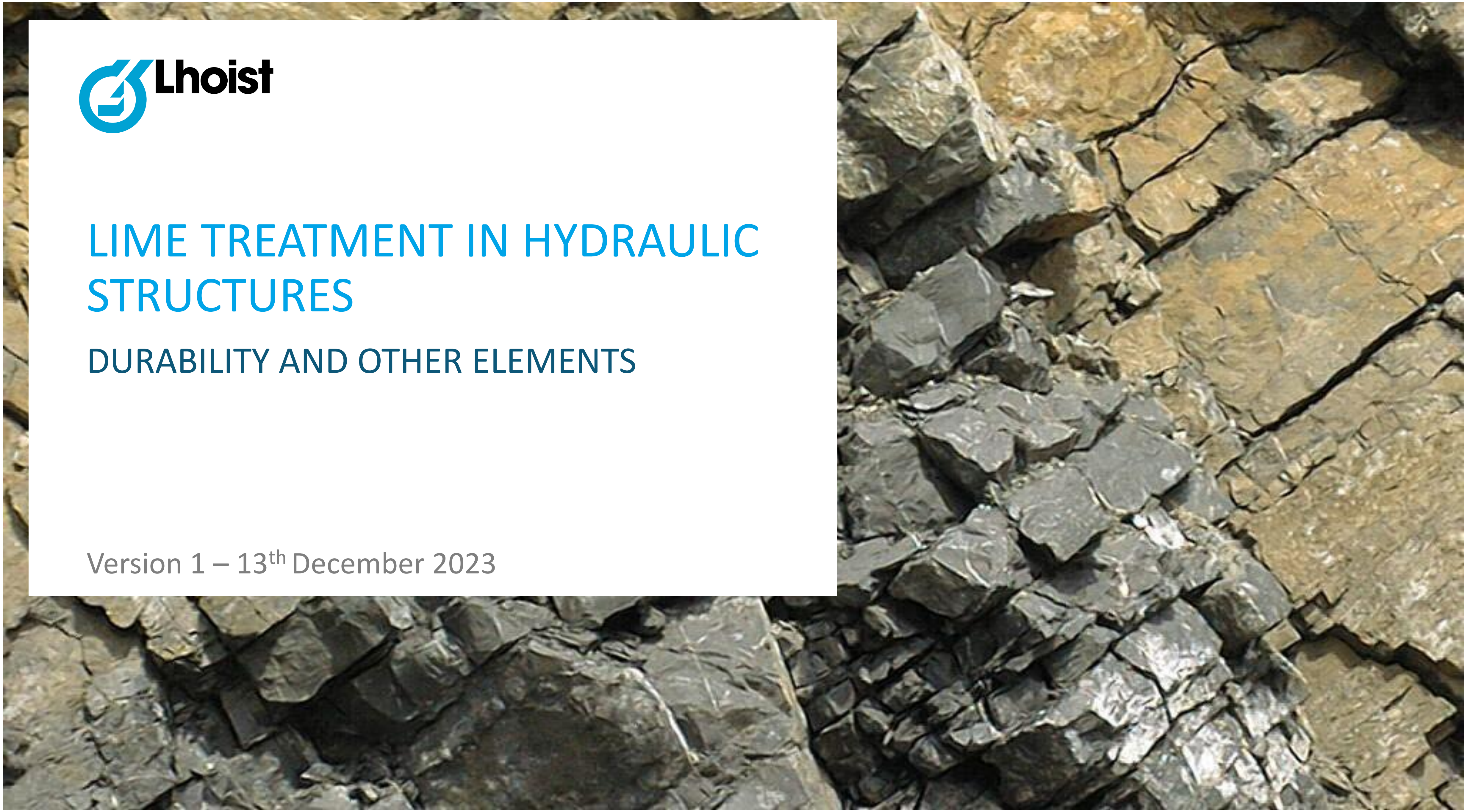


LIME TREATMENT IN HYDRAULIC STRUCTURES

DURABILITY AND OTHER ELEMENTS

Version 1 – 13th December 2023

FRIANT KERN CHANNEL (CALIFORNIA, US)

Construction details

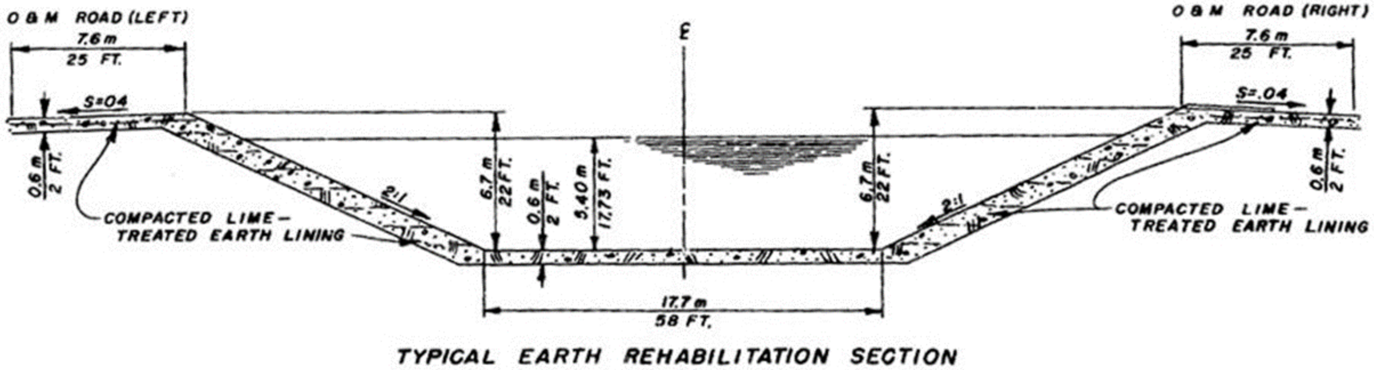
- 240 km irrigation channel
- Built in 1946
- Flow rate: 100 m^3/s
- Speed: 1,3 m/s
- I_P ~ 40

