REAL-SCALE TESTS ON SOIL MIX ELEMENTS

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Abstract Originally developed for ground improvement works, the deep mixing method (DMM) has increasingly been applied in recent years for the realization of soil and water retaining structures and as alternative to traditional foundation solutions. From practice, there is a real need for practical guidelines dealing with the execution, the design and the control of such applications. With the aim of developing such guidelines, the BBRI 'Soil Mix' project was initiated in 2009. Within this research project, deep soil mix (DSM) material from 38 Belgian construction sites has been tested. In spite of the large advances in the mechanical characterization of the DSM material, one major issue remains the representativeness of the typical core samples in comparison with the real scale behavior of the soil mix elements. There is among others the question of the influence of the unmixed soft soil inclusions on this behavior and the issue of the scale effect which must be considered in the design. In order to investigate these questions, 8 large scale UCS tests and 17 large scale bending tests have been performed on excavated soil mix elements. The present paper discusses results of this experimental campaign, presents some research perspectives and highlights different aspects related to the design of soil mix elements for the realization of retaining wall or foundation solution.

INTRODUCTION

Since several decennia, the deep mixing method (DMM) has been used to improve the strength and deformation characteristics of weak soils. In recent years, deep mixing has increasingly been applied – in Belgium and in other countries – for the realization of soil and water retaining structures and alternative foundation concepts. With regard to the execution of the DMM, one can refer to the European standard EN 14679 on deep mixing (2005) that was elaborated under the umbrella of CEN TC 288 "Execution of special geotechnical works". However, from practice, it has been experienced that this execution standard does not provide enough pragmatic information and guidelines, in particular for the more recent applications of the deep mixing method (with retaining and bearing functions). The same need by the sector for guidance rules linked to design aspects in the context of Eurocode 7 was experienced as well. With the aim of developing such guidelines and in order to provide feedback to the European standardization platforms, the Belgian Building Research Institute (BBRI) has initiated the BBRI 'Soil Mix' project (2009-2013) in collaboration with the KU Leuven and the Belgian Association of Foundation Contractors (ABEF), the Belgian branch of the EFFC. Within this research project, deep soil mix (DSM) material from 38 Belgian construction sites, with various soil conditions and for different execution processes (CVR C-mix®, TSM and CSM), has been tested (Denies et al., 2012).

The large amount of test samples from real construction sites has allowed
- to characterize in detail the hydro-mechanical behavior of the DSM material realized in Belgian soils,
- to identify the field of application of the DMM,
- to develop guidelines and QA/QC procedures with regard to the execution processes in Belgium.

An overview of the results of the research program obtained in the period 2009-2012 was published at the occasion of the ISSMGE TC211 International Symposium on Ground Improvement IS-GI 2012 (Denies et al., 2012).

In spite of these advances, one major issue remains the representativeness of *in-situ* core samples for *in-situ* behavior. There is among others the question of the influence of the unmixed soft soil inclusions on the mechanical behavior of the DSM material and the consideration of the scale effect which must be considered in the design. In order to investigate these questions, 8 large scale UCS tests and 17 large scale bending tests were conducted on excavated soil mix elements installed in Belgian soils. The present paper discusses the results of this study.

LARGE SCALE UCS TESTS ON SOIL MIX RECTANGULAR BLOCKS

In addition to traditional core samples (with a diameter around 10 cm), large scale Unconfined Compressive Strength (UCS) tests were conducted on rectangular blocks with approximately a square section, with a width corresponding to the width of the *in-situ* soil mix wall (about half a meter) and with a height approximately twice the width. After being excavated, soil mix elements from five construction sites have been tested. The results of all the UCS tests performed in KU Leuven are presented in Table 1. The details of the test procedure and results are given in Vervoort et al. (2012).

The main aim of testing large blocks is to get a better idea about the *in-situ* behavior and characteristics of real soil mix material. In particular, if the material is more heterogeneous: the scale effect should be more important. For example, if a soil inclusion with a diameter of about 5 cm is present or not in a core sample with a diameter of 10 cm, this will affect the strength and the stress-strain behavior of the core significantly, in comparison to the presence or absence of such a single inclusion in a block with a width of half a meter.

