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Application of soil mixing (CSM) in stiff clay for dike stabilization

Application de la méthode soil mix (CSM) dans de l'argile raide pour la stabilization de digues

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ABSTRACT: Along one side of the river Scheldt (Belgium), several slope instabilities have occurred over the last decades. All instabilities are related to a stiff tertiary clay layer with a limited thickness (3m) and with very low residual strength characteristics. Due to the low strength, it is nearly impossible to restore the slopes with a natural gentle slope and stabilizing measures are required. One of the aspired techniques is to install transverse soil mix panels in the dikes to stabilize the slopes. An on-site test was performed to validate the possibility of improving the soil characteristics of the stiff clay by using the cutter soil mix (CSM) technique. It is well known that stiff clays are difficult to mix, therefore, different W/C ratios, mixing depths and mixing energies were used to optimize the results. An extensive set of laboratory tests was performed to quantify the obtained strength. Furthermore, 3D finite element calculations are performed to validate the stabilizing technique with the obtained soil mix characteristics. An overview will be given of the laboratory tests, as well as the results of the 3D finite element model.

RÉSUMÉ: Plusieurs glissements de terrain ont été observés au cours des dernières décennies le long des rives de l'Escaut (Belgique). Les instabilités constatées sont liées à la présence d'une couche d'argile tertiaire raide, d'une épaisseur limitée (3 m), affichant des caractéristiques de résistance très faibles. C'est ainsi qu' il est impossible de stabiliser les talus en rétablissant une pente naturelle plus douce. Des mesures de stabilisation s'avèrent donc nécessaires. Une des techniques envisagées est d'installer des panneaux soil mix transversaux à travers les digues afin d'en stabiliser les pentes. Un essai sur site a été réalisé pour valider la possibilité d'améliorer les propriétés mécaniques de l'argile tertiaire incriminée en utilisant la technique du Cutter Soil Mixing (CSM). Il est un fait connu que les argiles raides sont difficiles à mélanger. En conséquence, différents rapports eau/ciment et différentes profondeurs de traitement et énergies de mélange ont été utilisés. De nombreux essais de laboratoire ont ensuite été effectués sur des échantillons pour quantifier les résistances obtenues. Ensuite, des simulations en éléments finies 3D ont été réalisées de manière à valider la technique de stabilisation en tenant compte des résistances du matériau soil mix obtenues. Le présent article fournit un résumé des essais de laboratoire ainsi qu'une vue d'ensemble des résultats des simulations numériques.

Keywords: Soil mixing, teriairy clay, dike/slope stabilization

1 INTRODUCTION

Along the right bank of the river Scheldt (Belgium), several slope instabilities exist between Melle and Dendermonde. These slope instabilities are all related to the presence of a stiff, layered, tertiary clay stratum, which has very low residual strength characteristics and which is tilted in the N-NE direction. Some of the instabilities are quite shallow and are limited in extent, whilst others are much larger (extending up to a distance of 100 m from the river, and reaching a depth of 15 m), depending on the depth of the clay layer at the respective location.