Disorders since construction

- Swelling clays (I_P ~ 40)
- Slope slides
- Failures of concrete cover

Repair activities

- 1972 – 1977: repair of 6,4 km banks
- ***Soil treated with 4% lime***



FRIANT KERN CHANNEL (CALIFORNIA, US)

Feedback after repairs

- The treated area has since behaved satisfactorily
- Not protected (protection initially planned with 20 cm concrete slab judged not useful)
- **Not eroded** by flow
- Requires **very little maintenance** (no erosion, no cleaning)

Monitoring performed in 2020

Permanent effect of lime for over 40 years

- Plastic characteristics of clays **permanently** altered
- **Reduced shrinkage/swelling behaviour**
- pH = 8,9 > 6,4 originally
- **No lime leaching**
- Presence of cementation products, calcite, available lime

[A.K. Howard, J.P. Bara (1976). **Lime stabilization on Friant-Kern Canal**. US Bureau of Reclamation, Report No. REC-ERC-76-20, Denver, CO (US), pp. 53-61]

[K. A. Gutschick (1985). **Canal lining stabilization proves successful**. Pit & Quarry, pp. 58-60]

[G. Herrier et al. (2012). **Principles and properties of soils treated by lime for hydraulic earthen structures**. Proceedings of the 3rd International Seminar on Earthworks in Europe, Berlin (D)]

[P. Akula et al. (2020). **Evaluating the Long-Term Durability of Lime Treatment in Hydraulic Structures: Case Study on the Friant-Kern Canal**. Transportation Research Record 0361198120919404]

[Belgian Research Road Center. Code of good practice R103 (2021). **Soil treatment with lime – European expériences for soil improvement and soil stabilisation. State of the art.** Brussels (BE), pp. 88-93]

MISSISSIPPI DIKES (US)

Construction details

- 350 km network of dikes along the Mississippi river
- Built between 1940 and 1950
- Local materials, incl. very plastic clays ($I_P > 50$)
- Height: 7 to 8 m
- Slope: 3/1

Disorders since construction

- Cracks in the body during dry periods (1 to 2 m deep)
- Water infiltration during wet periods through cracks
- Slope too steep for low residual resistance of very plastic swelling clays
- Surface slidings (tens of m) or even failure

Repair activities

- Until 1974 - excavation and replacement with better quality soil and softening of slopes
- After 1974 – absence of replacement materials:
  - ***Lime treated soil***
  - Renovation of 142 embankments
  - Reinforcement of 45 km (early 2010s)

[Belgian Research Road Center. Code of good practice R103 (2021). **Soil treatment with lime – European expériences for soil improvement and soil stabilisation. State of the art**. Brussels (BE), pp. 88-93]

[G. Herrieret al. (2012). **Principles and properties of soils treated by lime for hydraulic earthen structures**. Proceedings of the 3rd International Seminar on Earthworks in Europe, Berlin (D)]