Table 1: Overview of large scale tests and core samples for the five different sites

Sites	Knokke	Wetteren	Heverlee		Aalst		Leuven	
Soil type	Quaternary sand	Mixed soil and construction waste	Tertiary sand		(Sandy) loam		(Medium dense to dense) sand with local stones	
Execution system	Soil mix panel CSM	Soil mix panel CSM	Soil mix panel CSM		Soil mix Panel CSM		Soil-cement column TSM	
Block dimensions [cm]	61x53x124	55x48x90	57 x 75x 119	58 x 53 x 120	54 x 50 x 119	54 x 79 x 119	55 x 46 x 112	52 x 43 x 108
Block characteristics								
UCS [MPa]:	8.3	2.1	4.8	4.2	5.2	4.1	5.0	6.4
Young's modulus E_{tg} (tangent) [GPa]:	$13.6^{\dagger}$	$2.9^{\dagger}$	$5.6^{\dagger}$	$5.5^{\dagger}$	$6.0^{\dagger}$	$6.0^{\dagger}$	$5.3^{\dagger}$	$6.5^{\dagger}$
Young's modulus E_{sc} (secant) [GPa]:	$16.0^{\dagger}$	$3.3^{\dagger}$	$7.1^{\dagger}$	$6.7^{\dagger}$	$6.7^{\dagger}$	$6.8^{\dagger}$	$5.3^{\dagger}$	$6.7^{\dagger}$
Dimensions cores								
Diameter [mm]:	114	113	94		105		113	
Height [mm]:	230	230	200		200-210		225	
Characteristics cores = average values								
UCS [MPa]:	11.9	4.0	6.1		7.8		7.2	
Young's modulus E_{tg} (tangent) [GPa]:	$8.3^{*}/12.8^{\ddagger}$	$1.3^{*}/2.0^{\ddagger}$	$4.0^{*}/6.2^{\ddagger}$		$4.0^{*}/5.4^{\ddagger}$		$2.9^{*}/5.2^{\ddagger}$	
Young's modulus E_{sc} (secant) [GPa]:	$8.2^{*}/15.2^{\ddagger}$	$1.3^{*}/2.4^{\ddagger}$	$3.6^{*}/7.3^{\ddagger}$		$3.1^{*}/6.3^{\ddagger}$		$2.5^{*}/5.4^{\ddagger}$	

†Measurement performed with four LVDT (Linear Vertical Displacement Transducer) devices with measurement base of about one fourth of the height of the block, installed around the center of each vertical side

*Measurement performed with two LVDT devices, with measurement base corresponding to the entire length of the core sample, installed parallel to the samples axis

‡Measurement performed with two strain gages with measurement base of 60 mm, installed parallel to the sample axis

As reported in Denies et al. (2013), a linear relationship was observed between the test results obtained from the typical core samples (10 cm diameter) and the large rectangular blocks. Although there is a scatter in the test results, the UCS of the full scale blocks is about 70% of the average UCS of the typical core samples. Similar conclusion was previously drawn for soil-cement columns in Japan (CDIT, 2002). Such result should be taken into account, in the design, for the determination of the UCS characteristic value of the DSM material.

LARGE SCALE BENDING TESTS ON SOIL MIX ELEMENTS

Within the framework of the BBRI 'Soil Mix' project (2009-2013), 17 large scale bending tests were performed on excavated soil mix elements executed *in-situ* with three different systems (CVR C-mix®, TSM and CSM). The following paragraphs illustrate the execution of the soil mix elements *in-situ* and highlight some details of the preparation of the large scale bending tests. The description concerns the realization and the preparation of the soil mix panels (type CSM) but the approach is similar for soil-cement columns.

Preparation of the large scale bending tests

Firstly, soil mix panels were *in-situ* executed, such as illustrated in Fig. 1. Directly after the execution of the soil mix panels, instrumented steel profiles were introduced into the fresh soil mix material (see Fig. 2). These steel profiles had been previously equipped with two optical fibers installed in laboratory on the two opposite flanges of the steel profiles, as shown in Fig. 3. In the present case, the optical fibers (FBG/DTG technology) will be used as lost instrumentation systems for the measurement of the deformations of the two flanges of the steel profile during the bending test.

