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Feedback on durability of Loire River levees reinforced with soil mixing cut-off walls

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ABSTRACT: To capitalize 11 years of data on levees reinforced with soil mixing cut off walls, recommendations on field works and the monitoring phases of cut-off walls built using deep soil mixing (DSM) techniques has been proposed. The soil mixing methods lead to properties that depend on the natural soil and the soil mixing homogeneity. A procedure was proposed for the levees reinforced with this technique on about 20 field works between 2013 and 2024. The works led, among others, to the creation of a database combining in-situ and laboratory tests in order to improve the forecast of the properties of the soil mixing from initial parameters such as the type of soil, the cement content, the moisture content and the water addition...This database would help to determine the main parameters useful for design and the execution works of cut-off walls built with DSM method for levee reinforcement.

KEYWORDS: levees, cut-off wall, deep soil mixing, mechanical performances, hydraulic performances.

1 INTRODUCTION

The purpose of this article is to present the current state of knowledge based on the results of 11 years of feedback, adaptation and monitoring from cut-off walls construction on levees. The paper presents the conditions under which the technique is suitable, but also points out the limits of its application (soil types, depth, site).

The deep soil mixing (DSM) technique proposed on two experimental sites in 2013 uses a trencher-type mixing tool to disintegrate the soil in place by mixing it with a hydraulic binder in order to improve its homogeneity, watertightness and mechanical strength. The treatment is named wet method when the mixing is done using processes allowing the injection, via the mixing tool, of a grout (hydraulic binder and water) and dry method when the binder is introduced in powder form, the necessary water so that the soil mixing is self-compacting being added via the mixing tool (Figure 1).

The permeability of the levee and its foundation soils and the control of seepage are important elements in its design and durability. The watertightness of the levee involves a series of operations consisting of limiting seepage and thereby the risks linked to internal erosion.

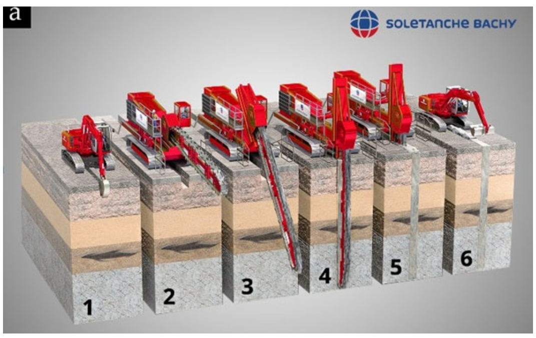

Figure 1. (a) Steps of Trenchmix® technique: (1) create a pre-trench; (2), (3) and (4) introduce the giant blade; (5) mix the soil-binder over the entire height; (6) remove the soil mixing spoils from the DSM mix (©Soletanche Bachy); (b) Reinforcement of a levee using the Trenchmix® technique (Amrioui *et al.*, 2023).

2 FEEDBACK OF FIELD WORKS AFTER 11 YEARS

Between 2013 and 2024, DREAL Centre-Val de Loire has carried out 21 projects to build cut-off walls to reinforce levees on several levees in the middle Loire against internal erosion. More than 32 km of cut-off walls were built.

The DSM techniques proposed use the CEMIII/C 32.5 N binder at 160 to 230 kg/m^3 of the soil mix. The hydraulic binder content depends strongly on the characteristics of the soils encountered. Its formulation is determined in the laboratory then tested and refined on a full-scale test. Cut-off walls have a thickness of 50 cm, a depth from 5 to 9.5 m, with an anchor in the foundation soil of the levee. The technique has limited impact in terms of noise and vibrations.

Despite different depth and levees structures, these techniques proved suitable in the majority of cases. However, some sections of levees could not be treated properly using these techniques, either because the mixture did not set, or because the expected characteristics of the cut-off wall were not achieved despite setting. This led first to walls repairs (installation of a new walls on the fresh cut-off wall without setting) and then to improve the mix by addition of quicklime to the cement (10 to 50 kg/m^3 of the soil mix) since the cause of the setting defects had been attributed in part to the presence of a high level of organic matter and/or clays. On certain sections where the mechanical strengths did not reach accepted values, a monitoring of the cut-off wall was set up to ensure the durability of the structure (in-situ permeability tests) as in Veuves (41) or La Riche (37).

Sometimes, these techniques have proved unsuitable due to particular geometry of the levee, transition zone with a lock, a bridge, a quay, etc., for reasons of space requirement for construction machines.

Table 1 provides a summary of these elements by major levees, based on the database of projects carried out by the DREAL Centre-Val de Loire.

DSM techniques were implemented in 76% of the length of the levees reinforced by a cut-off wall without any particular adaptation.