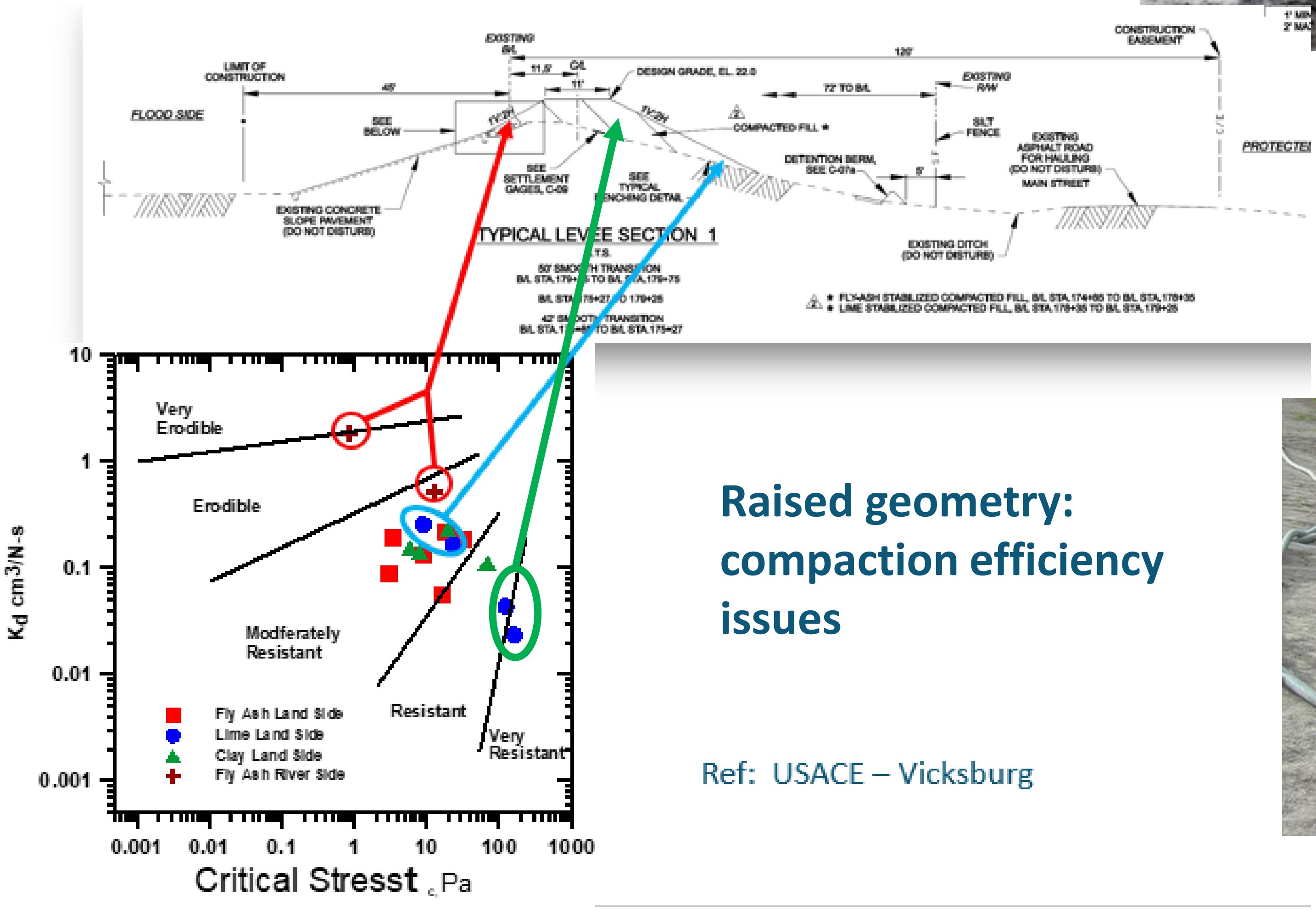
[P. Forsythe (1977). **Experiences in identification and treatment of dispersive clays in Mississippi dams**. In J.L. Sherard & R.S. Decker (Eds.), ASTM Special Technical Publication: STP 623. Dispersive clays, related piping, and erosion in geotechnical projects. (pp. 135-155). ASTM International. https://doi.org/10.1520/STP26985S]

[R.L. Fleming, G.L. Sills, E.S. Stewart (1992). **Lime stabilization of levee slope**. 2nd interagency symposium on stabilization of soils and other materials, Metairie, LA (US), pp. 79-87]

MISSISSIPPI DIKES (US)

Reinforcement of 45 km in (early 2010s)

- Plaquemine Parish dike
- ***Treatment with 8% lime***
- In-situ JET tests



Raised geometry: compaction efficiency issues

Ref: USACE – Vicksburg

VARIOUS CASES (CZECH REPUBLIC)

Dike of Chobot lake (2002)

- Breach after 2002 floods
- Reconstruction with ***lime treatment***


Dike of Hvezda lake (2004)

- Damages after 2002 floods
- Difficulties of reconstruction due to very wet soils
- Reconstruction with ***lime treatment***


Protective dike in Hradec Kralové (2005)


[G. Herrier at al. (2019). **Improving dams and dikes strength and resistance to erosion by means of lime treatment**. 11th ICOLD European Symposium, Crete (GR)]

[Belgian Research Road Center. Code of good practice R103 (2021). **Soil treatment with lime – European expériences for soil improvement and soil stabilisation. State of the art**. Brussels (BE), pp. 88-93]

VARIOUS CASES (FRANCE)

Borre Pradelles dike (2013)

- Expansion of the Bourre flood
- Local material (A2) ***treated with 2-3% lime***

Small protective dikes in Normandy/Northern France

- ***Lime*** used in construction site for a basin
- Very old use in the region where the soils are easily treated
- Good knowledge of public works companies
- Protection plans coordinated by water agencies and local administrative authorities
  - ASYBA CEREMA Rouen Seminar in March 2014

Reparation of the dike of the Mauranges pond (2023)

- Numerous leaks and loss of sealing at the level of the drain structure
- Changing the drain structure
- Earthworks and ***treatment*** of materials with ***lime*** in embankment

EDIT: ROUEN DEMONSTRATOR (FRANCE)

Construction details

- Silty Soil (I_P = 11)
- ***2,5% lime treatment***
- Height: 2m
- Slope: 3/2
- Mobile treatment facility