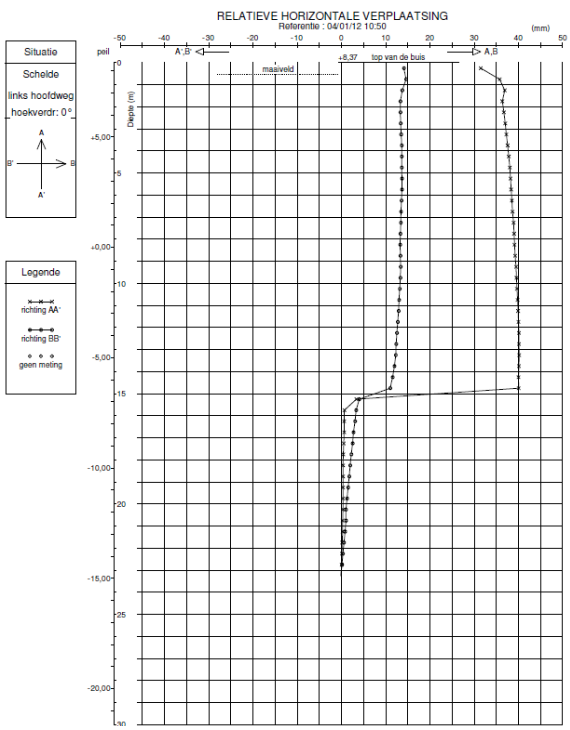

Figure 1. Example of inclinometer measurements within an instable area

Figure 1 shows inclinometer measurement within one of the largest instable areas, which demonstrates a horizontal displacement of 4 cm over a period of less than 1.5 year. The inclinometer measurements show a very localized displacement at the depth of the sliding surface. At most locations, the displacement does not continuously occur in time, but rather in small steps, when high ground water tables and low tides in the river coincide.

2 SOIL MIXING

The installation of transverse soil mix panels is considered to be a possible stabilization technique for the above described instabilities. Since several decades, the deep mixing method is used for ground improvement works and for the construction of cut-off walls and earth-water retaining walls, in particular in Belgium and in the Netherlands (BBRI/SBRCURnet, 2018). The deep mixing method (DMM) is an on-site soil treatment, mixing in-situ ground with cement (and/or other binders) and water, to obtain improved columns or panels. The soil mix columns or panels have an increased strength, a reduced permeability and a reduced compressibility. A continuous wall can be obtained by overlapping individual columns or panels.

In the USA, deep mixing is regularly used to improve the stability of embankments or levees (FHWA, 2013). Filz et al. (2012) report on three examples of levees, which were improved, after hurricane Katrina, by the use of continuous shear walls oriented perpendicular to the levee centerline. The main advantage in using transverse walls is that the soil hydrology is not disturbed.

Soils which are best suited for treatment with cutter soil mixing (CSM) are soft cohesive soils with high water content and loose, fine granular soils. Stiff soils, like tertiary clays appear to be less suited to be mixed in situ. However, as the required increase in strength to obtain a stabilized situation is limited, a test site was planned in order to investigate the possibility of using CSM in this specific case.

3 ON-SITE TEST AND LABORATORY TEST RESULTS

3.1 On-site test

In Melle, where the tertiary clay layer sits quite shallow underneath the ground surface, an on-site test was conducted to verify if the tertiary clay was mixable and to obtain the improved soil characteristics. The test was performed very close to an instable area, where the top of the clay lies 3 to 5m below the ground surface. The thickness of the clay layer varies between 3 to 5 m.

Four continuous shear walls, each made of three distinct panels, were executed, by the company Soetaert NV (Jan De Nul Group), with a CSM machine presenting two sets of counter rotating, vertically mounted cutter wheels. During the process, a water-cement slurry is injected, while the wheels cut the surrounding soil to form panels (see Figure 2). Different W/C ratios, mixing depths and mixing energies were used for the different panels, looking for the optimal result. For all panels, an amount of cement of 400 kg/m³ was used (binder type Holcim® Dorodur H50). The details of the CSM panels are shown in Table 1. For each second panel, the rotary cutter made an extra up and down movement. On this specific site, below the tertiary clay layer lies a clayey sand layer. Above the tertiary clay layer, the soil varies between soft clayey material and sand.

For each shear wall, the outer panels are first executed (primary panels), after which the intermediate panel is made.

Figure 2. CSM machine and cutter on the test site of Melle

3.2 On-site sampling

In order to obtain test samples for the laboratory tests, three different techniques were used: wet grab sampling, use of liners and core drilling.

The wet grab samples were obtained by the use of a wet grab sampler, allowing to take samples over the height of the clay layer. Samples were composed by tamping material in PVC cylinders (see Figure 3).

The liners consist of hollow PVC tubes with a diameter of 10 or 20cm, fitted in a steel tube, which is pushed in the fresh soil mix material, immediately after mixing. However, due to the stiffness of the mixture and the presence of large inclusions of clay, it was not possible to obtain representative samples with this sampling method.

Vertical core drilling delivered the best samples (10 cm diameter) for the laboratory tests.

