CIP 2018 Water Safety: Reinforcing dykes with lime

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Inhoud

1 Introduction

The concept of clay treated with lime is an accepted and certified technique in France for application in infrastructure projects, especially in the construction of dikes/dams. Soil improvement with lime treatment can therefore be seen as an innovation in dike upgrades also in the Netherlands. Within the framework of CIP 2018, a research has been conducted with the aim to provide information on the application of this technique and assess whether its use can be beneficial in the construction/maintenance of dikes in The Netherlands. This report is structured in four main chapters each providing detailed answers to the following questions:

Chapter 2: Why do the French use specifically the lime – treatment technique?
(*Waarom hebben de Franse specifiek deze oplossing gekozen?).*

Chapter 3: What is the French experience in regards to the use of lime in soil?
(*Wat zijn de Franse ervaringen met het toepassen van kalk?).*

Chapter 4: Is the use of lime a sustainable, environmentally friendly, cost effective technique?
(*Is het toepassen van kalk milieuvriendelijk, duurzaam, goedkoop/duur?).*

Chapter 5: Is lime treated clay suitable to be used as a reinforcement of grass covers?
(Hoe betrouwbaar is deze vorm in het verhogen van de erosiebestendigheid van gras?).

Chapter 6: Can the lime – treatment technique be beneficial for use in dike upgrades in The Netherlands?
(*Kan deze specifieke oplossing ook voor Nederland toepasbaar zijn?).*

The original description of this project is given below (in Dutch).

Deelproject 3: Versterken grasbekleding met kalk	*Onderzoek naar versterking van grasbekledingen nabij dijkmeubilair om deze erosiebestendiger te maken. Het plan is om eerst de Franse ervaringen te verzamelen en te inventariseren wat de mogelijkheden in Nederland zijn. Onderzoeksvragen zijn:* - *Wat zin de Franse ervaringen met het toepassen van kalk* - *Waarom hebben zij specifiek deze oplossing gekozen?* - *Hoe betrouwbaar is deze vorm in het verhogen van de erosiebestendigheid van gras* - *Is het toepassen van kalk milieuvriendelijk, duurzaam, goedkoop/duur?* - *Kan deze specifieke oplossing ook voor Nederland toepasbaar zijn.* *De POV DGG zal pas in 2019 hieraan verder werken. In tweede helft van 2018 afstemming hebben met de POV. Gegeven het momenteel beschikbaar gestelde budget wordt begonnen met het beantwoorden van de eerste 5 onderzoeksvragen*

It is important to notice that, compared to this first project description, the scope of the current report has been widened from reinforcement of only grass revetments to a wider range of possible applications of lime in clay, as it is considered beneficial to state in this report the full potentials/applications of the lime treatment technique in dike construction.

2 Why do the French use specifically the lime – treatment technique?

2.1 Introduction

Geotechnical engineers in France and worldwide are aware of the benefits of the lime – treatment technique in soil improvement, mainly in road applications. In summary:

- Lime treatment influences the physical, compositional and compaction characteristics of the soil. Lime treatment in cohesive soils generally causes a decrease in plasticity and compressibility and an increase in pH values and volume stability against swelling and shrinkage. Furthermore, the addition of lime transforms a clay soil which would otherwise soften, collapse and disperse in water into a firm, water resistance material while the workability of the soil is improved as the result of the low plasticity.
- The addition of lime to cohesive soils increases their optimum moisture content and reduces the maximum dry density for the same compaction effort.
- Clay generally show a significant increase in shear strength, undrained friction angle and cohesion when they are treated with lime.
- Lime - treatment dramatically modifies the erosion parameters with the lime - treated soils exhibiting a high external and internal erosion resistance.

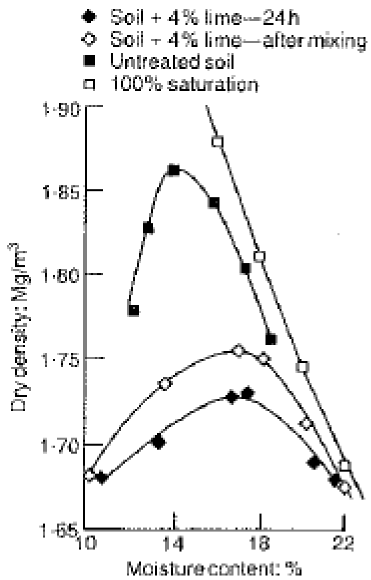
The last 30 years, geotechnical engineers, transposed the above benefits in the field of hydraulic structures with the lime - treatment technique used in France for the construction of dams and dikes. The French mainly see two benefits of this technique for use in dams and dikes. That is:

- Adding lime to the clay makes the material amenable to processing when its initial water content is high. In addition, the lime – treated material is less prone to swell and shrink after inclusion in the dike when water levels fluctuate. Furthermore, the use of lime – treated soils increase the mechanical stability, water tightness and the resistance against internal erosion of dikes /dams.
- Depending on the hydraulic conditions, erosion protection may be drastically reduced as the lime – treated soil is erosion resistant. Consequently, there is a high potential that surface protections such as rip-rap and gabions may not be required anymore with benefits being high with respect to cost and environment.

A number of studies/applications exist in the literature that deal with lime - treatment technique and how this technique influences the mechanical behaviour and the physical, compositional and compaction characteristics of lime - treated soils.

Known facts in regards to the lime treatment technique are:

(1) The addition of lime to cohesive soils increases their optimum moisture content and reduces the maximum dry density for the same compaction effort (Bell and Coulthard, 1990; Herrier et al., 2018). The changes in the optimum moisture content and maximum dry density are proportional to the amount of lime added (the more lime added, the lower maximum dry density and the higher optimum moisture content). A typical example of the influence of lime treatment on the compaction optima of a clayey soil is shown in Figuur 2.1



Figuur 2.1. Compaction curves for treated and untreated soils (after Bell and Coulthard, 1990).

(2) The lime-treated soils show a complex behaviour that is affected by many factors such as the physical-chemical properties of the soil, its porosity and the amount of lime, curing time and moisture content at the time of compaction (Mitchell, 1981; Consoli et al., 2008). Ideally, the quantity of lime to be added should be related to the clay mineral content of the soil, as the clay minerals are needed for reaction. According to Ingles (1987) as a rule of thumb in practice is to allow 1% by weight of lime for each 10% of clay fraction in the soil. The lower limit of lime additive appears to be 2%. At the other extreme, because it is exceptional for the clay content of a soil to exceed 80%, it is unusual to require an addition of lime above 8%.

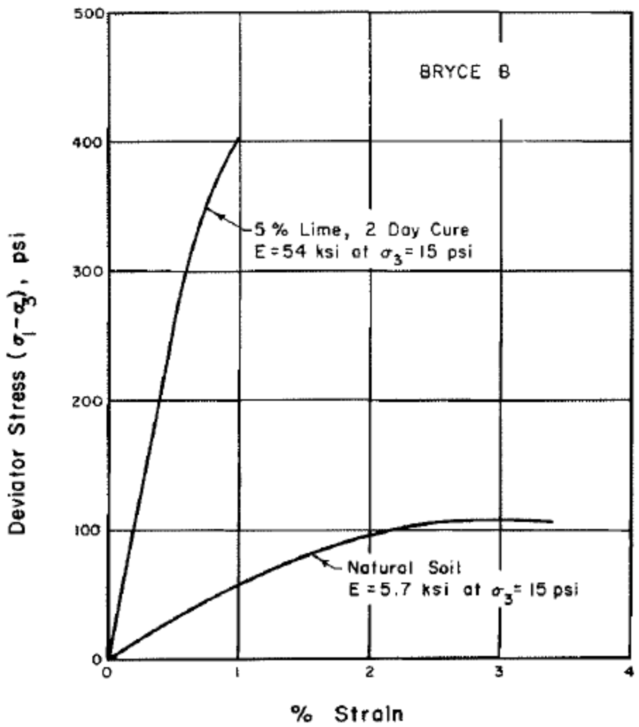
(3) During the lime hydration and modification process the inter-aggregates pore sizes and the percent of sand particles increases. This increase gives rise to the hydraulic conductivity during the hydration and modification phase while during the stabilization process lower hydraulic conductivity values are expected as the size of the inter-aggregates pores decreases. Experience in the use of lime-treated soils has shown, however, that when the lime-treated materials are compacted via kneading compaction at a moisture content above the Optimum Moisture Content (OMC), the permeability of the lime-treated material is equivalent to that of the natural compacted material (McCallister, 1990; Le Runigo et al., 2011; Herrier et al., 2012).

(4) The lime treatment has a favourable effect on the compressibility of the material which is mainly reduced compared to that of the untreated material up to the yield stress value of the lime-treated material (Herrier et al., 2012). This is because lime treated materials can be considered as “cemented” materials. Above a specific yield strength value the cohesive bonds induced by lime action are destroyed and the behaviour of the material becomes similar to that of an untreated soil. Lime treatment increases the yield stress of soils. This is consistent with the behaviour of cemented geomaterials (Mavroulidou et al., 2012).