In some casess, with soils with a dominant silty and clayey composition, an adaptation is required. Depending on the cases encountered, this can be explained by the nature of the clays and their capacity to adsorb water, the significant presence of organic matter or an impossibility of homogeneous mixing (incomplete destructuring of the soil making the soil mixing locally heterogeneous). For 19.5% of the linear of cut-off walls built, these techniques proved suitable with an adaptation: addition of quicklime in the formulation (18.3%) or remixing of the cut-off wall (1.2%). Thus, the cut-off walls produced using DSM techniques (with or without quicklime) now appear to be of good quality for 96% of the linear.

For 4.3% of the linear of cut-off walls built, the characteristics (most often mechanical strength, , measured by unconfined compressive strength UCS) are below expectations and have led to the implementation of a monitoring system over at least 10 years. The cut-off wall with the most worrying charcateristics is that of the Cisse-Vouvray levees, in Veuves.

Furthermore, for almost 3.5% of the initially planned linear cut-off wall, the technique has not been implemented (abandonment or another more suitable technique used).

3 SOME RECOMMANDATIONS ON CUT-OFF WALLS

In this paper, the feedback since 2013 is be used to try to propose some recommendations or procedures based on the cases that have been studied as well as perspectives that will allow to improve the knowledge on long-term performances of cut-off walls.

3.1 *Design*

For the design of levee reinforcement using a cut-off wall, geotechnical investigations (core drilling with intact samples taken, auger drilling with reworked samples taken, static penetrometer drilling, in-situ permeability tests, etc.) and geophysical investigations (electrical resistivity tomography, for example) as well as laboratory tests (soil identification, CU+u and CD triaxial shear tests, Hole Erosion Test (HET) and Jet Erosion Test (JET) erosion tests, soil mixing formulation study) are necessary for the characterization of the lithological assemblies within the levee and its foundation soil.

3.2 *Hydraulic flow modelling and slope stability calculations*

Generally, cut-off wall is designed to be anchored in low permeable foundation soil of the levee (if any), without reaching the substratum, so as not to block hydraulic seepage in depth (and to transfer them laterally).

Among the four internal erosion mechanisms identified, the risk of regressive erosion is assessed using two approaches: assessment of a hydraulic gradient using the Lane criterion and modelling of hydraulic gradients at the levee toe, on landside, using software such as Seep/w or Plaxis 2D. The model was carried out in steady-state and transient conditions using a modified limnigram with a maximum flood level maintained for 15 days, which is conservative with respect to the duration of Loire floods. In the model, the permeability of the cut-off wall is considered equal to 1.10^{-8} m/s.

Slope stability calculations, using software such as Slope or TALREN, have to include the temporary phases of works, in particular taking into account the floor area and weight of the Trenchmix® machine, when it is digging the mixed soil at the crest and the mixture is in a fresh state.

3.2.1 *Formulation methods and long-term control usually used on site*

During preparation phase on the field, the company is supposed to achieve a formulation study in order to estimate cement content as well as initial moisture content of the soils and water addition in the formulation. The different layers crossed by the cut-off wall are one of the key parameters to take into account. To reach this objective, it is necessary to collect a sample of soil from the surface until the chosen depth using an auger in order to be able to mix all the layers in the laboratory. From this homogenized material, mixtures are made in the laboratory at the prescribed contents, in order to evaluate hydraulic and mechanical properties of the materials and to check if the imposed criteria are reached: $UCS_{28} \geq 1,5$ MPa et hydraulic conductivity $k_{28} < 1.10^{-8}$ m/s).

Table 1. DSM works on levees led by the DREAL Centre-Val de Loire between 2013 and 2023.

Levees	Year	Length (m)	Main soil type	Cement & quicklime (m)	Cement setting failure[1] (m)	No-compliant UCS or k[2]
Cisse-Vouvray	2014	1 000	silt			1 000
Orléans	2013 to 2018	7 250	silt & clay	3 640	385	
Tours	2014 to 2021	13 100	sand & silt			400
Nevers	2020	770	sand & silt			
Blois	2021	1 430	sand & silt			
Ouzouer/Sully	2022 to 2023	910	silt	455		
Authion	2021 to 2023	8 100	silt	1 900		
Total	**2013 to 2023**	**32 560**	-	**5 995**	**385**	**1 400**

1 Needing for construction of a 2nd cut-off wall on the non-compliant one
2 Needing for implementation of a cut-off wall efficiency monitoring system

Several contents were then tested (CEMIII/C 32,5 N cement and, possibly, quicklime, depending on the organic matter and clay contents). UCS and permeability tests are then carried out in the laboratory at 7, 14, 28 and/or 56 and 90 days.