Table 1. Details of the shear walls

Wall	Ground level	Top of tert. clay	Depth of soil mix			W/C factor
			Panel 1	Panel 2	Panel 3	
A	+8,57 mTAW†	+3.5 mTAW	-2mTAW	-2 mTAW	-3 mTAW	1.5
B	+8,62 mTAW	+2.5 mTAW	-2mTAW	-2 mTAW	-3 mTAW	1.5
C	+8,69 mTAW	+3.0 mTAW	-2mTAW	-2 mTAW	-3 mTAW	1.5
D	+8,76 mTAW	+4.5 mTAW	-2mTAW	-2 mTAW	-3 mTAW	2

†TAW: reference point for the altitude in Belgium

A first set of cores was drilled after 14 days, while the material did not completely harden yet. A second set of cores was drilled after 1 month.

Figure 3. Wet grab sampling

3.3 Laboratory test results

The following parameters were determined:

- density,
- unconfined compressive strength (UCS),
- tensile splitting strength,
- shear strength,
- modulus of elasticity,
- percentage of unmixed soft soil inclusions (by visual analysis).

The drilled core samples were taken along the full height of the soil mix panel, but the lab tests were only performed over the height of the clay layer. The visual analysis, determining the percentage of unmixed soft soil inclusions was performed over the full length of the soil mix panel. This is performed by measuring the lengths of soft soil inclusions along 4 lines (applied every 90° around the core) and dividing the sum through the total length of the lines (see Figure 4).

Tests on the cored samples were performed after 28 days and after 77 days, to obtain information on the hardening of the material in time as well. The results of the lab tests are given in Figure 4 to Figure 8. Only the cores from the zone of the mixed tertiary clay were tested and are plotted in these figures.

Figure 4. determination of soft soil inclusions (BBRI/SBRCURnet, 2018)

Figures 5 and 6 show compressive and tensile splitting strengths, respectively after 28 and 77 days. After 28 days, the unconfined compressive strength varies between 0.6 and 2.2Mpa, with most samples giving a strength larger than 1Mpa. After 77 days, the UCS varies between 1 and 2.85Mpa. The minimum tensile splitting strength is 0.1 MPa after 28 days and 0.15 MPa after 77 days. It is clear that the strength of shear wall D (with a W/C factor of 2) is much lower than the strength of the other walls. The results of this panel were not taken into account when deducing the strength parameters of the soil mix material for the calculations.

Figure 7 shows the modulus of elasticity after 28 days. Apart from the shear wall D, all E-values exceed 1.1GPa.

Figures 8 and 9 show the cohesion and the friction angle (both peak and residual values), based on the results of direct shear tests. The direct shear tests were performed on quite large samples of 100 mm diameter. Peak cohesion exceeds 280 kPa for all samples, residual values vary between 40 kPa and 120 kPa.