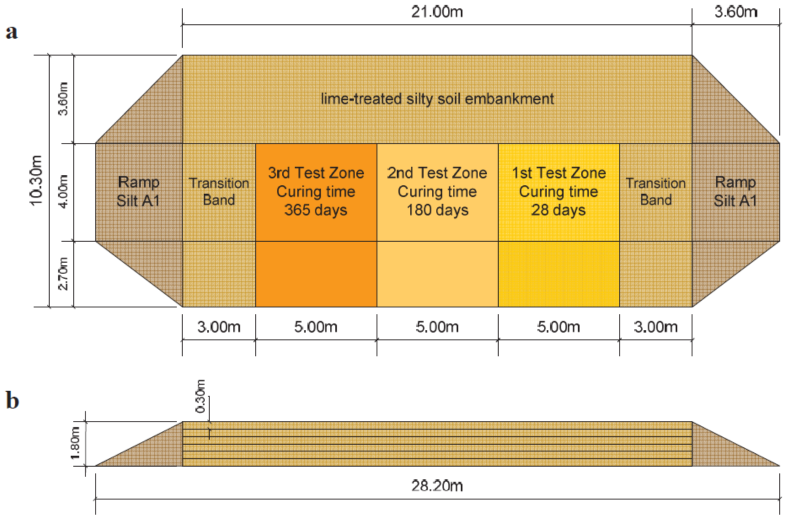
Testing & Monitoring activities

After 1 year

- Permeability
- Coring - mechanical performance
- Internal and external erosion
- Vegetation

After 7/8 years

- Physico-chemical analysis
- Sampling of blocks - mechanical performance
- Microstructural analysis



EDIT: ROUEN DEMONSTRATOR (FRANCE)

Main feedback

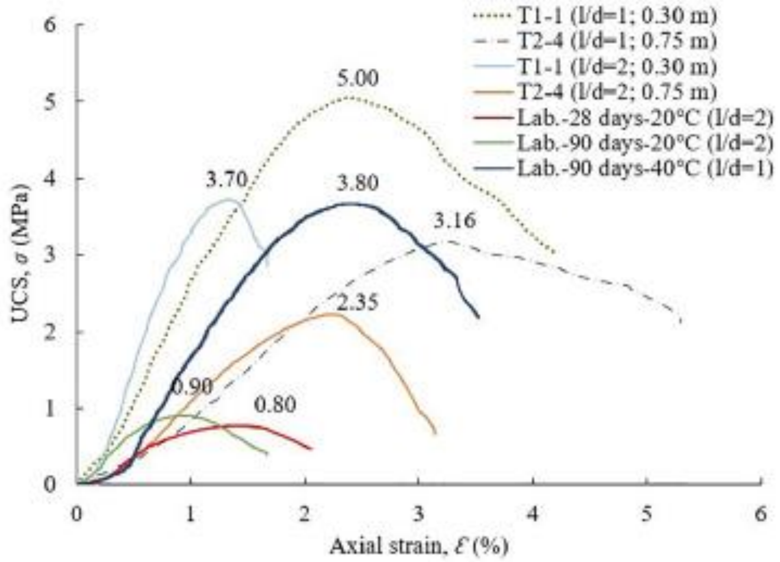
<u>After 1 year</u>

- Low ***permeability***
  Nasberg test and triaxial cells on core samples: 10^{-9} - 10^{-10} m/s
- Increased ***erosion resistance***
  MoJET and HET tests: x7 to x10 untreated soil
- Resistance to deep ***root penetration***
- Increased ***mechanical performance***
  Bearing capacity x5 to x30 after 1 month
  Cohesion x7 to x12 untreated soil

<u>After 7 years</u>

- Stable high ***mechanical resistance***
  Rc ~ 3 MPa (average, but heterogeneities)
- ***Stability*** of pozzolanic reaction products
- Improvement of ***water retention capacity*** of the embankment
- ***High pH*** maintained in the backfill (>11)
  Loss of lime effect on a small surface thickness (~10 cm)

			DIGUE EN LIMON NON TRAITÉ	DIGUE EN LIMON TRAITÉ À LA CHAUX	
Type d'essai		Unité		28 jours	180 jours
HET (Hole Erosion Test, érosion de trou)	Contrainte critique	kPa	179	→ 1000 (non atteinte)	± 800 (1er essai) → 1000 (non atteinte, second essai)
	Coefficient d'érosion k_{er}	s/m	9,8 10^{-5}	Non mesurable	-
	Indice d'érosion (=-log k_{er})	-	4,04	Non mesurable	-



[I. Charles et al. (2012). **An experimental full-scale hydraulic earthen structure in lime treated soil**. Proceedings of the Sixth International Conference on Scour and Erosion, Paris (F), Aug. 2012: 181–188]

[G. Herrier et al. (2012). **Principles and properties of soils treated by lime for hydraulic earthen structures**. Proceedings of the 3rd International Seminar on Earthworks in Europe, Berlin (D), Mar. 2012]

[I. Charles et al. (2015). **A real scale experimental dike in lime-treated soil: Evaluation of the methodology, mechanical and hydraulic performance**. Scour and Erosion – Cheng, Draper & An (Eds), Taylor & Francis Group, London (UK), 978-1-138-02732-9]

[L. Makki-Szymkiewicz et al. (2015). **Evolution of the properties of lime-treated silty soil in a small experimental embankment**. Engineering Geology, 191, pp. 8-22]