(5) After treatment Lime-treated soils have higher pH values than natural soils. The pH value of lime treated clays was found to be >10. Marks and Haliburton (1972) stated that pH values >10 are required for the pozzolanic reaction of lime with soil that leads to strength

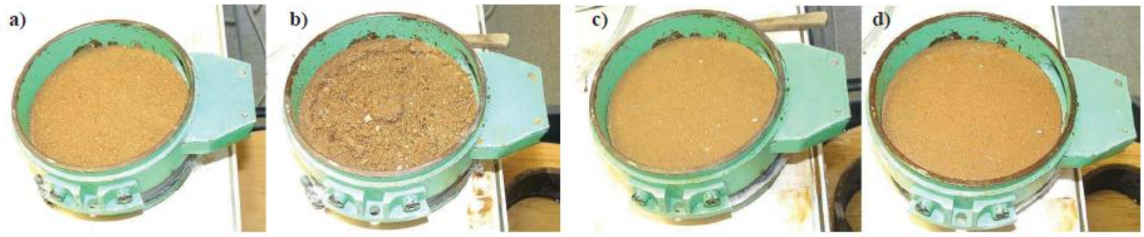
improvement. It should be pointed out that in regards to vegetation, agronomists are of the opinion that no plant life can be sustained on hydraulic constructions because of the cementation of the lime treated soils and the high pH values. Consequently for i.e. the lime treated dikes a topsoil layer can be placed on the structure before seeding (Perry, 1977).

(6) Clay generally shows a significant increase in shear strength, undrained friction angle and cohesion when they are treated with lime. This increase is more pronounced as lime content and curing time increases as long as the amount of lime is sufficient to cause the pozzolanic reaction required to form adequate cementitious products (Thompson 1966; Tuncer and Basma, 1991; Mavroulidou et al., 2012). Figuur 2.2 shows typical stress – strain curves of an untreated and lime- treated clay tested in the triaxial cell. Despite the beneficial effects of lime treatment on the soil strength properties, it was observed, however, that lime treatment increases the material brittleness with failure occurring abruptly at a peak compressive load under relatively low axial strains. Nevertheless, by increasing the lime percentage and curing time it is possible to postpone the brittle behaviour at higher strains; higher than the ones of the untreated samples.

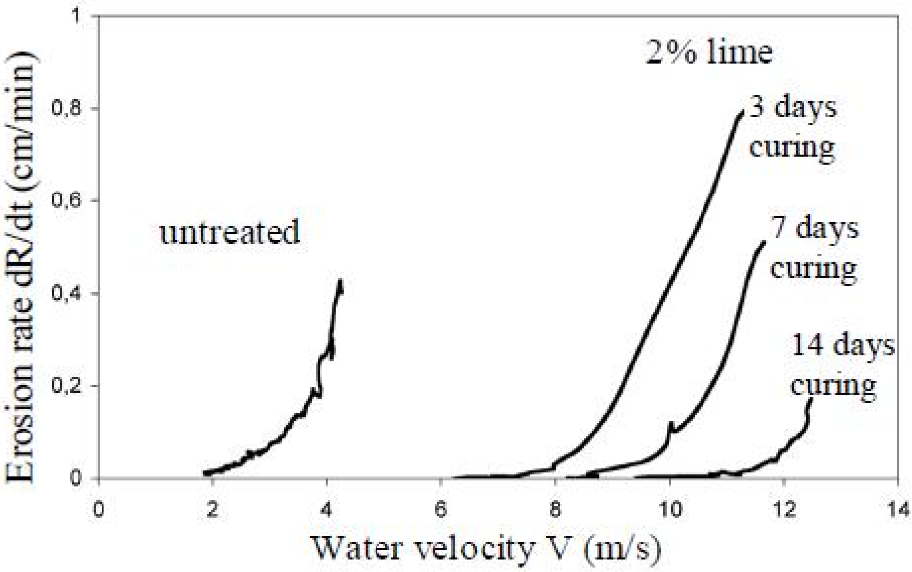


Figuur 2.2. Typical stress – strain curves for natural and lime-treated soils (after Thompson 1966).

(7) Laboratory and full scale experiments showed that lime-treatment dramatically modifies the erosion parameters with the lime-treated soils exhibiting a high external and internal erosion resistance. Chevalier and Herrier (2012) used have evaluated the external erosion resistance of a silty soil via the performance of Mobile Jets Erosion Test (MoJET). It is evident in Figuur 2.3 that for untreated soils erosion occurs whereas no significant erosion happens for the treated material. Herrier et al. (2012) internal erosion resistance of untreated and lime – treated clayey silt soils via the performance of Hole Erosion Test (HET). The test results as presented in Figuur 2.4 show that the internal erosion characteristic of a lime treated soil are dramatically improved compared to the untreated material.



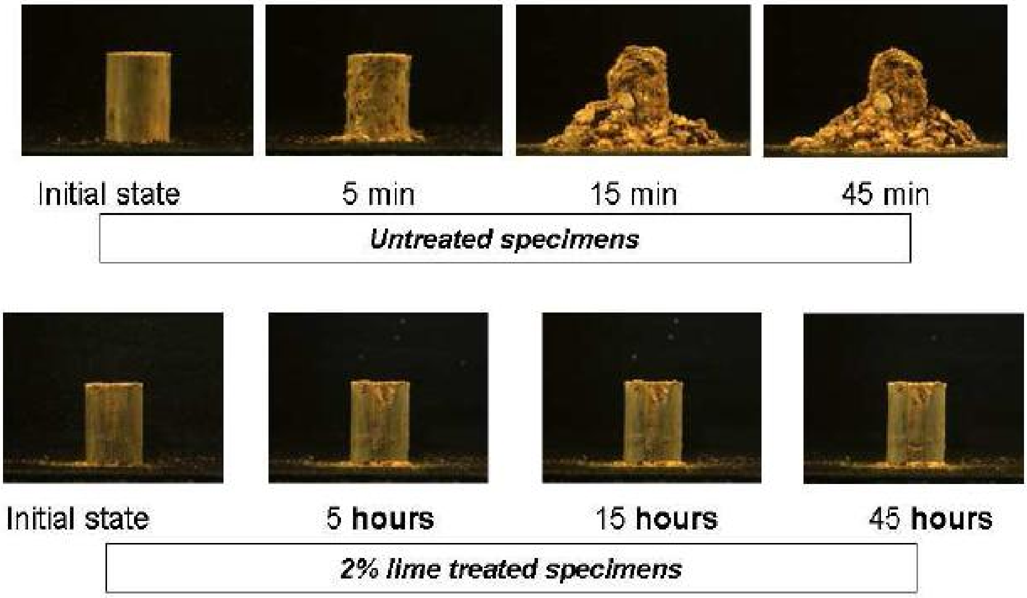
Figuur 2.3. Examples of tested specimens by (a) and (b) untreated silt before and after test; (c) and (d) lime – treated silt before and after test (after Chevalier and Herrier, 2012).



Figuur 2.4. Hole Erosion Test (HET): erosion rate vs water velocity for untreated and 2% lime treated clayey silt from a Camargue dike; without the presence of grass cover (after Herrier et al., 2012).

(8) Lime – treatment of soils reduces their shrinkage and swelling potential (Mateous, 1964; Bell and Coulthard, 1990; Bhasin, 1978; Herrier et al., 2012). Limiting the shrinkage of the soil will help in restraining the formation of cracks in hydraulic structures i.e. after a drought period.

Increasing the percentage of lime also decreases the percentage of dispersion. The ASTM D6572-06 standard "crumb" test was used by Herrier et al. (2012) to demonstrate the non-dispersive behaviour of an initially dispersive silty soil treated with 2 – 3% quicklime. As shown in Figuur 2.5 the untreated material collapsed after 15 minutes immersion whereas no degradation occurred for the lime treated sample even after 45 hours immersion.



Figuur 2.5. Crumb test performed on untreated and treated with 2% lime silty soil samples (after Herrier et al., 2012).

(9) Increasing the percentage of lime causes a reduction in the plasticity index (decrease of liquid limit and increase of plastic limit) (Croft, 1964; Brandl, 1981; Bell and Coulthard, 1990; Tuncer and Basma, 1991).

(10) The properties of soil-lime mixtures are influenced by several factors such as the soil type, type of lime and amount added, curing time, placement method, moisture content, unit weight and time elapsed between mixing and compaction. Consequently, it appears that there is no single recipe for soil lime - treatment. Most importantly, this technique depends primarily on whether a particular type of soil can be improved. The effectiveness of this technique depends on the predominant soil type and in particular the type and quantity of clay present in the soil. For instance, treatment with lime serves no useful purpose in those soils which are more or less devoid of clay or highly organic soils. On the other hand, lime usually reacts with most soils with a plasticity index ranging from 10 to 50%.To this end, the design of any hydraulic structure can only be done with proper knowledge of the properties of the lime-treated materials considering the encountered soil conditions.