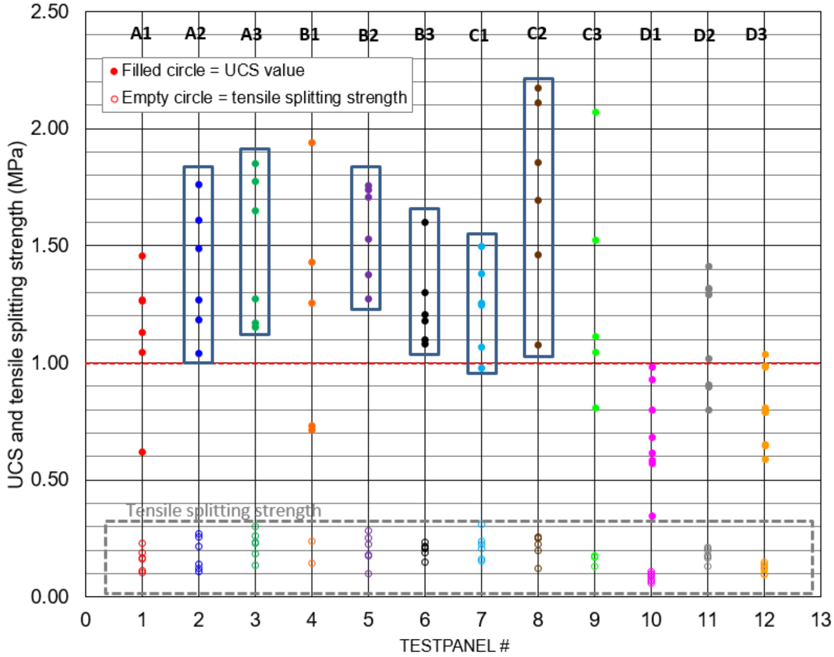

Figure 5. UCS and tensile splitting strength after 28 days

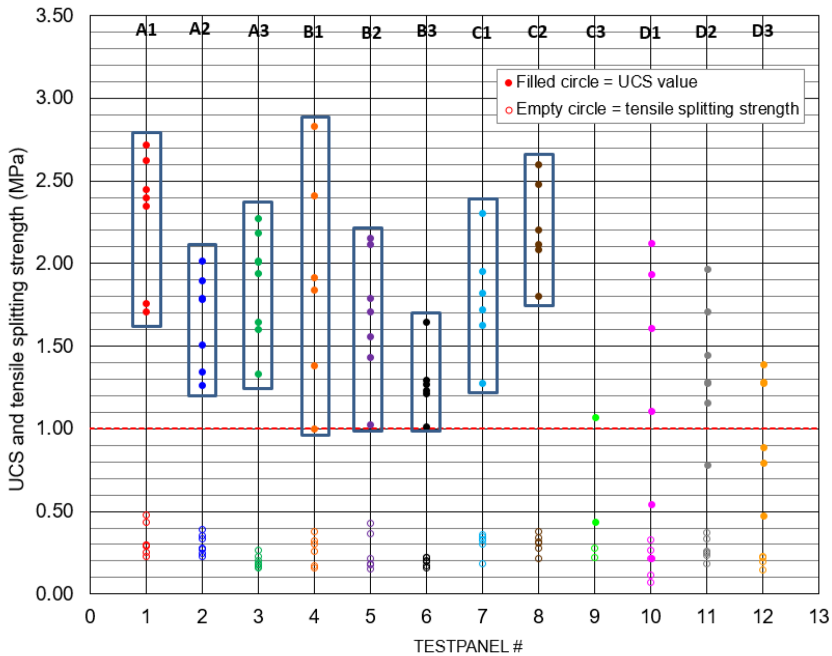

Figure 6. UCS and tensile splitting strength after 77 days

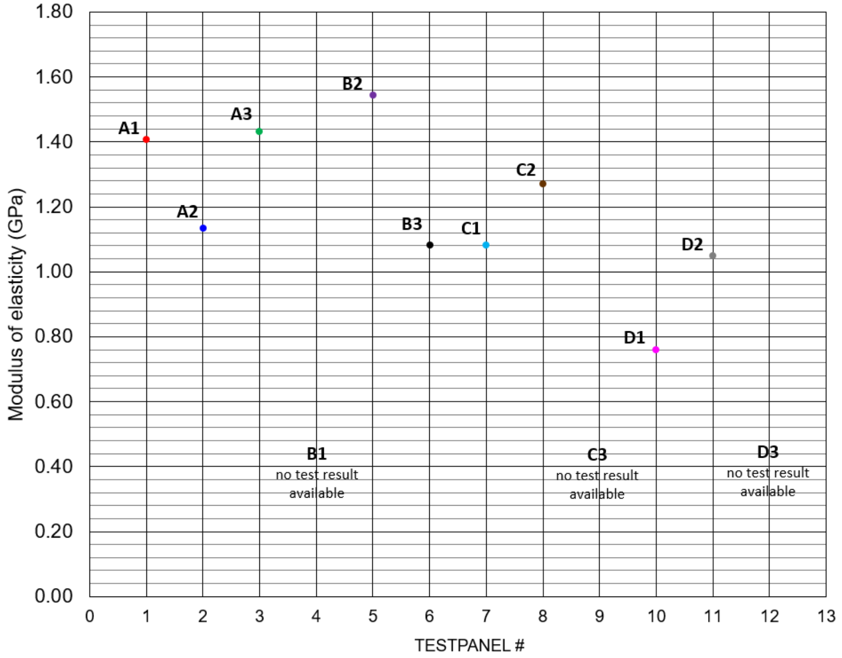

Figure 7. Modulus of elasticity after 28 days

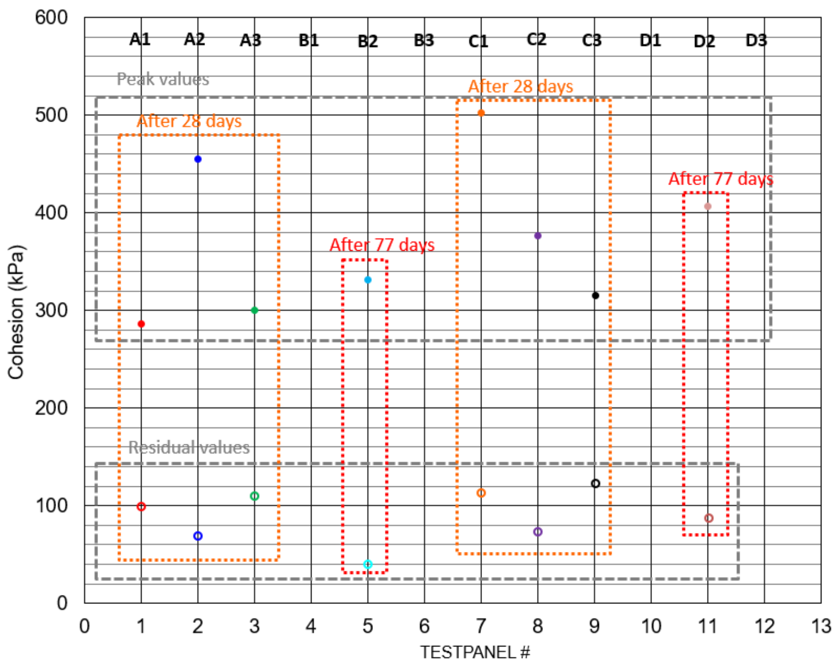

Figure 8. Cohesion, based on direct shear tests

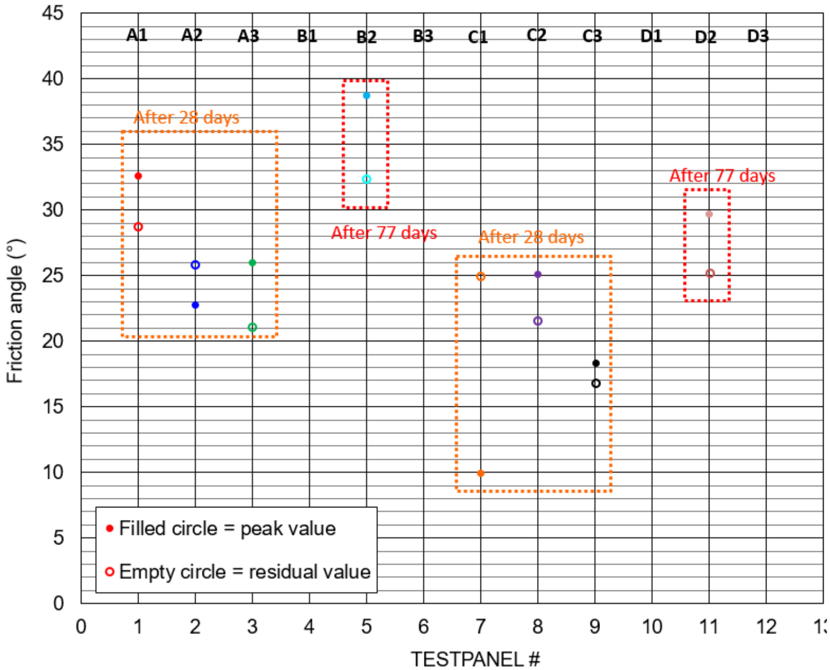

Figure 9. Friction angle, based on direct shear tests

A soil inclusion analysis was performed according to Denies et al. (2012) and the percentage of unmixed soft soil inclusions varies between 0 % and 18 % for the largest part of the cores. Some exceptions with percentages of inclusions larger than 20, 30 to 40 % were found, but they are probably due to the fact that the drilling was performed at the edge of the concerned panels and thus, the samples partly contain pure soil. Since the inclusions are local, it is assumed that this will not have an influence on the average strength along the sliding plane.