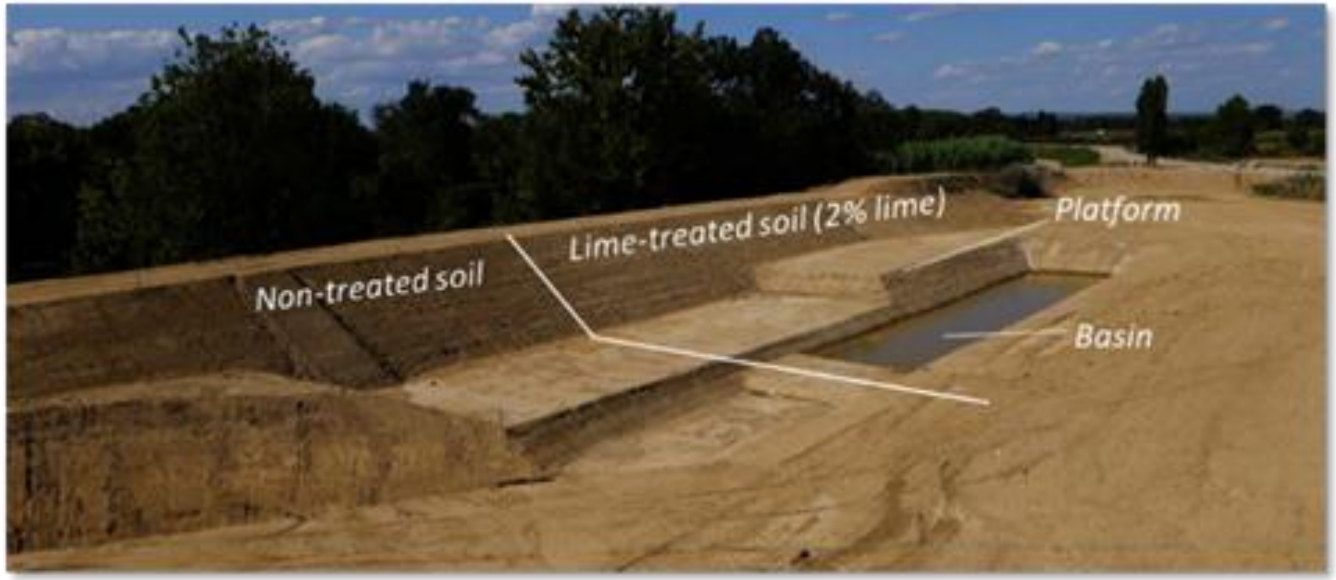
DIGUE ELITE: VIDOURLE DEMONSTRATOR (FRANCE)

Construction details

- Silty soil (I_P = 5)
- ***2% lime treatment***
- Height: 3,5m
- Slope: 3/2
- Mobile treatment facility

Testing & Monitoring activities

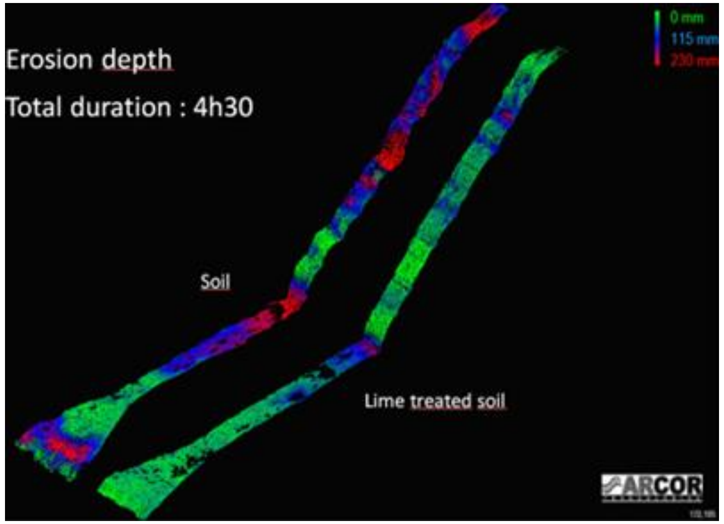
- Lab feasibility tests
- After construction
  - External erosion JET (1 – 6 years)
  - Overflowing tests (9 – 22 months)
  - Mechanical performance (7 years)
  - Physico-chemical analysis (6 years)

