number one: the fail – safe approach

The simplest conclusion one can have about the experience of the overtopping tests in the Hedwigepolder is that (given the observation that the well compacted top layer of each compaction level does not erode) a safe design will always consist of several of these levels of well compacted lime treated clay. The idea being that even if one level fails because construction has been insufficiently careful, there will be a next layer that does not erode. The probability of one layer having a local weak spot is plausible, however, two levels having a weak spot at the same point will be extremely small.

The way of construction of both the Hedwigepolder as the Vlassenbroekpolder can satisfy this demand. There is always more than one level of compacted material that has to fail before the entire cover layer fails. For the Hedwigepolder the horizontal steps of 40 cm high should be build up in two layers of compacted material of 20 cm high. In the case of the Vlassenbroekpolder the entire cover layer is built up consisting of 4 layers of 30 cm thick, each of which of course has a top level of very well compacted material.

In view of application of lime treated material around objects (encroachments) or as a transition between cover protections it should be noted that an additional wave overtopping test with an extra hole in the lime treated cover layer did not lead to progressive erosion as long as the lime treated cover is not penetrated. Even if the object itself or the transition is damaged the lime treated cover layer can prevent further erosion.

4.3 Design principle number two: keep quality control parameters within the limits of experience at the Hedwigepolder

Given the experience in the Hedwigepolder erosion resistance and compaction are strongly related. For new projects a design principle could be that it should be demonstrated that compaction and hardening effect should be at least as good as that of the Hedwigepolder. Although there is not yet a scientifically sound relation between erosion resistance and measured density available, the observations during the wave overtopping tests do give confidence that the construction and execution have been sound and have delivered reliable results.

In the Hedwigepolder so called PANDA tests have been performed directly after construction and three months later during the overtopping tests. The interpretation of the results were compared to French standards. The compaction control using the PANDA light dynamic penetrometer is carried out in accordance with the French standard NF 94-105. As a result the quality of compaction can be divided into four categories:

Compaction quality	Minimum value of the average density
Q5	90 % of the proctor optimum (standard Proctor test)
Q4	95 % of the proctor optimum (standard Proctor test)
Q3	98,5 % of the proctor optimum (standard Proctor test)
Q2	97 % of the proctor optimum (enhanced or modified Proctor test) NB: Not the standard Proctor test

The density at the Hedwigepolder after construction could be classified as mostly Q4, after three months this was mostly Q3. Considering that the density of the soil between these two moments has not changed, the change is due to the curing effect; the soil has gained in strength Hence the material was weaker during the wave overtopping tests.

4.4 Design principle number three: until experience is abundant check the result in the field

The proposed design principles are based on limited experience. It is advised to extend this experience. With each new experience knowledge grows and confidence is gained. With this in mind it is recommended to combine application in a new project with the support of wave overtopping tests.

Although tests with the Wave overtopping simulator require a considerable effort, they are a reliable way to demonstrate that the constructed cover layer performs to requirements. Reliable correlations between quality control parameters and erosion resistance have not yet been established. The need to perform wave overtopping tests will probably decrease with each new project, but for the first couple of projects it is recommended to perform these supporting tests, at least until a reliable correlation is found between quality control parameters and erosion resistance.

4.5 Design principle number four: check for other failure mechanisms

The permeability of a well compacted lime treated clay cover layer is in the order of 10^{-7} to 10^{-9} m/s. This indicates a near impermeable material compared to sand or a clay layer on a sand core. There is a possibility that water pressure can built up under the impermeable cover layer. This possibility has to be investigated for each particular situation and, if needed, mitigated. This can be done in three ways:

- Through measurements and/or groundwater flow calculations it can be shown that this is no threat (in better terms: the possibility that this leads to dangerous situations is small enough).
- A practical approach is to start the construction of the cover layer on a staircased profile (such as has been done in the Hedwigepolder). This is a method that is frequently used in dike renovation to prevent newly constructed layers sliding over the existing dike. A check has to be done for both sliding and uplifting of the cover layer.
- Another practical approach (for instance if the construction as used in the Vlassenbroekpolder is used) is to apply drainage near the toe. This drainage is to prevent water pressure built up beneath the cover layer.

Application on a smaller scale, around objects or as a transition between cover layers, requires a carefull design and construction, also considering all possible items that can go wrong. It would be recommendable to share some examples of actual situations and the way this application can be designed both in a practical as in a robust way.

5 Guidelines and remarks on maintenance aspects

5.1 Introduction

The main purpose of lime treated cover layers is to ensure safety against flooding. There are a number of other subjects that have to be taken into account when considering applying this new technique. This is the subject of this chapter.