4 3D FINITE ELEMENT CALCULATIONS

Based on the results of the on-site test, a 3D finite element model was built in Plaxis 3D (see Figure 10). A "slice" was modeled, with centrally one whole shear wall and at the edges two "half" walls. The required center to center distance of the shear walls to obtain a stable situation is 6 m. In order to obtain a stable temporary situation and for the purpose of making the soil mix panels on site, the existing dike has to be partly removed.

The following parameters were retained for the soil mix material in the calculations, based on the minimal obtained values in the laboratory tests after 28 days: UCS value of 742 kPa, tensile strength of 109 kPa, E-modulus of 1196 MPa.

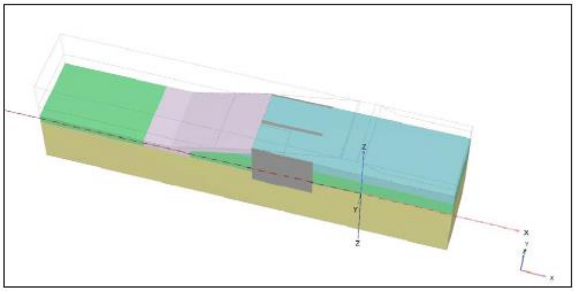

Figure 10. 3D finite element model in Plaxis

Figure 11 shows the displacements and the failure mode in the final stage (after levelling the dike to its original height). From the bottom figure, the arching phenomenon developing between the shear walls can clearly be seen.

One of the aspects which needs to be considered is the stability of the slope during the stabilization works. As the slope is already instable during low tides, and as the soil mix material is initially very soft (fresh/wet mixture of soil, water and cement), extra measures need to be considered to obtain a stable temporary situation.

Examples of such measures are ground water lowering, lowering of the dike and during the work progress, only executing panels after the adjacent panels are sufficiently hardened.

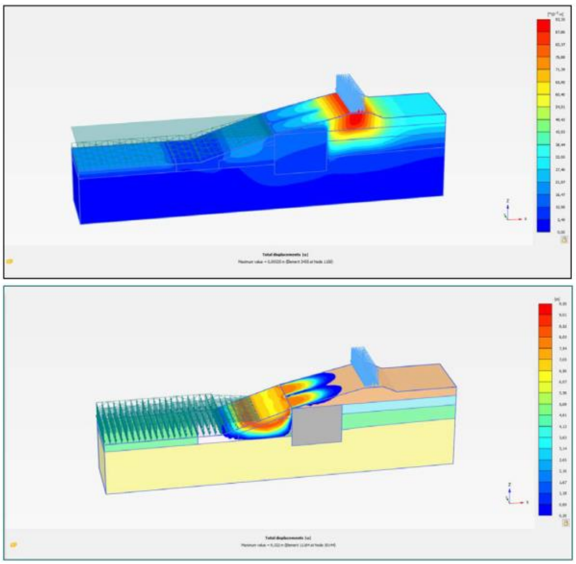

Figure 11. Results of the 3D-FEM calculation: top: displacements in the final situation & bottom: failure mechanism

5 CONCLUSIONS

In order to stabilize failing dike slopes along the river Scheldt in Belgium, the use of transverse cutter soil mix (CSM) panels is explored. An on-site test was conducted to verify if the stiff, tertiary clay, responsible for the slope instabilities, was mixable with the CSM technique and could be improved. Laboratory tests were performed on drilled cores, resulting in values for compressive and tensile strengths, E-modulus, shear strength and cohesion. 3D Plaxis calculations were performed for the purpose of validating the proposed solution with the soil mix shear walls, installed perpendicular to the centerline of the dike.

Based on the results, it is concluded that a solution based on soil mix panels, perpendicular to the river, can be achieved, even with the presence of the stiff tertiary clay layer. A quote request was recently sent out in order to stabilize a first area in Melle. A challenge will be to maintain the stability during the execution and the hardening of the soil mix panels.

6 ACKNOWLEDGEMENTS

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Most laboratory tests were performed by the Belgian Building Research Institute (BBRI).

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