Once the formulation study is conclusive, a full-scale test is carried out on site to confirm it.

Despite the precautions taken during the design phase, the formulation study may locally conclude that there are problems with the mix setting and require "overdose" incompatible with the DSM technique (content higher than 240 kg/m^3). A different technique will then be used locally: grouted wall or sheet piles, for example.

The formulation of the cut-off wall can have a significant financial impact on the project. Being generally at 180kg/m^3 of CEMIII/C 32,5 N, the cement content can rise to around 250kg/m^3 and require the addition of lime to neutralise the organic matter. Beyond that point, it is appropriate to change the reinforcement technique. It is therefore important to assess this parameter at the design stage.

3.2.2 *Integration of cross networks*

Crossing networks represent weak points in the levees. Therefore, they have to be integrated into the watertight reinforcement at the design stage.

Shallow networks (up to 1.5-2 m of depth) can be integrated into the reinforcement using a DSM technique, provided that they are rerouted for the duration of the construction and a reservation is made in the cut-off wall.

Watertight devices are then positioned and cast in excavable concrete when the pavement structure is repaired.

The integration of deep networks is also possible but it is not presented in this paper.

3.3 *Control during execution works*

3.3.1 *Full-scale test*

The full-scale test is generally realised on 40 m minimum per formulation to be tested.

3.3.2 *Production phase of the cut-off wall*

During the construction, the depth of the cut-off wall is checked with a depth gauge and its position by a surveyor's reading. The width of the cut-off wall is determined by the width of the tools of the trenchmix machine.

A control procedure is implemented consisting of the company taking samples in the fresh material every 100 m in order to have density of the fresh soil mixing, UCS and permeability at 7, 28 and/or 56 days, and 90 days and compare the results with the threshold values.

The continuity of the cut-off wall is ensured when reinforcement works on a cut-off wall built during previous works, as well as when reinforcement works on a cut-off wall created after a work interruption on this site (end of day, weekend, incident, etc.):

- Existing cut-off wall from a previous operation or interruption due to an incident: cover of 5 m over the entire depth of the cut-off wall
- Cut-off wall interrupted at the end of the day or during the week: cover of 2m over the entire depth of the cut-off wall.

3.4 *Recommendations to evaluate long term properties of the treated materials*

Following the works carried out on different sites, an initial proposal for a control and monitoring procedure has been made (Figure 2).

1. The company leads a formulation study on all soil layers to be treated with cement over 7, 28 and 90 days to check that the required parameters are reached.
2. The external control leads also a formulation study on all soil layers to be treated with cement over 7, 28 and 90 days, on same soils samples and, possible, on different linear of the cut-off wall.
3. The external control adds tests at 6 months. The 6 months tests confirm that the proposed formulation allows to maintain the hydraulic and mechanical performances at long term. These data can be useful for database. The six months tests have to be defined by the owner.
4. Construction of the cut-off walls by the company with sampling every 100 m at two depths. Every 200 m, samples are prepared for UCS and k tests at 7, 28 and 90 days.
5. The external control follows construction of the cut-off wall and samples soil mix about every 600 m, for UCS and k tests at 7, 28 and 90 days.
6. After cut-off wall construction, samples that have not tested are kept by the external control for 6 months tests.
7. After 6 months, core drilling of the cut-off wall and UCS, k tests will be performed. The results are compared to the external control tests, formulation study and control tests.
8. Long term properties could be measured through core drilling of the cut-off wall between 1 and 10 years (or more). Indeed, long term properties can still evolve 8 years (Patouillard *et al.*, 2024).

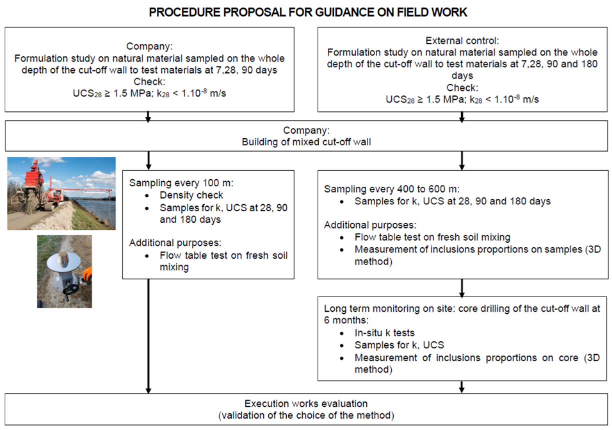

Figure 2. Procedure for long term control of cut-off wall.