5.2 Grass cover

It is difficult for grass to grow on a lime treated clay layer. In the Vlassenbroekpolder, part of the investigation is to use different types of grass seed to see which type of grass seed has the best result. The research is on the initiative of Flanders Hydraulic Research (FHR). After a couple of years it is planned to perform overtopping tests on the grass and lime treated clay layers. The grass has been there since one and a half years. It is difficult to get a good grass cover on the lime treated material, see Figures below (lit. [24]).

Figure 5-1 Two examples of grass on lime treated material (figures courtesy of FHR).

The reason that grass has difficulty in growing on lime treated soil is that the soil hardens, making it difficult for the grass roots to grow into the depth. As is shown in lit. [14], see figure below, the roots tend to divert sideways, and do not grow into the lime treated soil.

Fig. 6.10
After natural seeding, roots cannot penetrate the lime treated soil and are diverted to the surface of the embankment (left); same situation with buddleia ("butterfly bush") (right)

Figure 5-2 Roots cannot penetrate the lime treated soil (Source ICOLD, lit. [14]).

In most cases it is considered desirable to have a grass cover for landscaping, recreational and agricultural reasons. There is however no objection to apply a layer of top soil on top of the lime treated clay layer to support a vegetation. In this way a grass cover can develop. The grass cover is not necessary for safety reasons, so maintenance of the grass cover has no restrictions coming from safety against flooding. Besides grass all kind of herbs can grow on the dike, enhancing the ecological value of the grass cover. It should be noted that in practice it is not unusual to use a layer of top soil for grass to grow if the clay on the slope is suitable for use on a dike, but less suitable for a good grass cover to grow on.

5.3 Animal burrowing

Animal burrowing in dikes is becoming more and more of a problem. Especially if the animals are protected species, like beavers and badgers, there is no alternative but to try to prevent animals from burrowing into dikes. Beavers, rats, rabbits and badgers are among the animals that can cause serious damage to levees. Some literature to confirm that animals can seriously harm the integrity of dikes can be found in lit. [25] and [26].

There is little or no literature on the question frequently asked by dike managers: “does lime treatment prevent animals from digging into the levee?”. It seems likely that a well compacted layer of lime treated clay is hard to dig in by animals. The best reference of this is shown below, and stems from lit. [14].

Fig. 6.11
Attempt to dig a burrow in a levee treated with 2.5% lime (left)
and rabbit burrow dug in an untreated levee (right)

Figure 5-3 Different results of animal burrowing in lime treated soil and untreated soil (source lit. [14]).

It seems likely that an ongoing layer of hardened soil will prevent animal burrowing. If the main purpose (or a desired effect) of lime treatment is to prevent animal burrowing the construction of such a layer must be uninterrupted, meaning that it consists of layers constructed alongside the slope (the Vlassenbroek principle). A comment on that may be that curing of the lime treatment may not perform well if the layer is exposed to air. This is true for the first few centimeters below the surface of the slope, which are impacted by external elements and by a higher carbonation rate (preventing the desired pozzolanic reactions). It is advised to monitor this, or use at least two layers, so it is ensured that at least one layer will perform well.

5.4 Long term behaviour and resistance to weather (drought, frost)

The ICOLD publication on Cemented Material Dams (lit. [14]) discusses the experience with long term behaviour and resistance to weathering effects. Cemented materials cover both cemented soils as lime treated soils. The rehabilitation work of the Friant-Kern Canal is the best referenced example of a lime stabilized hydraulic structure. After more than 40 years the

behaviour of the repaired canal lining sections is still excellent, showing no erosion. Temperatures near the canal ranged from -6 to 40 degree Celsius.
There are also examples from the United States, where cemented soil and lime treated soil was used with excellent results until today.
Another example can be found in the Czech Republic where the 15 m high levee was protected with lime treated soil was done in 2003.
In ICOLD bulletin no 54 one example of frost damage was reported to a maximum depth of 15 cm.

Long term behaviour seems to be no problem in terms of deteriorating properties according to documented experiences found so far (up to 40 years). Some damage might occur in case of frost/ defrost cycles. These findings can be a reason to apply a thicker layer of lime treated material or to apply a top soil layer for grass to grow on to diminish these effects.

A different (long term behaviour) question asked by dike managers is “Can lime treatment help against drought issues in dikes?”. The first remark on this is that has not been researched. A second remark is that problems with drought in the Netherlands usually concern peat dikes. There is some literature on soil stabilization of peat (using both cement as lime), but the question of additives solving drought issues in peat dikes has not been researched as far as we know.

5.5 Environmental issues

Environmental issues are dealt with in the ICOLD Publication On Cemented Material Dams, Appendix C (lit. [14]). The use of lime treatment on the direct environment through leaching and groundwater flow appears to be very limited. The lime treatment does have an effect on the pH value of the treated soil, but the effect on the direct environment is limited to a short distance. The chemical reactions seem to be stable within the treated soil. In view of the fact that there are numerous projects that use cement and lime as soil improvement techniques it would appear that there are no major environmental issues concerned.