After a few days, necessary to obtain a sufficient hardening of the soil mix material, the soil mix panels were excavated and transported to the laboratory facilities of the BBRI (see Fig. 4, as illustration). Half CSM panels were then cut and transported for bending tests. The rest of the material was used for the realization of the large scale UCS tests at KU Leuven and for the mechanical characterization on typical core samples, such as illustrated in Fig. 5.

Reasons for the large scale bending tests

The large scale bending tests of the BBRI 'Soil Mix' project (2009-2013) were mainly executed:

- to analyze the moment-deflection relationships,
- to determine the "real-scale" stiffness of the soil mix walls,
- to compare the theoretical and the measured stresses in the steel reinforcement.

Configurations and monitoring of the large scale bending tests

The large scale soil mix elements (half panels and full-length columns) were subjected to 3- or 4-point bending tests, such as illustrated in Fig. 6.

The following data were continuously monitored (sampling of 0.1 Hz) during the bending test:

- the force applied to the soil mix element by means of a load cell: 1 measurement;
- the central deflection, δ, of the soil mix element (mid-length zone: under the application of the force) measured with the help of two Linear Vertical Displacement Transducers (LVDT) installed on both sides of the soil mix element as represented in Fig. 6a (2 measurement devices);
- the vertical displacement of the soil mix element at each support beams, $\delta_{support}$, measured with the help of two LVDT's installed on both sides of the soil mix element (4 measurement devices);
- the sliding between the steel profile and the soil mix material, $\delta_{sliding}$, measured with the help of one LVDT as represented in Fig. 6d (1 measurement device);
- the deformations measured with the help of the optical fibers installed on both sides of the steel profile (10 measurement bases for the inferior flange and 10 measurement bases for the superior flange of the steel profile).

FIG. 1. Execution of a soil mix panel (type CSM) on the construction site of Heverlee (Belgium)

FIG. 2. Installation of an equipped steel profile in the fresh soil mix panel just after execution

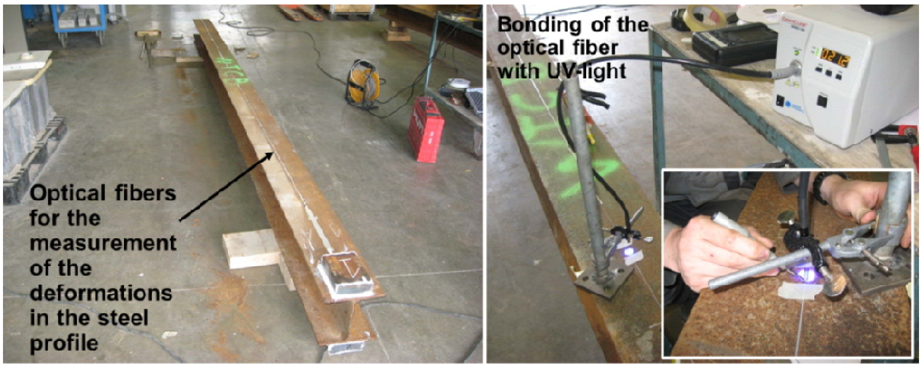

FIG. 3. Bonding of optical fibers on the two opposite flanges of a steel profile in laboratory

FIG. 4. Excavation and transportation of a real-scale soil mix panel (type CSM)

FIG. 5. Preparation of the test samples (cores, blocks and half panel) for the large scale mechanical characterization of the soil mix material

FIG. 6. Examples of test configurations used within the framework of the BBRI Soil Mix project a) 4-points bending test on a soil-cement column reinforced with a steel profile, b) 3-point bending test on a soil-cement column with a reinforcement cage, c) and d) respectively 3-point and 4-point bending tests on a half CSM panel reinforced with a steel profile

Loading procedure of the large scale bending tests

The static loading force is increased in steps until failure of the half CSM panel and each step is held constant over 5 minutes.

Test results of the large scale bending tests

The present section discusses the results of a 3-point bending test applied on half a CSM panel reinforced with a steel profile type HEA 240 (steel grade S235). This CSM panel had previously been executed in a sandy loam on the construction site of Aalst (see Table 1 for additional information).