4 SOME IDEAS FOR CHARACTERIZING FRESH AND CURED MATERIALS

4.1 *Fresh material characterisation*

Tests were conducted on two sites, respectively in 2017 and 2018: the flow table test was used to determine the consistency of the mix in the fresh state.

Based on the initial results, it appears that the impact table test is more suitable for to the soil mix materials than the Abrams cone.

This test should also be used on future projects to determine whether there are any relationships between the characteristics measured in the fresh state and those measured at different curing times.

Similarly, comparisons between the characteristics obtained in the laboratory during the formulation study and those obtained on the control samples will be compared in order to establish a database.

4.2 *Effect of the inclusion proportion on mechanical and hydraulic properties of treated materials*

Quantifying the of the inclusions proportion in samples from control tests and in cored samples could provide a better understanding of the properties of the material produced using the Trenchmix® technique.

Amrioui *et al.* (2023) developed innovative 2D (measurements on sample surface) and 3D methods (measurements on sample slices of 3 to 45 mm thickness), involving image analysis, to characterize the heterogeneities of DSM materials, with different volume fraction, size and shape distribution of unmixed soil inclusions and gravels (Figure 3), revealing their impact on the engineering properties of DSM materials, particularly the impact on water permeability, which had not been explored in the literature. They complete previous 1D and 2D methods (Denies et al., 2012).

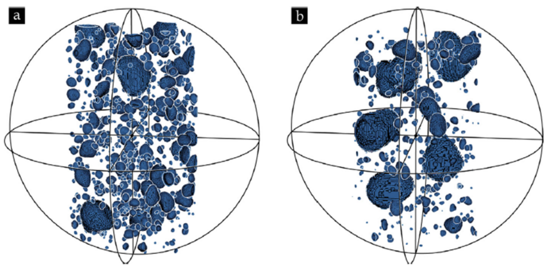

Figure 3. Generation of a DSM model: (a) soil inclusions; (b) gravels with volume fraction.

Numerical simulations, using real inclusion mesostructures or artificial ones, have enabled 2D and 3D models to be set up to accurately assess the hydromechanical properties of DSM materials, while considering their specific features, such as the presence of unmixed soil inclusions and the interfacial transition zone (ITZ) that surrounds them. Indeed, microstructural investigations carried out on DSM samples from the site partially revealed the existence of an ITZ several hundred micrometers thick surrounding the soil inclusions, a less cemented zone with poorer mechanical and microstructural properties than the soil-cement matrix.

The procedure in Figure 4 describes the steps from image analysis to the calculation of mechanical properties using Finite Element Modelling (FEM) such as COMSOL and DISROC.

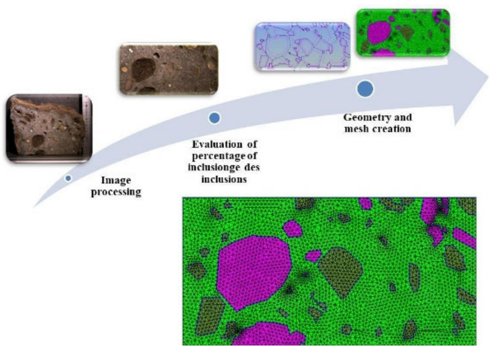

Figure 4. Procedure for model construction from image analysis to evaluate mechanical and hydraulic properties.

For hydraulic properties, the geometry and mesh of the model are shown in Figure 5. The flow lines and velocity variations are presented and illustrate the effect of inclusions and their permeabilities on the seepage in the model. It highlights the importance of the matrix's interconnectivity effect on the equivalent permeability. Mechanical strength decrease and hydraulic conductivity increase as the inclusions proportion increases, especially for larger inclusions.

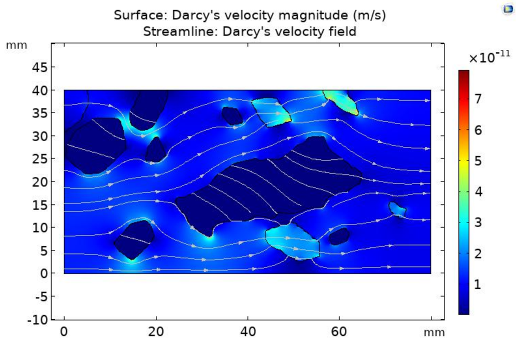

Figure 5. Evaluation of hydraulic properties from the model.

4.3 *Comparison between data obtained from laboratory mixtures and those obtained from samples taken on site*

Depending on the natural materials encountered, the correlations between the parameters obtained from periodic sampling and those obtained by laboratory studies are completed by the construction sites carried out and the construction sites to come. They differ according to the natural materials treated.