The production of lime can generate substantial amounts of CO_2 gasses. On the other hand, the use of lime in soil treatment appears to bind greenhouses gasses and have a positive effect. A positive effect is the use of local soils with lime additives instead of borrowing and transporting large quantities of clay of superior quality. Studies concerning the Life Cycle Analysis (LCA) of different solutions (both traditional and lime treatment) have been started by Lhoist, but at the date of appearance of this report have not been published yet, so this paragraph is somewhat tentative.

An important aspect regarding Dutch regulations is the amount of lime added. As it stands now, adding 5 % or less lime to a natural soil means that the result is considered a building material. That is an important qualification, because that means that the material can be (re)moved and re-used as normal soils. Mixtures using substantially more than 5 % added lime may be classified as ‘chemical’ or even chemical waste. This has serious repercussions for the removal of the material. It is therefor advised to limit the lime dosage to 5 % or less, or contact the proper authorities about legislation and permits.

5.6 Maintenance of cover layer and extendability

It is not to be expected that maintenance of lime treated clay covers is necessary. It seems that strength of the cover layer will only grow in time.

If it appears that a treated cover layer does not perform well, it is not possible to extend the working by simply adding lime. The only way to get a proper cover layer is by removing the constructed cover layer and replacing it with a properly handled and compacted new layer, or construct a new layer on top of the old one.

The same will have to be done after the lifetime of the cover layer has expired. After how many years a lime treated cover layer is at the end of its' lifetime is hard to say. Probably the lifetime of the cover layer will exceed that of the dike renovation (usually 50 years).

During its life time care has to be taken when cables and/ or pipelines and/ or road maintenance requires digging through the material. Digging may prove to be more difficult. Repairing the dig will require removing the material from the site and replacing it with well compacted lime treated clay or another erosion resistant solution.

5.7 Deformation issues

There can be some concern that the lime treated cover layer will become very strong and rigid when after some time the curing has done its work. This could be comparable to a non-reinforced concrete slab. If the subsoil subsides the slab can not follow this and hollow spaces below the cover layer could form and/ or the cover layer could crack. Also, around houses, connections of pipes for water and gas, could fail if the cover layer does not subside the same as the surrounding soil. As there is little experience with these issues it is advised to carefully monitor and inspect for deformation issues. If it is to be expected that housing and surrounding soil (lime treated clay) can have different deformation special attention has to be paid to the connection of cables and pipelines to the house.

5.8 Cost – Benefit analysis

The benefits of the lime treatment technique are numerous and have been discussed ample in this handbook. Among others:
- Saving houses and objects from removal for dike renovation.
- Optimization of use of the natural materials available on site.
- Reduction of external borrowing.
- Reduction of required crest height (less cubic metres of clay required, as well as a smaller footprint for the dike base).
- Reduction of heavy trucks traffic.
- Reduction of cost and duration of earthworks.

To some extent lime can be used to improve the workability of (too wet) clay and reduce the construction time. It is not recommended to work under too wet conditions and with too wet clay however.

The matter of cost had not been mentioned yet in this handbook. The reason is that the costs are not (or not mainly) dependant on material cost for the lime to be added. The main cost lies in the required operations to get a good quality lime treated clay cover. These operations are quite extensive compared to simply shovelling and compacting clay. The question to what extent an efficient process can be designed for construction of the lime treated clay cover will to a great extend determine the cost level.

The choice for a lime treated clay cover layer should for each project be based upon a cost - benefit analysis.

6 Concluding remarks

After a literature survey and laboratory research. large scale testing has confirmed the viability of the technique of lime treatment of clay to enhance the erosion resistance of the cover layer of a dike slope under wave overtopping conditions. The next step to be made is from ‘experiment’ to ‘project’. It is possible that scaling up from experiment to practical application will possibly raise new issues that have not come up yet during the research so far. Examples of such issues are:

- Can construction of lime treated covers be scaled up to project size with similar quality as in the Hedwigepolder and how can the required quality be assured?
- If lime treatment is accepted as an alternative providing sufficient safety against flooding, how does lime treatment compare to more traditional design options?
- After effectiveness and comparison turn out favourable, what questions in regard to maintenance and practical applications do arise if a design for project application is made?
- Establish a design method for the required crest height using lime treated soil as a revetment, taking into account the observed strength in tests and uncertainties in both the strength and load.

Answers to these questions can be provided if project managers will work out lime treatment as an alternative within their own project. A statement could be that it is no longer a matter of further scientific research, but a matter of building confidence by applying the method in actual dike reconstruction projects. Lime treatment is considered a possible solution for projects with a crest height issue (or projects where this will become an issue in the future) or for application around objects or transitions in cover layers to prevent erosion.

Other applications may be promising, but need further research.

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