The collaboration between the steel reinforcement and the soil mix material is first demonstrated with the analysis of the evolution of the measured deflection, δ, in function of the applied flexural moment, M. The relationship between the deflection and the flexural moment in the center of the half CSM panel is presented in Fig. 7. The measurement of the deflection is corrected taking into account the vertical displacement at the support beams ($\delta_{support}$).

The theoretical deflection of the steel profile only is given on the same graph for the sake of comparison. As a first result, the measured deflection is always smaller than the theoretical deflection of the steel profile only. As observed in Fig. 7, δ_{el} can be defined as the theoretical deflection of the steel profile only, at yield strength, and M_{el} is the corresponding value of the flexural moment. The collaboration with the soil mix material can be quantified considering the ratio between the measured deflection, δ, and the theoretical deflection, δ_{el}, of the steel profile only, at yield strength, when $M=M_{el}$. In the present case, the ratio δ/δ_{el} is equal to 0.40 (-) implying 60% gain due to the soil mix material.

Moreover the maximal moment applied during the test (defined as the moment at failure), M_{max} = 303 KNm, is largely greater than the flexural moment corresponding to the yield strength of the steel profile only, M_{el} = 159 KNm. In the present case, M_{max}/M_{el} = 1.91 (-).

These results clearly demonstrate the participation of the soil mix material to the bending resistance of the soil mix wall.

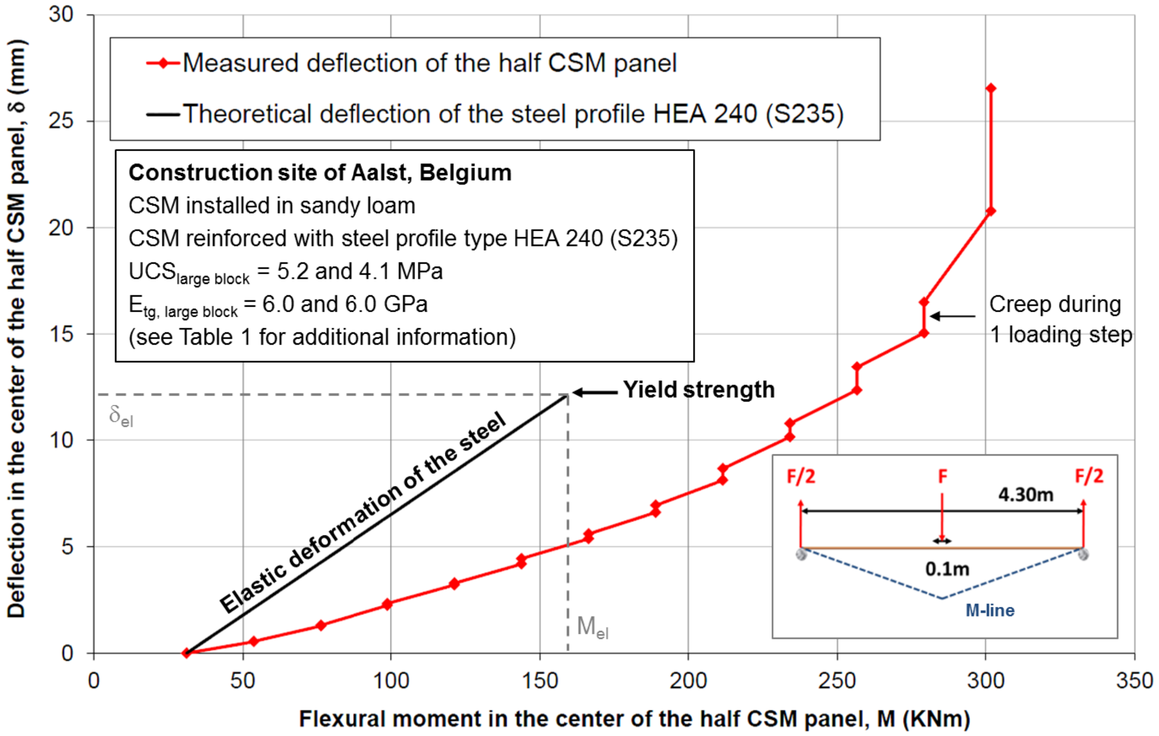

FIG. 7. Evolution of the deflection of the half CSM panel during the 3-point bending test

With regard to Fig. 7, it can be noted that there is an initial applied flexural moment different from zero which can be related to the flexural moment due to the weight of the panel put on the two support beams. In the present case, M_{weight} = 31.1 KNm. This initial flexural moment have certainly an influence on the onset of the cracking in the half CSM panel, as discussed hereunder. The measurement of the deflection is started once the force is applied to the half CSM panel. Initial deflection due to the weight of the half CSM panel is not considered in the present analysis.