(11) The effectiveness of stabilization of a clay soil by the addition of lime is influenced by the percentage of organic matter present in the soil. This is because organic matter delays or inhibits hydration of the lime. This has a significant effect upon the unconfined compressive strength developed by soils treated with lime. Tabel 2.1 shows that the gain in the Unconfined Compressive Strength strength (UCS) of 8% lime treated samples, cured for a period of 7 days, is substantially lower for the soil with the highest organic matter percentage. This reduction is probably related to buffering capacity of the organic matter that is present, or the fact that organic matter reacts with the lime, rather than the clay minerals. Since typical Dutch clays have an organic content of approximately 2 – 5%, it is consider essential to assess the effectiveness of the lime treatment technique when this is used on such soils. It should be mentioned that it is not reported in the literature what the organic content of typical French clays is, therefore, no direct comparison with Dutch clays can be consider.

Tabel 2.1. Effect of organic matter on UCS strength of soil treated with lime (after Bell and Coulthard, 1990).

Soil	Organic matter: %	Strength: kN/m²*	
		Untreated	8% lime
Dark brown silty clay (CHO)†	14	105	224
Brown silty clay (CH)†	2	485	1610
Heavy black clay (CH)†	0·2	350	4680

* 7 day unconfined compressive strength at optimum moisture content.
† British Standard classification symbols: CHO organic clay of high plasticity; CH clay of high plasticity.

(12) In regards to the use of lime-treatment technique in hydraulic structures it was concluded that through lime treatment, the properties and behaviour of the treated materials can meet three basic factors insuring the construction, design, durability and limited maintenance of a hydraulic earthen structure. That is low permeability, mechanical and volume stability, external and internal erosion resistance. Additionally, the lime treatment technique is reported to decrease the overall construction costs, offering the possibility to reuse local soils with poor initial engineering properties. In the light of the above, lime-treatment is considered to be a promising technique for the construction and maintenance of dikes, levees and dams.

2.2 Conclusions

The lime stabilization technique has proved to be an effective technique in improving the engineering properties of cohesive soils and has been successfully used in France in road and hydraulic structures construction. In addition, literature studies have highlighted a series of benefits of this method in improving the mechanical behaviour and the physical and compaction characteristics of lime – treated soils. Consequently, lime treatment technique can be seen as a promising technique in dike construction/maintenance in The Netherlands. It is essential, however, to evaluate the effectiveness of this technique when applied to typical Dutch clays which have a relatively high organic content.

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3 What is internationally the experience in regards to the use of lime in soil?

3.1 Introduction

The application of lime treatment technique for soil improvement has been successfully used for roads, highways and platforms constructions in France. In the recent years, however, attention is given in the use of lime in hydraulic structures (dikes, levees, dams). Consequently, various research French institutes (IFSTTAR, IRSTEA CER, Cemagref, EDF, SEREMA, Ecole Centrale Paris) and French Universities are now investigating the influence of lime in soil. As part of this investigation, full - scale dike applications has been performed or plan to be performed in France coming years. Typical examples are presented in what follows.

3.2 Experimental full scale applications in France

3.2.1 DigueELITE and Digue2020 (2015, 2019)

As part of the French research and development programs DigueELITE (www.digueelite.fr) and Digue2020 (www.digue2020.fr), two experimental platforms are built in the South of France to study in real scale the behaviour of embankments in response to hydraulic loadings. Both platforms are made of one part built with natural and local material and another part built with the same material treated with lime. The construction of DigueELITE platform was completed in August 2015 and the Digue 2020 platform will be built in 2019. In Digue ELITE program, the experimental dike is part of the rehabilitation work of the dike network along the river Vidourle while the Digue 2020 platform will be built on an existent dike.

The treatment with lime is used in these two experimental platforms to allow a comparative study of non-treated and treated soil behaviour. Emphasis is given in assessing the resistance against external erosion and the evolution of parameters such as water content, temperature, pressure and suction during the dikes’ lifetime (aspects such as grass cover and wave loading were not taken into account). The final objective of the research program was to provide guidelines for designing innovative overflow resistant earth-fill dikes.

The DigueELITE experimental earth fill dike made of lime-treated silt is 50 m long and 3.5 m high. The dike was tested against external erosion by applying steady artificial overflow. The part of the dike constructed with non - treated soil showed several erosion channels in contrast to the lime – treated part of the dike (see Figuur 3.1).

For further information the reader can refer to Nerincx et al. (2016).

Figuur 3.1. ABOVE: Non – treated soil at left hand side, with erosion channels; lime treated soil at right hand side, with no erosion channel. BELOW: Contrast of extrernal erosion resistance between non treated soil (upper part) and lime treated soil (lower part) (after Nerincx et al. 2016).

3.2.2 CER (2011)

Two experimental full scale dikes were constructed at the CER (Research and Experimentation Centre) site in France in 2011. The aim of these experiments was to evaluate the short and long term development of mechanical, stability, permeability and erosion resistance properties of lime - treated soils through in situ and lab tests (aspects such as grass cover and wave loading were not taken into account). For further information the reader can refer to Charles et al. (2012). For the construction of these dikes silty soil from Marche-les-Dames in Belgium was used. The geotechnical characteristics of this soil are given in Table 3.1. This material was deemed to be unsuitable for use in hydraulic structures. To improve the quality of the material, the lime treatment technique was applied. Treatment was achieved with 2.5% of Proviacal DD produced by Lhoist.

Table 3.1. Geotechnical characteristics of Marche-les-Dames silty soil

CLAY FRACTION (<2 µM) (%)	SILT FRACTION (2 TO 50 µM) (%)	PASSING THROUGH 80 µM (%)	METHYLENE BLUE VALUE (G/100 G)	PLASTICITY INDEX (PI) (%)	MOISTURE CONTENT AT SAMPLING (%)
12	82	99.5	2.50	7 to 8	17.9

The first dike was built using the lime treated soil. This dike is 28.2 m long, 10.3 m wide at its base, 21 m long and 4 m wide at the top with a final height of 1.8 m. The dike is divided into 5 m long sections which correspond to three test campaigns at 28 days, 180 days and 1 year after construction of the dike. The second dike was build using untreated material. Its total height is 0.9 m with a length of 10 m and a width of 2 m.

Test on the site and tests in laboratory were performed for assessing the mechanical properties of the lime – treated soil at construction, 28 days, 180, one year and two years after construction of the dikes. The results from these tests are summarized in Table 3.2 and show the benefits of lime – treatment in improving the material's mechanical properties. Specifically, this table shows the evolution of the bearing capacity, penetration resistance, pressuremeter and dilatometer tests. Laboratory triaxial tests were also carried out on core samples in order to highlight the evolution of cohesion parameters and shear strength.

Table 3.2. Summary of mechanical properties of untreated and lime treated soils.

				UNTREATED SILT DIKE	LIME-TREATED SILT DIKE				
	Test type		Unit		At construction	28 days	180 days	1 year	2 years
	IBI Proctor needle		%	11	20				
	Light Felling Weight Deflectometer (FDW)		MPa	9 to 26	35	250		280	
ON SITE TESTS	Pressure meter	Pf*	MPa	0.15		2.53	2.51	3.65	
		Pl*	MPa	0.25 to 0.36		3.77	4.23	±6	
		E_M	MPa	1.6 to 2		38.6	52.7	±80	
		E_M/Pl*		5.5 to 6.5		10.2	12.5	±13	
	Dilatometer	Cyclic E young's modulus	MPa				400 to 480		640 to 960
		Dilatometer module G	MPa				50 to 90		160 to 270
TESTS IN LABORATORY	Triaxial (CD)	Cohesion (residual)	kPa	5 to 10		41 (at 75 days)	61 (at 195 days)	75	
		Friction angle (residual)	Deg.	35		39	39	39	
		Small deformations secant modulus	GPa			0.7 to 1		1.16 to 1.43	

Permeability measurements were also taken on the site and in the laboratory. These measurements are summarized in Table 3.3 and show that the permeability levels of the untreated and lime-treated material are approximately the same regardless the time interval after construction the dikes. It should be highlighted that the moisture content of the lime-treated materials was 1.6% above the Optimum Moisture Content (OMC) defined with the standard Proctor test. The target dry density after compaction is established at 95% of OPN density. The homogeneity of the lime-treated material was monitored in a mobile mixing plant [see Figure 3.2(a)]. The untreated and treated soil was compacted via kneeding compaction with a sheepfoot roller compactor [see Figure 3.2(b)]. This implementation procedure ensures that a permeability equivalent to that of the natural compacted material can be obtained.

Table 3.3. Summary of permeability measurements of untreated and lime treated soils.