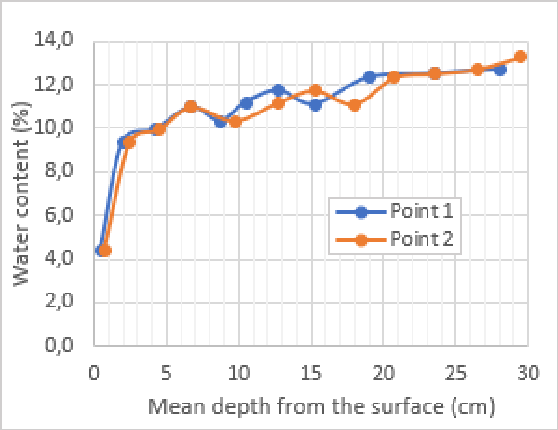


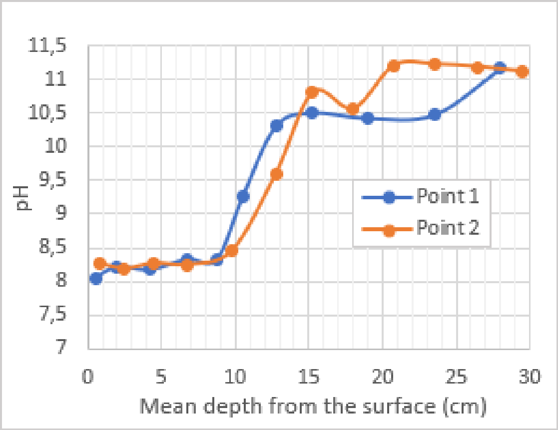
DIGUE ELITE: VIDOURLE DEMONSTRATOR (FRANCE)

Main feedback

- ***Low permeability***: 10^{-8} to 10^{-10} m/s after 6 years from the construction
- Increased resistance to ***internal and external erosion***
  Overflowing test & JET: x2 to x100 more resistant after 6 years ($50 < \tau_c < 2000$ Pa)
  HET test in-situ sampling: no erosion ($\tau_c > 500$ Pa - device measurement threshold)
- Increase and maintenance of ***mechanical resistance*** (some heterogeneities)
  0,2 MPa natural soil | 1,2 MPa soil reconstituted in lab (1 year) | 0,8 < Rc < 2,4 MPa (6 years)
  Cohesion x12 – x20 compared to natural soil
- ***Superficial cracks*** rapid drying/suction phenomena (high temperature during construction)
- Thickness of ***environmental degradation:*** 10-20 cm







[N. Nerincx et al. (2016). **Impact of lime treated soils performance on design of earthfill dikes**. FLOODrisk 2016 - 3rd European Conference on Flood Risk Management, E3S Web of Conferences 7, 14004]

[N. Nerincx et al. (2018). **The DigueELITE project: lessons learned and impact on the design of levees with lime treated soils.** Hydropower and Dams, vol. 25, issue 6]

[G. Herrier at al. (2018). **Erosion resistant dikes thanks to soil treatment with lime**. 3rd International Conference on Protection against Overtopping, 6-8 June 2018, Grange-over-Sands (UK)]

[S. Bonelli et al. (2018). **Quantifying the erosion resistance of dikes with the overflowing simulator.** 3rd International Conference on Protection against Overtopping, 6-8 June 2018, Grange-over-Sands (UK)]

[F. Bertola et al. (2024). **Evaluation of the geomechanical properties of lime-treated silt samples extracted from an experimental levee 6 years after the construction**. XVIII ECSMGE 24, Lisbon (P) - *will be presented 26-30 August 2024*]

SALIN DE GIRAUD DEMONSTRATOR (FRANCE)

Construction details

- Mix of sandy - silty soil + clay (average I_P = 9)
- ***2% lime treatment***
- Height: 2m
- Slope: 2,5/1
- Treatment on the platform
- Saline environment

Testing & Monitoring activities

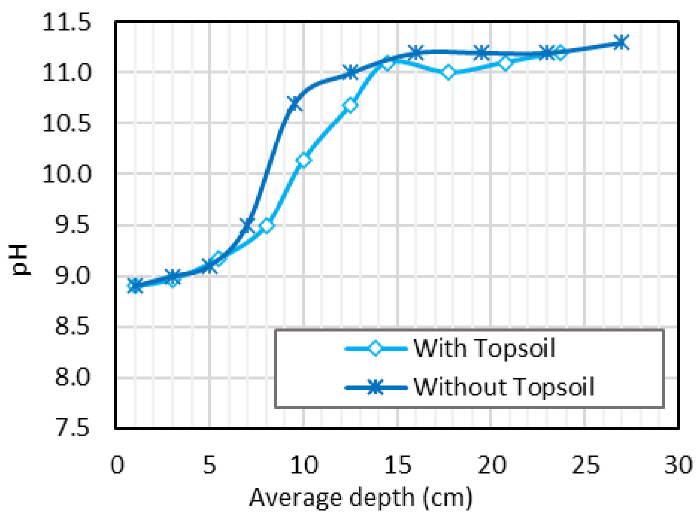
- Lab feasibility tests
- After construction
  - Overflowing tests (6 months)
  - Internal/external erosion HET/JET on cores (1 year)
  - JET tests (5 years)
  - Mechanical tests on cores (5 years)
  - Physico-chemical analysis (5 years)

[S. Nicaise et al. (2024). **Evolution des performances de digues traitées à la chaux en climat méditerranéen (Performance trends for lime-treated dikes in a Mediterranean climate)**. Digue 2024, Aix-en-Provence (F) – *will be presented 27-29 March 2024*]

SALIN DE GIRAUD DEMONSTRATOR (FRANCE)