The progressive sliding arising between the steel profile and the DSM material is illustrated in Fig. 8. Further investigation will be performed to question the influence of the adherence between both materials on the bending resistance of the soil mix walls. Indeed, the flexural behavior of the half CSM panel seems to remain elastic until the onset of the sliding. Creep is then observed in spite of the short duration of the loading step, as illustrated in Fig. 7.

The next stage of the study is the assessment of the real scale stiffness of the half CSM panel. The real scale stiffness, EI_{real}, of the half CSM panel can be appraised considering the following equation:

$$EI_{real} = \frac{(M - M_{weight})L^2}{12\delta} \qquad (1)$$

where L is the distance between the two support beams.
The evolution of the real scale stiffness of the half CSM panel in function of the flexural moment is illustrated in Fig. 9. During the test, the real scale stiffness decreases with the increase of the flexural moment – as a result of the progressive opening of the cracks into the soil mix material – and finally reaches the stiffness of the steel profile only, at failure (once $M = M_{max} = 303$ KNm).

In Fig. 9, the evolution of the real scale stiffness of the half CSM panel is compared to:
- the theoretical stiffness of the steel profile only,
- the theoretical stiffness of the soil mix material only (computed on the basis of the geometrical properties of the section and considering the tangent modulus of elasticity obtained from the real scale UCS test, E_{tg} = 6 GPa, as given in Table 1),
- the total theoretical stiffness of the reinforced half CSM panel (the sum of the two previous values).

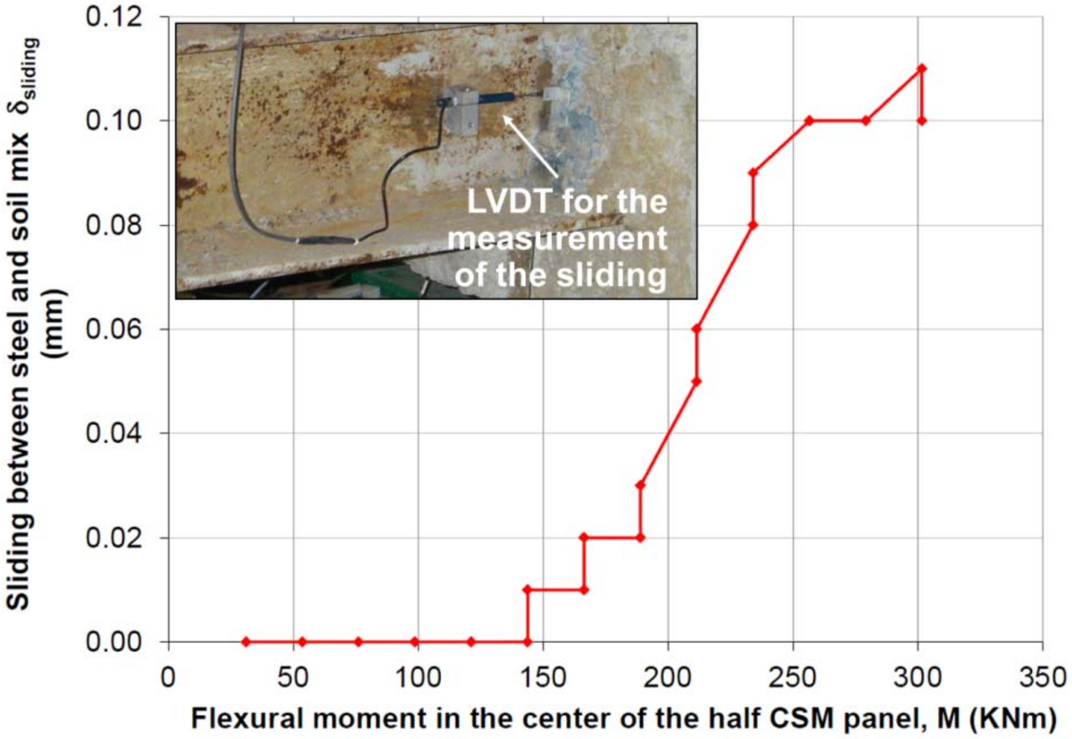

FIG. 8. Evolution of the sliding between the soil mix material and the steel profile during the 3-point bending test