In the preliminary study for design, only criteria in hydraulic conductivity values ($k_{28} < 1.10^{-8}$ m/s) and UCS ($UCS_{28} \geq 1,5$ MPa) are imposed. However, in the cases studied in the laboratory, it has been shown that mechanical criteria based only on UCS are not sufficient and the values of the elasticity modulus are often used. E_{50}, V_p or correlations between these moduli and UCS for example allows to frame the values obtained from samples taken on site (Amrioui *et al.*, 2022).

4.4 *Test database*

A database has been established from site works as well as from laboratory tests. In this paragraph, an example of feedback on a cut-off wall is given and the work on the laboratory database is presented.

4.4.1 *Feedback on the use of quicklime complementary to CEM III/C 32.5 N cement*

As mentioned above, adaptations to soil mixing formulations have sometimes led to the use of quicklime. This use is justified in the presence of soils whose organic matter content, measured by calcination, exceeds 3%. One example of the use of quicklime is the construction site of a cut-off wall in Sigloy in 2018. In 2021, a check was carried out by coring followed by permeability and UCS tests in the laboratory.

Figure 6 shows the results of the control tests carried out on the material of the cut-off wall. Its hydraulic and mechanical characteristics are satisfactory and confirm the relevance of the chosen formulation.

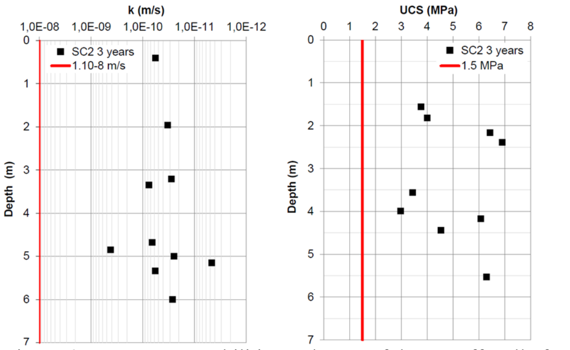

Figure 6. Permeabilities and UCS of the cut-off wall after 3 years.

4.4.2 *Laboratory database*

A database has been established from laboratory tests with different types of soils, cement content, water/cement ratio W/C …

Szymkiewicz (2011), Guimond-Barrett (2013) and several construction projects helped to increase the database for laboratory tests as well as for in-situ tests.

Some correlations to evaluate mechanical strength of soil mixing materials are proposed for different type of soils, such as for example Szymkiewicz *et al.* (2012) for sand.

Tinoco *et al.* (2019) purposed a novel approach based on soft computing techniques for UCS prediction of soil cement mixtures, reproducing the major effects of the input variables W/C ratio, cement content, organic matter content and curing time, which are known as preponderant in soil cement mixtures behaviour.

Similar procedure has been used with our database to validate the correlations that could exist between the different parameters. The second step would be to merge laboratory database with field database. This is still in progress.

As far as laboratory database is concerned, it has been entered into the R software, which consists of performing a statistical analysis of the available data. It is based on the principle of machine learning. This database is available in order to predict the properties of materials based on input parameters such as soil type, clay type, cement content, water content, W/C ratio, etc.

5 CONCLUSIONS AND PERSPECTIVES

The DSM cut-off walls built during experimental projects on the Orléans levee in 2013 demonstrated good performance over time, with satisfactory hydraulic and mechanical characteristics after 10 years.

Larger projects conducted over the same period by the DREAL Centre-Val de Loire have shown that this technique adapts well to different levee structures in the majority of cases encountered. However, knowledge of the soils and the accompanying water table of the river are essential for its implementation.

A full-scale test is necessary to validate the technique at the start of the works, as well as regular checks of the cut-off wall's characteristics during its construction (samples for UCS and permeability measurements).

The DSM technique for cut-off walls construction offers significant advantages (no excavation required, limited vibrations, no concrete plant needed when dry method is used, for examples), making it easy to use for levee reinforcement, on long linear. However, this technique can have limitations which need to be known at the design stage:

- Depth, limited to 9.5m
- Formulation with a maximum hydraulic binder content of 240 kg/m^3
- Material sensitive to clay fraction and/or setting disruptors

In some cases, additional investigations may lead to the recommendation of another technique (5% of the linear). On some sections, the cut-off wall poor performance has led to the implementation of a long-term monitoring.

A database of all the soil mixing materials produced in the laboratory and on site will be used to predict the hydraulic and mechanical performances of cut-off walls in short and long terms.

Feedback from these projects contributes to the technical guide for levee reinforcement published by the French Committee for Dams and Reservoirs (CFBR, 2021).

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