Main feedback

- ***Low permeability:*** 10^{-9} to 10^{-10} m/s after 5 years from the construction
- Very good resistance to ***external erosion*** (overflowing tests)
  Little to no erosion vs breakdown of untreated soil (2h of stress under q = 400 l/s/m, h = 35 cm)
- High resistance to ***internal erosion***
  HET tests after 5 years (τ_c = 450 Pa)
  JET tests on samples taken in situ after 1 year (τ_c = 350 Pa)
  JET tests on surface after 5 years (100 < τ_c < 150 Pa) to be compared with values on material taken in situ (in progress)
- Mechanical characterization ongoing (5 years)



Untreated soil

Soil treated with 2% lime

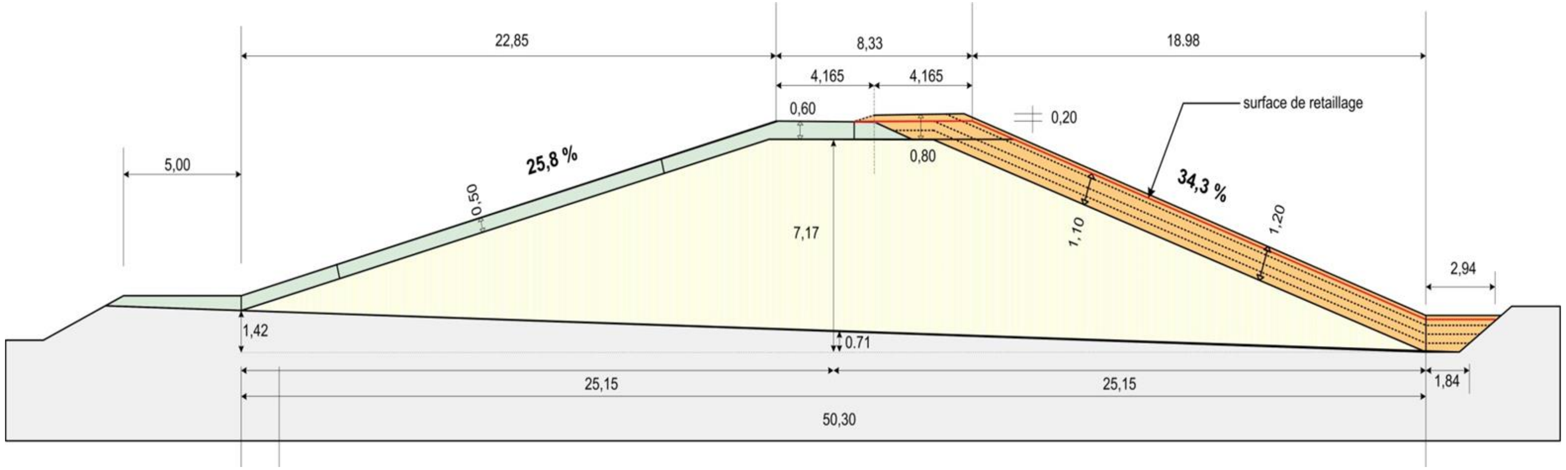
VLASSENBROEK DEMONSTRATOR (BELGIUM)

Construction details

- Silty Soil (I_P = 8-10) → ***2% lime treatment***
- Sandy Soil (I_P = 3) → ***3% formulated lime treatment***
- Protective shell
- Height: 6,5m
- Slope: 3/1
- Treatment on the platform
- Compaction in the direction of the slope

Testing & Monitoring activities

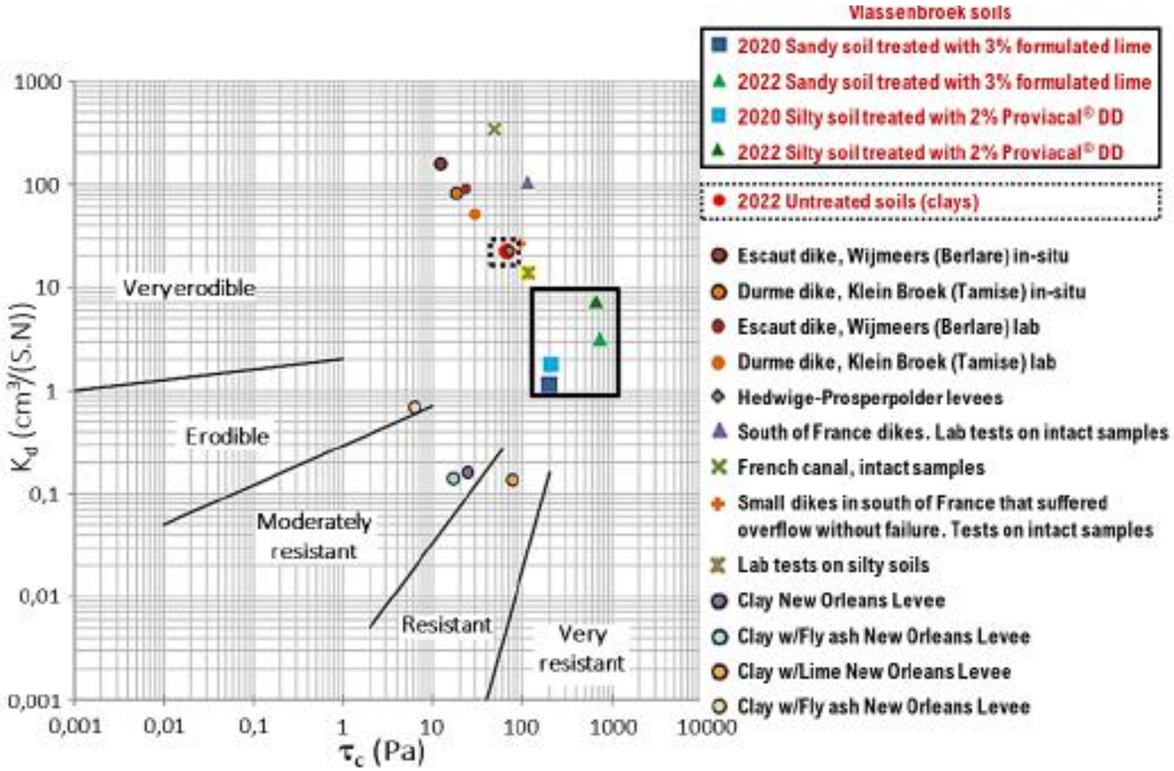
- Lab feasibility tests
- After construction
  - Permeability
  - Vegetation growth
  - Mechanical performance
  - External erosion (JET)
  - Overflowing tests planned for 2024/2025