			UNTREATED SILT DIKE	LIME-TREATED SILT DIKE		
Test type		Unit		28 days	180 days	1 year
On site	Variable load	m/s	-	0.8 10[illegible]	2 10[illegible]	8.5 10[illegible]
	Constant load	m/s	1.5 10[illegible]	2.8 10[illegible]	9.4 10[illegible]	1.2 10[illegible]
In laboratory	Triaxial CD	m/s	1 10[illegible]	10[illegible] to 10[illegible]	1 10[illegible]	1 10[illegible]

In situ erosion jets tests (MoJET) and hole erosion tests (HET) performed in the laboratory on core samples at the time intervals of 28 and 180 days. The results given in Table 3.4 show the erosion resistance increases considerably for the lime-treated soil.

Figure 3.2 (a) Production of treated material at the plant and (b) compaction with a sheepfoot roller on lime treated dike.

Table 3.4. Summary of Hole Erosion Test (HET) measurements of untreated and lime treated soils.

			UNTREATED SILT DIKE	LIME-TREATED SILT DIKE	
Test type		Unit		28 days	180 days
HET (Hole Erosion Test)	Critical stress	kPa	179	> 1,000 (not reached)	± 800 (1st test) > 1,000 (not reached, second test)
	Erosion coefficient k_{er}	s/m	9.8 10[illegible]	Non measurable	-
	Erosion index (= -log k_{er})	-	4.04	Non measurable	-

Figuur 3.3 provide a significant overview of the benefits of using lime – treatment in terms of external erosion. This figure shows the untreated and treated samples after a mobile water jet test. During this test an eroding unit projects water jets perpendicular to the soil surface which one wants to measure the sensitivity to erosion. Deep holes are created from water jetting in the untreated sample as can be seen in the left side graph in Figuur 3.3.

Figuur 3.3. Appearance of the embankments after the external erosion tests: untreated embankments on the left and treated with lime on the right.

Besides France, the lime treatment technique was successfully applied to a variety of projects worldwide to submerged or partially submerged structures (Gutschick, 1986, McDaniel, 1979). A typical example is the extensive use of lime treatment in construction and repair work in dikes, levees and earth dams where piping and erosion problems in dispersive soils and sliding problems in clays have been encountered. Case studies of such projects in which the lime-treatment technique is applied are presented and discussed in what follows.

3.3 Experimental full scale applications worldwide

3.3.1 Mississippi River levees

A significant number of slides had occurred in the riverside slope of the Mississippi river levees. These levees were constructed with riverside slopes that consist of high plasticity clays. The slides typically developed in the riverside slopes which are usually steeper than the landside slopes. Failure of the slopes was triggered by heavy rainfall after the levees' materials were weakened from weathering effects (during seasonal shrinkage and swelling). Prior to the early 1980's the method for repairing these slopes normally consisted of excavating the failed material and rebuilding the slopes on a flatter angle with new material from a borrow source.

Atterberg limit tests on soil from the slope indicated that materials susceptible to slides may be characterized as having a liquid limit higher than 60 and a Plasticity Index, PI, greater than 40. Since 1985 the lime treatment technique has been extensively applied to repair slopes because a material having a PI less than 40 was not available within a reasonable distance from the levees. As discussed in Section 3.2, the addition of lime causes a reduction in the plasticity index values and could therefore be a promising technique in reducing the amount of slide failures.

The optimum amount of lime for the high plasticity clays of the Mississippi levees was chosen as the percentage of lime that will lower the plasticity index below 40 and produce a pH of approximately 12. It should be pointed out that Marks and Haliburton (1972) stated that pH values >10 are required for the pozzolanic reaction that leads to strength improvement of lime treated soils.

It remains unknown what type of lime was used for the soil treatment of Mississippi levees. The slided material was removed from the slopes, lime treated and placed back in the levees. With the lime treated material the slopes are reconstructed to the original grade using material from the slide itself reducing with this way the need for additional borrow of material. In overall, the use of lime had proved to be a cost effective method of repairing slides on the Main Line Mississipi river. Figure 3.4 shows a cross-section of the Mississippi river levee and a photo taken during placing and compacting of the lime-treated clay.

Further information on the construction procedures in the field can be cited in Fleming et al. (1992).

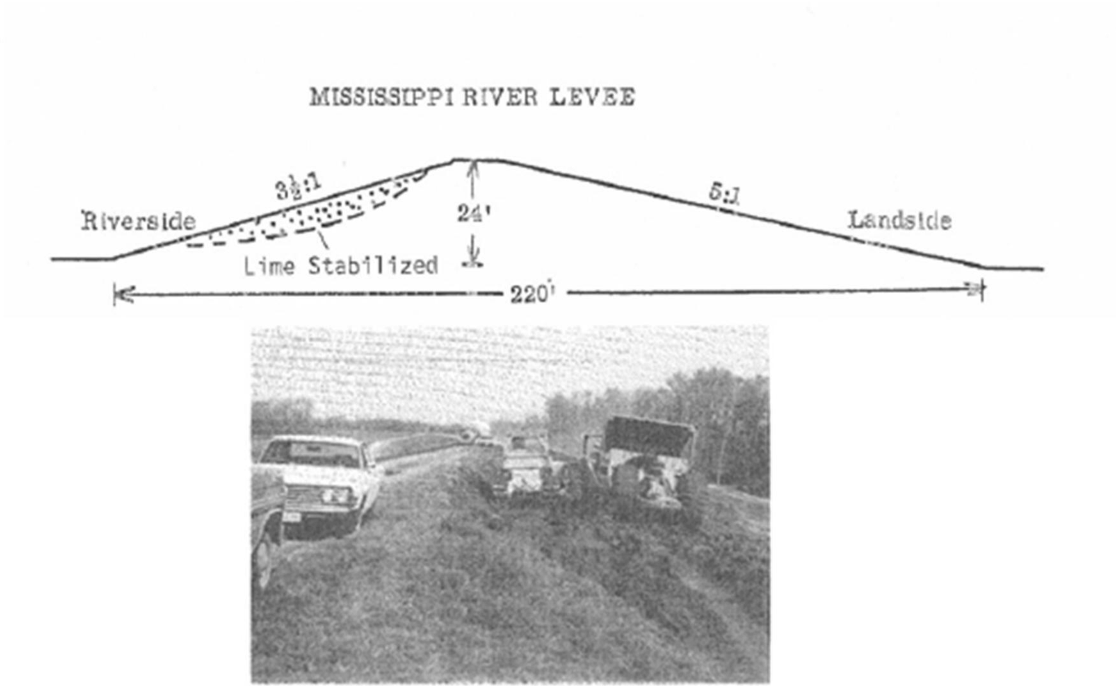

Figure 3.4. Cross section of Mississippi River levee and placing/compacting of lime-treated clay (after Gutschick, 1978).

3.3.2 Mississippi dams

Mississippi dams were constructed using dispersive clay soils. In these soils the erosion process is enhanced resulting in open gully erosion on the slide slopes of the dam. Heavy rains aggravated the erosive condition of 55 dams of these dams in the Bluff hills to the extent that repairs were necessary. It was decided to use the lime-treatment technique on 18 of the damaged dams.

The physical soil characteristics from 6 of the above dams' site locations where the lime treatment technique was applied are summarized in Table 3.5. Hydrated lime was added at the rates of 1, 2 and 3 percent on a dry weight basis. Based on laboratory dispersion tests (i.e. pinhole, crumb tests), it was found that the addition of lime to a dispersive soil converts it to a nondispersive state for all the above rates of lime used. Eventually a 2% hydrated lime was selected a minimum application for the tested soils considering the accuracy of filed controls over application rates of lime to soil.

The soil was excavated from the dam, treated with lime and replaced on the dam. Repairing of the dams with the lime treatment technique resulted in a decrease in cost on a per unit volume basis. The success of this technique in the remedial treatment of dams has led to its use to new dam construction mainly in providing a protective blanket to prevent erosion and also as a core material to minimize leakage and provide extra strength (Bass and Jones, 1969; Ryker, 1977).

In regards to vegetation, agronomists were of the opinion that no plant life can be sustained on the dams because of the cementation of the lime treated soils and the high pH values. Therefore for the lime treated dams it was decided to place a topsoil layer on the structure (on top of the lime treated soil layer) before seeding. Additionally the topsoil reduces the tendency for drying cracks to form.

Further information on the construction procedures in the field for the Mississippi dams can be cited in Perry (1977).