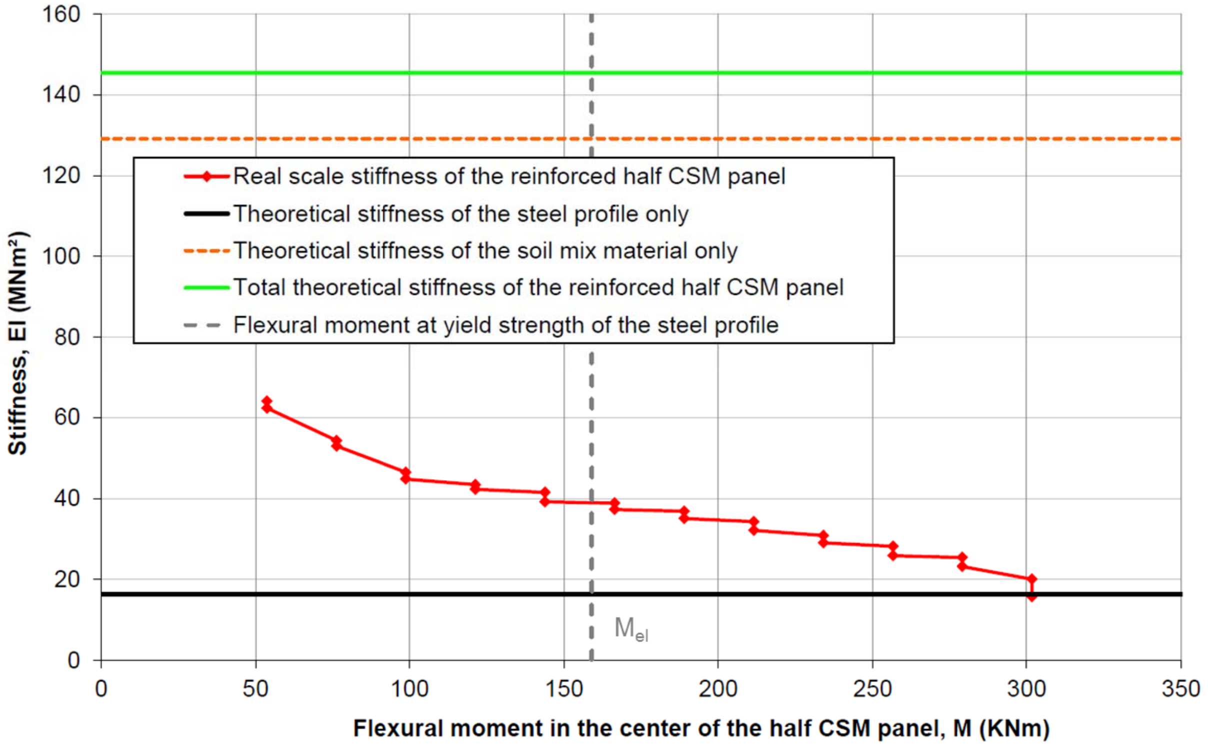

FIG. 9. Evolution of the real scale stiffness of the half CSM panel during the 3-point bending test

At the beginning of the test, the real scale stiffness seems to have already decreased with regard to the total theoretical stiffness. That could be related to the flexural moment due to the weight of the panel put on the two support beams. Indeed, M_{weight} (31.1 KNm) is really close to the flexural moment corresponding to the onset of the cracking in the soil mix material. This flexural moment is met when the tensile strength of the soil mix material is reached. It can be computed as:

$$M_{crack} = 0.1\,UCS_{block}\frac{I}{v} \tag{2}$$

where the tensile strength is computed as one-tenth of the UCS of the large soil mix block and *I/v* is the section modulus of the half CSM panel. The assumption for the determination of the tensile strength is based on previous results obtained from tensile splitting strength tests on soil mix material (Denies et al., 2012).