VLASSENBROEK DEMONSTRATOR (BELGIUM)

Main feedback

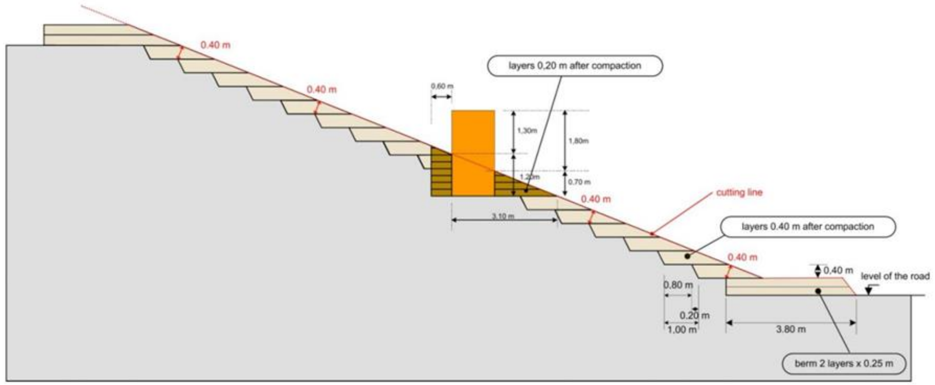
- Increase ***external erosion*** through JET (1 year to 3 years)
  160 < τ_c < 250 Pa to 280 < τ_c < 1000 Pa
- Gradual improvement in ***vegetation growth***
- Monitoring of ***permeability*** by infiltration tests using tubes or double rings on in-situ samples
  Average permeability ~10^{-7} m/s
- Evolution of ***mechanical resistance*** monitored with a light penetrometer
  Too high resistance (in the first 20-40 cm) after 1 year
  Onsite coring planned for 2024-2025
- Overflowing tests planned for 2024-2025



HEDWIGEPOLDER DEMONSTRATOR (THE NETHERLANDS)

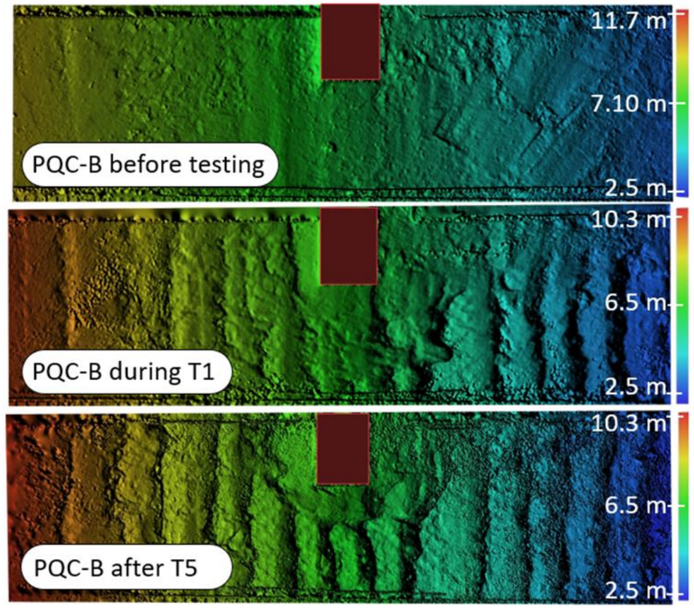
Construction details

- Clayey Soils (I_P = 20 to 45)
- ***4% - 5% lime treatment***
- Protective shell
- Height: 8m
- Slope: 2,5/1
- Treatment on the platform
- Staircase compaction
- Presence of obstacles on the slope



Testing & Short term monitoring activities

- Lab feasibility tests
- After construction: overtopping tests after 3 months



Main feedback

- Good resistance to ***external erosion***
- Improved ***availability*** of usable materials
- Increased ***resistance to erosion around obstacles***

[M. Konstadinou et al. (2023). **Lime treatment: Evaluation for use in dike applications in the Netherlands**. Journal of Materials in Civil Engineering, 35(3): 04022465]

QUESTIONS?

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