Table 3.5. Summary of physical and test data – lime treated dams (after Perry 1977)

Site no.	Sample no.	Grain size distribution, percent finer			Atterberg limits		Unified class	pH	Lab dispersion	Total soluble salt	Percent sodium, Na	Pinhole	Crumb test		Shrinkage limits
		0.002 mm	0.005 mm	0.074 mm	LL	PI				MEQ/L			H_2O	NaOH	
<u>Potacocowa</u>															
Y-31a-3	74F70	8	10	100	27	0	ML	5.6	80	1.32	62	D1			25.9
percent															
lime added	1				28	0		10.6	0			D2			24.8
	2				29	0		11.2	0			ND1			27.1
	3				29	0									25.5
	4				30	0									26.2
Y-31a-13	74F71	22	29	100	46	19	CL or ML	5.2	31	1.71	43	ND1			19.7
percent															
lime added	1				45	20		8.4	17			ND			19.3
	2				50	19		10.6	0			ND1			19.9
	3				49	17									25.0
	4				51	14									23.4
<u>Big Sand</u>															
Y-32-3	74F30	15	20	71	32	16	CL	5.2	70	0.48	75	D			
percent															
lime added	1				33	16			0			ND			
	2				34	14			0			ND			
<u>Pelucia</u>															
Y-33a-1	74F36	14	15	77	29	11	CL	5.4	87	0.67	81	D			
percent															
lime added	1				29	9			0			ND			
	2				31	8			0			ND			
	74F37	14	19	93	37	15	CL	5.2	42	0.17	88	ND			
percent															
lime added	1				35	12			0			ND			
	2				37	11			0			ND			
Y-33a-12	74F36	14	17	78	23	6	CL-ML		6			D1	1	3	17.8
percent															
lime added	1								0			ND1			18.3
	2								0			ND1			10.7
	3								0			ND1			19.0
<u>Abiaca</u>															
Y-34-8	75P38	18	24	100	42	18	CL		38			D1	4	4	21.3
percent															
lime added	1								0			ND1			22.1
	2								0			ND1			22.5
	3								0			ND1			22.9

3.3.3 Mnjoli dam

The effectiveness of lime treatment technique on improving the behaviour of dispersive soils was also evaluated in practise in the case of Mnjoli dam in Swaziland. This dam was constructed in 1976 and is a 42 m high and 1500 m long earth and rockfill embankment. For this dam dispersive clay soil was used as a fill material. Dams constructed with this type of soils can fail by piping or can experience severe erosion. For this dam 2% hydrated lime – treated material for the dam site was placed on the downstream portion of the core to protect the face at which selective erosion would start in unfavourable conditions. The addition of lime had a marked effect on the physical properties between the natural and lime treated material. This properties for the natural and lime stabilized material are shown in Table 3.6. Lime stabilization of potentially dispersive clays has been used in a number of other major dams (Logani, 1979; Phillips 1977).

Further information on the construction procedures in the field can be cited in Forbes et al. (1980).

Table 3.6. Summary of the physical properties of the core material (after Forbes et al., 1980)

		Natural material	Lime-stabilized material
Laboratory tests			
Laboratory max. density	(Mg/m^3)	1.688	1.670
Laboratory OMC	(per cent)	16.6	17.9
Liquid limit	(per cent)	46.61	42.99
Plastic index	(per cent)	25.12	19.26
Linear shrinkage	(per cent)	11.47	10.64
Free swell	(per cent)	83.32	57.70
Swell potential	(per cent)	5.03	—
Dispersion (double hydrometer method)	(per cent)	56.7	<5
Number of samples		154	108
Field tests			
Fill density	(Mg/m^3)	1.783	1.705
Relative compaction	(per cent)	105.6	102.0
Fill moisture content	(per cent)	14.88	18.03
Variation from optimum	(per cent)	−2.01	+0.04
Number of tests		211	144

3.3.4 River flood dikes in Czech republic

The need to build new dikes as well as to renovate existing ones came up in the Czech republic after the floods in 2002. Proviacal lime produced by Lhoist was used in the following years for the building and reconstructing of dikes and flood dikes in the Czech Republic. Below a list of field applications where this technique was successfully applied:

- Chobot dike/Hradec Kralove dike.
- These dikes were destroyed by floods in 2002. The quality of the existing soil was improved by adding Proviacal lime and the dikes were reconstructed. Photos of the Chobot dike before and after its reconstruction are shown in Figure 3.5 and Figure 3.6 respectively. Photos from the construction of the Hradec Kralove dike is shown in Figure 3.7.
- Pardubice dike.
- This flood dike was constructed using the lime treatment technology. The flood dike has been built from excavated river sediments treated with Proviacal RD in 2004 (see Figure 3.8). The floods in 2006 proved the right use of soil treatment technology in such important flood constructions.

Figure 3.5. Destroyed dike of Chobot pond near Milevsko during floods in 2002.

Figure 3.6. Dike of Chobot pond near Milevsko after reconstruction when soil treatment technology with Proviacal® was used.

*Figure 3.7. Soil treatment technology with **Proviacal®** used during building of flood dike in Hradec Králové.*

Figure 3.8. Excavated sediment from Labe river near Pardubice is treated with Proviacal® and used for flood dikes construction.

3.4 Conclusions

The use of lime-treated soil in full scale applications in France and worldwide, highlighted a series of benefits of this method for the construction and maintenance of hydraulic structures such as dikes, levees and dams. Based on these applications the investors can see at least three main benefits of the lime treatment technology:

A. Firstly, the soil properties of the lime treated material is improved compared to the natural untreated soil. Lime treated soils exhibit a considerable increase in erosion resistance, increase of cohesion and strength while the workability of the material is improved and the permeability is maintained at low levels similar to those of original, natural materials.
B. Secondly, the time spend on preparing and carrying out the project is shortened since no delays in the field work due to adverse weather conditions occur as lime treatment can be carried out also in wet weather. Moreover, adding lime to the clay makes the material amenable to processing when initial water levels are high and less prone to swell and shrink after inclusion in the dike when water levels fluctuate.
C. And finally, unsuitable construction material can now be improved in quality on the site, reducing the project costs and the amount of transport involved.

It should be highlighted that to the authors' knowledge there are no published data from full scale applications related to dike durability and evolution of soil parameters in the dike with time. In addition, the application of lime – treated material for building coastal dikes (characterization of the sustainability of lime-treated soil versus saline environment, wetting-drying cycles etc.) has not yet been investigated to date. A full scale experimental lime-treated coastal dike it is plant to be built in the Mediterranean coast; Digue 2020 project (Baecque and Chevalier, 2017).

4 Is the use of lime a sustainable, environmentally friendly, cost effective technique?

Soil improvement with lime appears to be a sustainable technique both environmentally as well as economically. Some of the impacts of this technique in regards to the environment and the costs of a construction are listed below.

Cost impacts:

- Unsuitable construction material can now be improved in quality on the site, reducing the project costs and the amount of transport involved.
- The high external erosion resistance of lime –treated soils could drastically reduce the costs of surface erosion protection measures such as use of expensive concrete or grouted rip – rap, gabions, especially for the case of low dams or dikes designed considering overflow over the earth-fill itself.
- Theoretically, the high internal erosion resistance of lime –treated soils could allow for a simplification of the filter and drains system within the earth-fill reducing the construction costs. As suggested by Nerincx et al. (2016), filters and drains within the earth-fill may even not required anymore, if internal erosion resistance is confirmed by preliminary laboratory tests.
- The improved performance of lime-treated soils in terms of permeability, resistance to internal and external erosion and mechanical stability can be considered in optimizing the design of dikes and in decreasing the construction costs. For instance, the improved mechanical stability of lime – treated soils may lead to slope structure modification. Slope steepening may be considered to spare material and space.

Environmental impacts:

- A number of studies state that chemical soil stabilization via the use of additives such as lime is an environmentally friendly method for soil treatment. Worldwide this method has shown to improve the soil properties to such extend that catastrophic phenomena as landslides, failure of hydraulic structure - with tremendous negative impacts on the environment - can be prevented (Amiralian et al., 2012; Krithiga et al., 2017). Other studies, however, claim that the production of any calcium – based material such as lime involves the calcination of calcium carbonate. This calcination process occurs at a very high temperature. Therefore, the process is responsible for a considerable percentage of carbon dioxide emission in addition to high energy consumption (Birchal et al., 2000; Shand, 2006). Hence, the production of calcium based additives may have a negative impact on the environment (Jawad et al., 2014). According to Ochoa et al. (2012) and the European Commission (2011) the production of 1 t of lime entails the emission of around 1.2 t of CO2. In general, the amount and characteristics of the process emissions depend on the plant lime production technology, the operation standards and the raw material consumed (Gutiérrez et al., 2012).
- To the authors' knowledge, there are no incidents reported on lime – treated soils being harmful to animals. On the other side, burrowing animals cannot easily dig holes in the treated soil and thus the damage cause in the external surface of dikes is reduced.

A picture illustrating this is given in Figuur 4.1. Burrowing animals holes in non - treated soil (left) and unsuccessful attempts in lime treated soil (right).

- It should be noted that the soil pH after lime treatment is increased which may have harmfull effects on the environment such as threatening the quality of the ground water or limiting vegetation.
- It is legally unclear whether lime - treated soil would be treated as "soil" or a "building product" within the environmental legislation (besluit bodemkwaliteit, regeling bodemkwaliteit), as different government entities have treated the matter differently over the years. If it is to be regarded as a building product, then the environmental evaluation can be performed on the basis of leaching test results according to either the NEN7373 (equivalent to Belgian CMA/2/II/A.9.1) or the NEN7383 standards.