Nevertheless, as observed in Fig. 9, there is without doubt a participation of the soil mix material to the stiffness of the soil mix wall. In order to determine which part of this stiffness can be considered in the design of the soil mix wall, it is first of all necessary to define the range of flexural moments endorsed by the soil mix wall in the considered application and to compare this range with regard to the flexural moment corresponding to the yield strength of the steel profile only. Secondly, it should be determined if this contribution of stiffness could be considered only in the serviceability states or until failure.

The last stage of the study is the analysis of the deformations arising on both sides of the steel profile during the test. There are 10 measurement bases on each flange of the steel profile. The evolution of the deformations during the test is represented in Fig. 10. The asymmetrical development of the deformations during the test (on both sides of the profile) can be related to the progressive cracking of the soil mix material in the tensile zone and to the positioning of the steel profile with regard to the section. The positioning of the steel profile has a governing influence on the real scale stiffness of the *in-situ* soil mix wall.

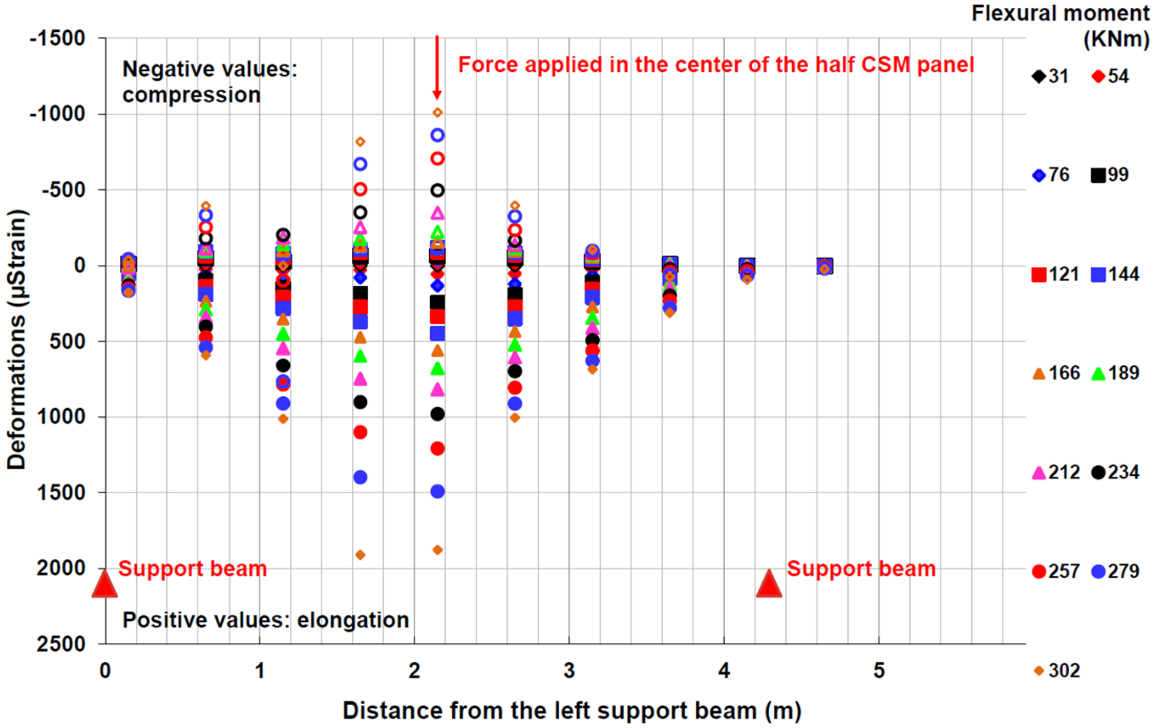

FIG. 10. Evolution of the deformations along the steel profile during the 3-point bending test

The stresses along the steel profile are then computed on the basis of these deformations. The evolution of the stresses in the center of the half CSM panel is represented in Fig. 11 in function of the applied flexural moment.