Figuur 4.1. Burrowing animals holes in non - treated soil (left) and unsuccessful attempts in lime treated soil (right). (after Nerincx et al. 2016).

5 Is lime treated clay suitable to be used as a reinforcement of grass covers?

5.1 Introduction

Over the past years in the Netherlands a large number of erosion tests on grass covers on dikes have been performed using the overflow or wave impact generator from Rijkswaterstaat (see Figuur 5.1). This has resulted in the current WBI procedures to determine the strength of grass covers under wave attack (outer slope of the dike) or wave overflow (inner slope of the dike). As it appears a well-developed grass cover can resist substantial hydraulic loads. However, with the newest regulations in the Netherlands and the newest climate scenarios a serious problem could occur in that more wave overflow (the dikes are too low) is to be expected in large parts of the river Delta area. This would ask for measures by either raising the dike crest or reinforcement of the grass cover on the inner slope of dikes.

Apart from that, a known fact is that the presence of objects on the dike and transitions (for instance grass along an asphalt road – see Figuur 5.2) form weak points as they enhance (turbulent) hydraulic loads and hinder the development of a well rooted grass cover (decrease strength).

Figuur 5.1. Erosion around a tree during testing of wave overflow


Figuur 5.2. Transition from the road to the grass cover is a weak point

In this a light two questions on the use of lime as a means of strengthening the grass covers call for an answer:

- Can lime treatment be used to upgrade the erosion resistance of complete grass covers?
- Can lime treatment be used to protect the grass and soil around object and along transitions to enhance erosion resistance?

5.2 Erosion of lime reinforced grass covers and soil around objects/transitions in the revetment

The treatment of clay with [active (as opposed to natural)] lime changes the properties of the clay. It is important to make the distinction between active lime (quick lime) and natural lime. Whereas natural lime is used to enhance the growth of a good grass cover in your garden, quick lime also alters the conditions of the subsoil. It is far from certain that (even if the lime addition is only a small percentage) the working together of clay boulders and grass roots (which provides the strength of a regular grass cover) will work in the same way. Some tests on grass growth on lime treated clay will be necessary to give some more insight in this question. In general lime – treated soils have a pH > 10. This might prevent the growth of grass. If grass does not grow well on lime treated soil, then a more or less layered revetment would be thinkable, consisting of a lime enforced clay layer that provides the erosion resistance underneath a loose soil (leeflaag) for the grass cover. That would more or less take the form as shown in Figuur 5.3.

Figuur 5.3. A revetment consisting of two layers

A disadvantage of such a layered system is of course that the top layer can experience a substantial amount of damage during loading conditions and would have to be restored. This is however very seldomly the case and if this appears to be a problem there is nothing against forming and maintaining a good and erosion resistant grass cover that only damages under very severe conditions, in which case the lime treated clay provides extra erosion resistance.

A distinct advantage of lime treated soil as an erosion measure on the inner slopes of (river) dikes is probably that steeper slopes can be maintained than without lime stabilisation. As outlined in the introduction that could be part of the solution for larger amounts of wave overtopping and wave overflow. It would be interesting to further test this idea with the wave generator that has been used in the grass erosion research on a test site with a treated subsoil.

The point of grass growth on lime treated soils is of paramount importance when it comes to the use of lime in erosion resistance along transitions and around objects. It is not desirable that grass will not grow around objects. Also, mixing and densification of mixed clay and lime around objects is a difficult subject. In general, the treatment of larger amounts of soil is economical more feasible than small scale applications.

6 Can the lime- treatment technique be beneficial in the Netherlands?

Nowadays soil treatment with lime in civil engineering is widespread in many countries. The interest of the hydraulic work community regarding this technique is currently growing as lime-treated soils showed high level properties such as homogeneity, low permeability, internal and external erosion resistance and mechanical stability. A recent example is the performance of full scale dike experiments, build up with lime treated soil in France as part of the research and development programs DiqueELITE (www.digueelite.fr) and Digue2020 (www.digue2020.fr) – see Section 3.2. For additional information in regards to soil improvement via the use of lime, the reader can refer to Appendix A.

In The Netherlands, the lime - treatment technique has been mainly used in railway construction. Tests on lime - treated clays, used as foundation for the rail tracks, demonstrated the effectiveness of this technique (see Appendix A, Bijlage B). At present, lime is used little, if at all, in clay for dike upgrades in The Netherlands, generally because the clay has to meet the prevailing quality requirements in RAW 2015, which apply only to natural soil deposits and not clay with additives.

The full scale applications in France and worldwide highlighted a series of benefits of the lime treatment method in improving the mechanical behaviour of the soil used in dikes. These applications indicate that the use of lime is a promising technique and can be seen as an innovation in dike upgrades in The Netherlands.

One of the main advantages of the lime-treatment technique is the increase in soil strength and bearing capacity. In dike construction this indicates that solutions such as the construction of sheet piles in case of strength deficiencies or problems related to insufficiency of locally available clay to meet the requirements for use in dikes can be solved with the use of lime. In addition, the increase in erosion resistance of lime – treated soils can be of use in the reinforcement of grass coverings (making the grass more widely applicable or grass can be added to the cross section over a greater height). In addition lime – treatment can be use in strengthening the grass on the inner slope of the dike; this has particular application for locations which have been planned in the river side where the crest height might be insufficient.

The effectiveness, however, of the lime - treatment technique needs to be evaluated when applied to typical Dutch clays used as dike material which have a relatively high organic content (2 – 5%) as the addition of lime is influenced by the percentage of organic matter present in the soil. It is expected that organic matter delays or inhibits hydration of the lime (Bell and Coulthard, 1990).

Potential applications of the lime - treatment technique in Netherlands can be:

- Improve soil strength with the purpose of avoiding having to use constructions like a sheet pile.
- Increase of erosion resistance of clay around non-water retaining object (dijkmeubilair).
- Increase of erosion resistance in the inner slope of the dike for allowing more transhipment.

- Increase of erosion resistance in the outer slope of the dike (expand the use of grass coverings compared to hard coverings).
- Upgrading of a locally available material to a suitable material for use in dikes (POV Dijkversterken met Gebiedseigen Grond).

The applicability of the lime – treatment technique in dike reinforcements can be evaluated on the basis of an action plan that may incorporate the following stages:

A. Experimental assessment of the soil behaviour of lime treated Dutch clays. Is lime treatment beneficial for Dutch clays and what is the application potential, use as core material, or as revetment material or as both? Is lime - treatment an economically feasible technique? What are the environmental effects and effects on water management in and around the dike?

B. Drafting of design and in-practice guidelines concerning the use of lime in dikes. For the practical application of lime solutions in dikes, it is necessary the development of a framework for in-practice guidelines that takes into account the uncertainties in the composition of the clay, the mixing and processing of the lime addition, the compaction and the weather conditions, which calculations models and which soil parameters are to be used, performance aspects and long – term characteristics.

C. Design, execution and analysis of a full scale test in The Netherlands. It is essential at this step to decide prior to the design of the full scale test which parameters have the major interest and need to be evaluated (i.e. erosion resistance, long – term behaviour, erosion resistance of grass cover in combination with a lime - treated clay subbase, resistance to wave loading, impact of sea water on the lime – treated material).

7 Recommendations for further research

Based on the findings of this report (literature and international experience) it can be stated that the application of lime in clay has high potential for use in dikes and revetments in the Netherlands. There are some aspects that have been mentioned in this report that deserve attention as they have been mentioned but not resolved:

- The influence of salt on the lime - treated clay.
- Durability of the lime technique.
- Grass growth on lime - treated clay.
- More information on CO_2 emission resulting from lime production.
- The behaviour of treated material if it is remoulded (how does the material behave after a certain curing time if it has to be (re)moved)? Is a lime – treated material a re-usable material?
- Resistance of lime - treated clay to burrowing from animals.
- Legislative aspects.

Overall it is clear that lime - treated clay is very erosion resistant, has a high shear strength and adding lime to wet or soft clays greatly enhances the workability of the material. To enable the practical use of these advantages further steps toward practical pilot tests should be made. It is advisable to explore the possibilities with the following (ongoing or to be started) investigations:

- The Rijkswaterstaat CIP 2019; follow up of this report. An application has been done for a budget of 100 k€ for further laboratory research (parameter, above mentioned topics) and incorporation of the use of lime - treated clay in current rules and legislations.
- A pilot within the project Kleirijperij; mainly aimed at making dredged material suited for application in dikes within a shorter timespan.
- Investigations within the framework of a POV DGG (Dike Reinforcement using Local Soil); to be started.
- Model tests with RWS ITC (Innovation Test Centre); mainly focussed on testing of the erosion resistance during wave runup and wave overflow.

It is recommended to try to realize more than one of these mentioned investigations in order to enhance the probability that significant progress can be made within the coming year.

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A Appendix A

Memo

Aan
Theo Stoutjesdijk
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Onderwerp
Kalkbehandeling; grond mengen met kalk

In Nederland zijn eeuwenlang dijken gebouwd met grond, die ter plekke voorhanden was. In de laatste decennia zijn strengere eisen aan grond gesteld, zodat in sommige gevallen deze grond vervolgens verder weggehaald moest worden. Klimaatdoelstellingen en potentiële besparingen dagen ons uit om weer meer gebruik te maken van gebiedseigen grond. Deze beschikbare grond bepaalt hoe de dijk eruit komt te zien. Dit vraagt om een andere houding en meer grondkennis bij de dijkbeheerder en de dijkontwerper.'

Thans wordt dijkmeubilair (inspectiewegen, bushaltes, trappen, moestuintjes, bomen, etc.) niet beoordeeld, gewoonweg omdat hier geen WBI-richtlijnen voor zijn. Niet alleen recente overstromingen (bijv. Katrina) maar ook praktijkproeven op Nederlandse dijken hebben aangetoond dat als gevolg van golfoploop en/of golfoverslag de grond/grasbekleding rondom dijkmeubilair zeer gevoelig voor erosie is ofwel deze locaties zullen ten opzichte van dijken met alleen een grasbekleding eerder falen/bezwijken.

In het kader van CIP (innovatieve/kansrijke ideeën voor RWS) worden in dit memo twee vragen beantwoord. Zij hebben betrekking op het verbeteren van gebiedseigen grond door grond te mengen met kalk en zijn vooral gericht om kennis vanuit Frankrijk te halen:

1) Wat zijn de Franse ervaringen met het toepassen van kalk?
2) Waarom hebben de Fransen specifiek voor deze oplossing gekozen?

Ad 1 Volgens Christophe Chevalier (IFSTTAR) en Jean Jacques Fry (EDF) wordt in Frankrijk grond met kalk gemengd, indien de grondeigenschappen voor dijken/dammen verbeterd moeten worden. De kosten van het verbeteren zijn volgens hen ten opzichte van de (hoge) transportkosten verwaarloosbaar. Deze filosofie komt sterk overeen met de doelstellingen uit POV-Gebiedseigen-grond. Gebruik van gebiedseigen grond kan in projecten met veel grondverzet € 0,25 tot € 0,50 miljoen per km besparen (zie voor meer info “De gebiedseigen dijk: een prachtige kans http://hoogwaterbescherming.nl/nieuwsbrieven/december-2017/artikel-5.html).

Het mengen van natte klei met kalk verbetert niet alleen de verwerkbaarheid van grond maar ook de eigenschappen ervan, bijv. toename van schuifsterkte en verhoging van de erosiebestendigheid. In de wegenbouw wordt deze techniek van grondverbetering wereldwijd toegepast, zie bijv. BACMI, 1986 (vooral voor de verwerking van grond en het vergroten van de schuifsterkte; niet zozeer voor het erosiebestendiger maken van de grond naast de verharding).

Naast het mengen van grond met kalk/cement worden ook andere technieken zoals bestrating (met klinkers) toegepast; zie onderstaande figuren en memo ‘Falen van de grasbekleding nabij dijkmeubilair als gevolg van erosie, een witte vlek bij het ontwerpen en beoordelen van dijken’ d.d. 24 april 2017, waarin diverse alternatieven voor het tegengaan van erosie worden besproken.

In het verleden hebben Amerikanen en Australiërs dammen versterkt met kalkachtig vermengde grond voor het vergroten van de stabiliteit, voor het tegengaan van interne erosie en voor een betere/snellere verwerking van grond (zie onderstaande box; bron: National Lime Association, 2004).

Om slappe gronden in dijken te stabiliseren kan een kalkbehandeling worden gebruikt, hetzij wanneer ze voor het eerst worden gebouwd, of als onderdeel van het repareren van falende taluds (Figuren 1 en 2).

Figuur 1: Preliminary mixing of lime and embankment soils in mixing area

Figure 2: Returning treated soils from mixing area to embankment

In 1973 zijn verschillende dijken langs de Mississippi overstroomd. Traditionele dijkversterkingen bleken niet mogelijk te zijn vanwege het gebrek aan goede materialen. Daarom zijn de dijken in Arkansas en Illinois vanaf 1974 versterkt met kalk (with 5% hydrated lime). Naast rivierdijken zijn ook aarden dammen in Oklahoma, Mississippi, Texas en Arizona met kalk behandeld voor het tegengaan van interne erosie (i.e. concentrated leak erosion, contact erosion and backward erosion).

Voor grond met een hoog kleigehalte wordt kalk gebruikt; terwijl voor grond met een laag kleigehalte kalk-puzzolaan (bijvoorbeeld vliegas) mengsels worden gebruikt. Deze behandelde grondsoorten moeten een watergehalte hebben dat 1 tot 3 procent hoger is dan optimaal, om ervoor te zorgen dat de kalkreactie voldoende water heeft voor voltooiing.

De Fransen gebruiken ook deze techniek van grondverbetering. Verschillende onderzoeksinstellingen (IFSTTAR, CER, Cemagref, EDF) en Franse Universiteiten onderzoeken nu in samenspraak met Lhoist de invloed van kalk in grond. Volgens EDF (bron: Fry) worden verschillende kleine dammen, enkele delen van grote dammen en sommige dijken met kalk versterkt. De nadruk ligt hierbij op de bescherming van de dijken/dammen (i.e. interne en/of externe erosie; volgens Fry: protection of dams/levees). Voor meer achtergrond-informatie: zie ook ICOLD 2018 Vienna en ICOLD TC Cemented Soils Dams. In de Nederlandse dijkenbouw is weinig tot geen ervaring met deze verbetering van grond, wel in de wegenbouw. Zeer recent heeft Prorail een praktijkproef uitgevoerd waarbij de invloed van kalk in klei nader is uitgezocht, zie Bijlage B.

Ofschoon laboratoriumproeven hebben aangetoond dat de erosiebestendigheid van kleiige gronden vermengd met kalk aanzienlijk hoger is, is thans onvoldoende bekend of de grond in prototype condities ook zo reageert (in het bijzonder voor golfoploop en/of golfoverslag). Schaalfactoren zouden hierbij een rol kunnen spelen, zie onderstaande figuren. De onderbouwing hiervan is gebaseerd op enkele conferentiebijdragen, die tijdens ICSE-6 in Parijs (2012) zijn gepresenteerd (b.v. Herrier et al. 2012, Chevalier et al. 2012).

Figure 1. Lime-treated material production with a mixing and treatment mobile plant.

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

Ad 2) (Waarom hebben de Fransen specifiek voor deze oplossing gekozen?)
Overslaande golven veroorzaken erosie en kunnen het buiten- en binnentalud van dijken zodanig verzwakken dat ze kunnen bezwijken/falen. Bij de storm 'Xynthia', die op 28 februari 2010 langs de Franse Atlantische kust raasde, kwamen 51 mensen om (zie onderstaande foto). Op basis hiervan heeft de Franse regering in 2014 een groot onderzoeksprogramma geïnitieerd te weten: SSHEAR (Soils, Structures and Hydraulics: Expertise and Applied Research; http://www.agence-nationale-recherche.fr/Project-ANR-14-CE03-0011). Dit programma is zeer breed neergezet, omdat Frankrijk vele waterbouwkundige constructies telt (15.000 km dijken en 300 grote dammen voor drinkwater, irrigatie en elektriciteitsopwekking).

Foto AFP 'A man stands on the roof of his house in a flooded street, on March 2, 2010, in Aytre, western France, after a storm dubbed "Xynthia", which killed 51 people, unleashed gale force winds and torrential rains, destroying roads and houses along France's Atlantic coast.

French electricity distributor EDRF said in a statement that 49,700 homes remained without electricity and it had 5,000 staff out working to restore power'.

Thans is onduidelijk waarom de Fransen specifiek voor het behandelen van grond met kalk kiezen, zie onderstaande samenvatting van emailwisseling tussen Hoffmans en Fry. Hieronder volgen enkele subjectieve waarnemingen van Gijs.

Samenvatting emailwisseling Hoffmans-Fry (juli-augustus 2018)

In the Netherlands the idea of lime treatment in dikes will be studied. Therefore, the following questions seem to be relevant. Hopefully, you have time to answer them.