Once again, it is interesting to compare the value of the measured stresses of the steel profile with the elastic value of these stresses once the yield strength of the steel is reached ($M=M_{el}$). The ratio σ/σ_{el} is equal to 0.56 (-), in the lower side of the steel profile, for $M=M_{el}$, implying 44% gain due to the soil mix material.

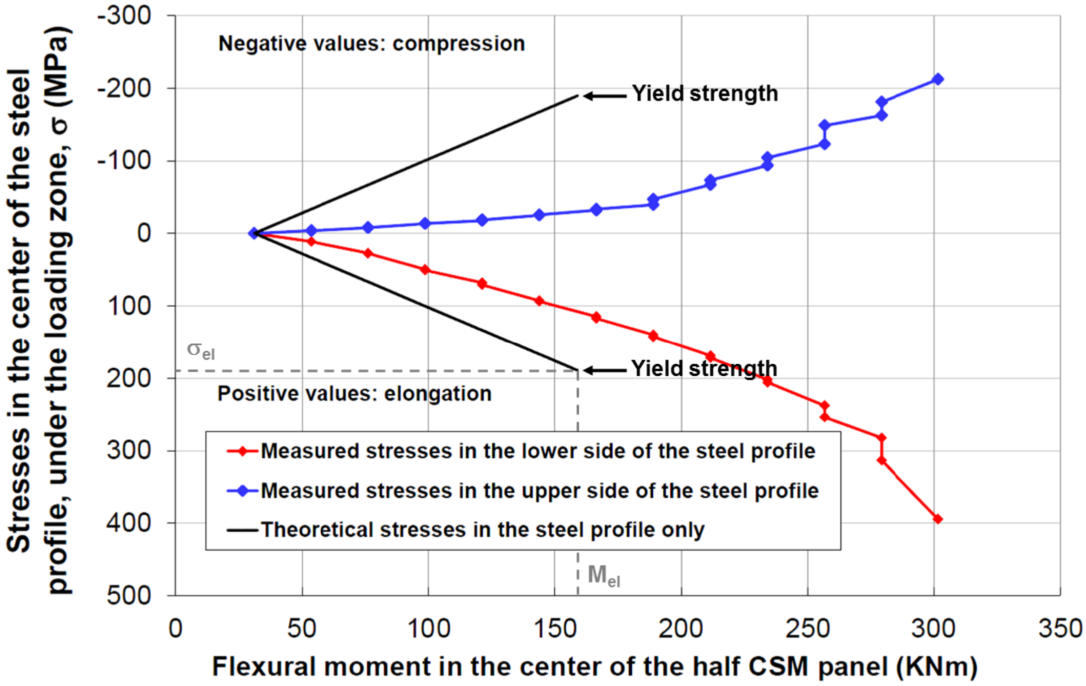

FIG. 11. Evolution of the stresses along the steel profile during the 3-point bending test

CONCLUSIONS

The present paper discusses the results of 8 large scale UCS tests and presents the first results of large scale bending tests performed on excavated soil mix elements.

The authors propose to take into account in the design a reduction of 30% of the UCS characteristic value of the DSM material considering the scale effect observed in the large scale compressive tests.

The analysis of the first results of the large scale bending tests has highlighted the participation of the soil mix material in the bending resistance of the soil mix elements with a real gain considering the deflection and the stiffness of the soil mix element and the stresses measured in the steel profile.

The following stage of the study is to compare the results of the 17 large scale bending tests with regard to these aspects. The main aim of this complete analysis is:

- to determine which part of the stiffness of the soil mix material should be considered in the computation of the flexural moment applied to the soil mix wall in the design,
- to take a decision concerning the admissible reduction of stresses (with regard to the participation of the soil mix to the bending resistance) for the choice of the steel profile.

This analysis will be reported in the proceedings of the next IFCEE 2015.

ACKNOWLEDGEMENTS

The authors wish to thank members of the BBRI for their technical assistance in the realization of the large scale bending tests: Bernard André, Rosario Bonsangue and Christian Verbeke. This research program is financially supported by the Agency for Innovation by Science and Technology of the Flemish Region IWT (BBRI, 2009-2013).

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