1) for what kind of problems do you (the French) use lime?
Ad 1) protection of levees and dikes

2) what are the French experiences with the use of lime?
Ad 2) several little dams in chalk, some part of large dams, some small levees, two trial test embankments

3) why do you chose specifically for this solution? (are these costs or other specific advantages?)
Ad 3) savings for protection function and increase strength when clay is too wet

4) do you have some sources (papers, publications or reports) that we can draw on, that should help us with making the proper decisions.
Ad 4) ICOLD 2018 Vienna, and ICOLD TC Cemented Soils Dams

Vanaf 2012 (tijdens ICSE 2012) heeft Gijs met diverse Franse onderzoeksinstellingen contact over allerlei erosieachtige onderwerpen (filters, Darcy diagram, etc.). Ook heeft Gijs waargenomen dat de Belgische kalkfabriek Lhoist zeer goede contacten heeft/onderhoudt met Franse onderzoeksinstellingen. Dit blijkt niet alleen uit gezamenlijke inzendingen van papers/publicaties voor internationale conferenties, maar ook dat Gontran Herrier (van Lhoist) een professionele gesprekspartner is in inhoudelijke discussies.

Gijs heeft Gortran verschillende keren ontmoet onder meer in Parijs (2012) en in Perth (2014) en hem erop geattendeerd dat Nederland net als Frankrijk veel dijken rijk is en dat er gelijksoortige problemen zijn. Gijs heeft parallel RWS (Koos Saathof) geïnformeerd over interessante technieken welke de erosiebestendigheid van grond kunnen verhogen.

Op grond van deze goede betrekkingen hebben de Fransen naast allerlei bureaustudies ook een praktijkproef voorbereid en uitgevoerd. In deze studies staat de erosiebestendigheid van grond vermengd met kalk centraal. Naar andersoortige oplossingen voor het oplossen van de erosiebestendigheid van grasbekledingen zijn de Fransen zoekende (zie ook voor papers '2018 protections' N:\Projects\11200500\11200704\C. Report - advise\Final publications).

2A) Is het mengen van klei met kalk milieuvriendelijk en duurzaam? Het antwoord is ja. Zie bijlage A.

Samenvattend:

Het is wereldwijd bekend dat het mengen van (natte) klei met kalk leidt tot een betere verwerkbaarheid en tot een hogere schuifsterkte (BACMI, 1986; National Lime Association, 2004). Bovendien neemt de erosiebestendigheid toe (Herrier et al. 2012; Chevalier et al. 2012).

Frankrijk heeft ervaring met de techniek ‘grond mengen met kalk’. Deze kennis komt voort uit de wegenbouw en de ‘vergeten’ natte waterbouw. De Fransen willen deze grondverbetering toepassen voor het versterken van dammen en dijken (zie mailwisseling Hoffmans - Fry).

Laboratoriumproeven hebben laten zien, dat de erosiebestendigheid van klei met kalk aanzienlijk hoger is dan ongemengde klei. Het lijkt erop dat praktijkproeven (overloop) dit beeld bevestigen, echter voor golfoploop en/of golfoverslag moet de erosiebestendigheid van deze grondverbetering nog worden aangetoond. Nederland is qua kennis eigenlijk net zo ver, maar wil men dit spoor ingaan en aansluiting zoeken op internationaal niveau, dient aandacht te zijn voor laboratorium- en praktijkproeven (zie ook systematisch praktijkonderzoek van erosiebestendigheid van grasbekledingen; periode 2007 – 2014). Hier liggen weer kansen voor een samenwerking met de Fransen.

Gemengde klei met kalk is milieuvriendelijk en duurzaam. Kalk bevordert de omzetting van organisch materiaal zoals drijfmest, graszoden, wortel- en stoppelresten. Plantenvoedsel komt hierdoor eerder vrij (zie bijlage A).

Bijlage A: Landbouw en kalk (overgenomen uit: http://www.vitasol.nl/over/landbouw-en-kalk/)

Kalk wetenswaardigheden:

- Kalk is nodig als plantenvoedsel. Alle planten hebben kalk nodig. Sommige veel, bijvoorbeeld suikerbieten, een kalkminnend gewas. Andere weinig, bijvoorbeeld aardappelen, een kalkmijdend gewas.
- Kalk bevordert de omzetting van organisch materiaal zoals drijfmest, graszoden, wortel- en stoppelresten. Plantenvoedsel komt hierdoor eerder vrij.
- Kalk bindt schadelijke zuren in de grond.
- Kali, ammoniumstikstof en magnesium worden door kalk verdreven uit hun vaste binding met klei en humusdelen. Hierdoor komen ze voor de plant beschikbaar. Kalk kan in water opgeloste fosfor aan zich binden waardoor deze fosfor niet meer uitspoelt.
- Kalk werkt structuurverbeterend op kleigrond doordat kleideeltjes door kalk aan elkaar gebonden worden. De kleigrond wordt losser, minder slempig, sneller droog en warm, beter bewerkbaar.
- Het bodemleven ontwikkelt zich beter bij een voldoende hoeveelheid kalk in de grond.
- Meer of minder kalk in de grond heeft invloed op het optreden van plantenziekten. Op grond met weinig kalk komt bijvoorbeeld veel sneller magnesiumtekort voor.
- Een goede kalktoestand en pH bevordert sterk het rendement van de aan de grond toegevoegde kunstmest en organische mest. Bij een slechte kalktoestand wordt veel dure kunstmest verspild.
- Op kleigrond komt van nature kalk voor in de vorm van koolzure kalk, soms wel 10%. Ook in sommige zandgronden aan de kust. Die koolzure kalk is belangrijk als leverancier van die kalk die gebonden is aan klei- en/of humusdelen, de ‘actieve kalk’.
- Door opname van planten, door uitspoeling, door zure meststoffen en zure regen verdwijnt er kalk uit de grond. Als er van nature geen voorraad is waaruit wordt aangevuld zoals bijvoorbeeld kleigrond met schelpen, moet dit verlies regelmatig door bekalken worden aangevuld.

pH – zuurgraad

De waardemeter voor de kalktoestand is de pH. Dit is de zuurgraad. Minder kalk maakt zuurder, meer kalk maakt basischer of minder zuur.

- De verschillen in pH zijn erg groot en lopen uiteen van 3.5 tot 8.5.
- Kleigronden hebben over het algemeen een hogere pH dan zandgronden.
- Sommige gewassen vragen een betrekkelijk hoge pH, andere een lagere.

Elk gewas heeft een eigen optimale pH waarbij het gewas de hoogste opbrengst geeft. Bij een hoger percentage organische stof, bijvoorbeeld dalgrond, is de optimale pH lager. Op zware klei is de optimale pH hoger dan op lichte klei of zavelgrond.

Uit de bemestingleer kennen wij tabellen die een optimale pH aangeven voor bepaalde gewassen of landbouwplannen op bepaalde grondsoorten bij bepaalde humusgehalten. Wanneer de pH van de grond niet optimaal is zullen gewassen geen maximum opbrengst geven. Hieronder als voorbeeld de opbrengstverliezen bij maïs op zand-,dal- en lössgrond als de pH te hoog of te laag is (bron NMI-Agro te Wageningen).

Bijlage B Praktijkproef ProRail (overgenomen uit: **https://www.prorail.nl/nieuws/stabiel-dankzij-kalk**)

Inleiding: Klei is instabiel als ondergrond voor spoorrails. Maar als je klei vermengd met kalk, wordt de grond stabiel. Dit blijkt uit een proef die ProRail en VolkerRail hebben uitgevoerd. De uitkomsten zijn niet alleen verrassend, maar ook duurzaam en bieden veel mogelijkheden voor de toekomst.

Primeur bij spoorbouw: Om treinen over kleigrond te laten rijden, wordt vaak ter versteviging een dikke funderingslaag (PSS) aangebracht. Hiervoor moeten vrachtwagens tonnen zand aanvoeren. Bij de aanleg van snelwegen wordt een speciaal kalkmengsel gebruikt die een funderingslaag overbodig maakt. De vraag deed zich voor: werkt dit ook bij een spoorbaan? Daarom heeft ProRail bij Ressen een proef laten uitvoeren met dit speciale kalkmengsel. En wat blijkt nu? Het werkt! Dit is een primeur voor de spoorwereld.

Hoe werkt die kleilaag?: De techniek zorgt ervoor dat de samenstelling van de klei door een chemische reactie met het kalkmengsel korrelachtig wordt. De kleilaag wordt hierdoor zo stevig, dat de dikke funderingslaag overbodig wordt.

De proef: ProRail heeft samen met VolkerRail bij Ressen het kleimengsel beproefd. In een proefvak van 100 meter is het mengsel aangebracht en aangewalst. Verrassend snel werden er hoge schuifsterkte waardes gemeten. Vervolgens werd een deel van het kalkmengsel aangebracht zonder de gebruikelijke funderingslaag. En wat bleek na meerdere proeven? Het kan ook zonder de laag.

Duurzaam en minder overlast: Dat betekent nogal wat: het scheelt tonnen zand en dus minder vrachtwagens, minder uitlaatgassen en minder overlast. Deze techniek is daarmee duurzaam en biedt veel voordelen voor de toekomst.

ProRail verduurzaamt: ProRail werkt op allerlei manieren aan een duurzaam spoor. Daarom gebruiken we duurzame energie, waar mogelijk duurzame materialen en duurzame werkmethodes. We kijken bij alles wat we doen naar het effect op de omgeving

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