Design of Deep Soil Mix Structures: considerations on the UCS characteristic value

Dimensionnement des structures en soil mix : considérations sur la valeur caractéristique UCS

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ABSTRACT: Since several decades, the deep soil mix (DSM) technique has been used for ground improvement works. But in recent years, this technique has been increasingly used for structural applications. Standardized guidelines for the execution and the design of this kind of applications are not currently available. For the purpose of developing such guidelines, mechanical characteristics of DSM material were investigated. Within the framework of a Flemish regional research program (IWT 080736), DSM material from 38 Belgian construction sites, with various soil conditions and for different execution processes, has been tested. Internationally QA/QC activities are commonly related to tests on core samples for the determination of the Unconfined Compressive Strength (UCS) and the modulus of elasticity (E) of the material. Both values allow an approach of the design which takes into account the bending characteristics (EI), the deformation (E), the arching effect (UCS) and the structural resistance (UCS) of the element. For the semi-probabilistic design approach presented in Eurocode 7, a "characteristic value" of the UCS has to be defined as part of the design of DSM structures. The present paper discusses the definition of this value.

RÉSUMÉ : Depuis plusieurs décennies, la technique du soil mix est utilisée comme procédé d'amélioration du sol. Mais ces dernières années, elle est de plus en plus utilisée pour des applications structurelles. Aucune directive n'est actuellement disponible pour l'exécution et le dimensionnement de telles applications. De manière à développer de telles directives, les caractéristiques mécaniques du matériau soil mix ont été investiguées. Dans le cadre d'un programme de recherche financé par l'IWT, l'agence gouvernementale flamande pour l'innovation, des échantillons de soil mix de 38 sites de construction ont été testés pour différents types de sol et différents systèmes. La qualité du matériau soil mix est généralement contrôlée à l'aide d'essais, réalisés sur des échantillons carottés in situ, par lesquels sont déterminés la résistance à la compression simple (UCS) et le module d'élasticité (E) du matériau. Ces deux grandeurs permettent une approche du dimensionnement tenant compte de la rigidité flexionnelle (EI), des déformations (E), de l'effet de voûte (UCS) et de la résistance structurelle (UCS) de l'élément. Au vue de l'approche semi-probabiliste de l'Eurocode 7, il est important de définir la valeur caractéristique de la résistance du soil mix (UCS) à prendre en compte dans le dimensionnement. Le présent article discute de la définition de cette valeur caractéristique.

KEYWORDS: Deep soil mix wall, structural design, ucs characteristic value

1 INTRODUCTION

The Deep Soil Mix (DSM) process was introduced in the 70's in Japan and in the Scandinavian countries. Since several decennia, DSM has been known as a ground improvement (GI) technique. According to the classification of GI methods adopted by the ISSMGE TC 211, DSM can be classified as ground improvement with grouting type admixtures. Numerous reviews and recent progresses of the DSM technique are referred in Denies and Van Lysebetten (2012). The results of national and European research programs have also been published in multiple interesting reports (such as Eurosoilstab 2002), while the European standard for the execution of deep mixing "Execution of special geotechnical works – Deep Mixing" (EN 14679) was published in 2005. Most of these research projects focused on the global stabilization of soft cohesive soils such as clay, silt, peat and gyttja (result of the digestion of the peat by bacteria). More recently, DSM is increasingly being used for structural applications such as soil mix walls (SMW) for the retaining of soil and water in the case of excavations.

In the DSM process, the ground is mechanically mixed in place, while a binder, based on cement, is injected. For SMW applications, the DSM cylindrical columns or the rectangular panels are placed next to each other, in a secant way. By overlapping the different soil mix elements, a continuous SMW is realized. Steel profiles are inserted into the DSM fresh material to resist the shear forces and bending moments. The main structural difference between SMW and the more traditional secant pile walls is the constitutive DSM material which consists of a soil – cement mixture instead of concrete.

Elements such as piles or diaphragm walls only comprise standardized components and their characteristic strength can be defined by the strength class of concrete. The design approach for the DSM material is very different since the existing soil is used as an essential component of the final product. Moreover, the DSM strength depends not only on the soil type, but also on the DSM technique, the amount and the type of binder, etc.

Within the framework of the BBRI "Soil Mix" project initiated in 2009 in collaboration with the KU Leuven and the Belgian Association of Foundation Contractors (ABEF), numerous tests on in situ DSM material have been performed. A good insight has been acquired with regard to mechanical characteristics that can be obtained with the CVR C-mix®, the TSM and the CSM systems in several Belgian soils as reported in Denies et al. (2012). BBRI information sheets (BBRI, 2012a and b) have been published for the purpose of helping contractors to improve the quality control (QC) of their finished product, but guidance rules for the design of SMW are still lacking in particular for the determination of a "characteristic value" representative of the strength of the soil mix material. Neither in the Eurocode 7 nor in the European standards for grouting (EN 12715), jet-grouting (EN 12716) or deep-mixing (EN 14679), specifications are given for the internal strength of the material.

In practice, Quality Assurance (QA) and Quality Control (QC) activities are commonly related to tests on core samples for the determination of the Unconfined Compressive Strength (UCS) and the modulus of elasticity (E) of the material. Both values allowing an approach of the design taking into account the bending characteristics (EI), the deformation (E), the arching effect (UCS) and the structural resistance (UCS) of the element. For engineering purposes and as part of the semi-probabilistic design approach presented in Eurocode 7, it is thus essential to define the UCS characteristic value that can be taken into account in the design of DSM structures. The following paragraphs discuss the definition of this value.

2 DETERMINATION OF THE UCS CHARACTERISTIC VALUE OF DSM MATERIAL

2.1 *On the basis of an X% lower limit value*

The first methodology consists in the calculation of the characteristic strength as the X% lower limit on the basis of a statistical distribution function. Nevertheless, in practice, the wrong assumption is often made that the datasets of UCS values of soil mix material are normally distributed (see Fig. 1a). The characteristic UCS value is then erroneously calculated as the X% lower quantile of the normal distribution with parameters corresponding to the dataset. Moreover, this often results into negative and thus useless characteristic UCS values. The mathematically correct solution would be to apply the best fitting standard distribution function, for example a lognormal distribution in case the distribution is skewed and/or does not contain subpopulations. The X% lower limit can then be calculated on the basis of this theoretical distribution function, as illustrated in Denies et al. (2012) for a lognormal distribution (see Fig. 1b). Possibly, a factor β has to be added to the values to obtain an optimal fit with a normal distribution after transformation. However, this way of working is probably too complex to apply in practical situations.

The second methodology to determine the X% lower limit is based on the cumulative frequency curve of the original experimental dataset and thus independent of any theoretical distribution function. Note that to apply this method, enough data points have to be available (for an accurate determination of the 5% lower limit without extrapolation, at least 20 samples are necessary). This approach seems rather simple but any other method probably results in a large uncertainty. Figure 2 presents the cumulative frequency curve for the UCS values of the dataset illustrated in Fig. 1.

2.2 *On the basis of an average value with safety factor*

A second approach to determine the UCS characteristic value is the use of the average value of the dataset in combination with a safety factor:

$$f_{c,k} = \alpha \overline{q_{uf}} \tag{1}$$

where $\overline{q_{uf}}$ is the mean UCS value and α a factor representing a certain confidence and safety level (α < 1).

In the formalized design approach (DIN 4093, August 2012) used in Germany, the UCS characteristic value is defined as the minimum value of three parameters:

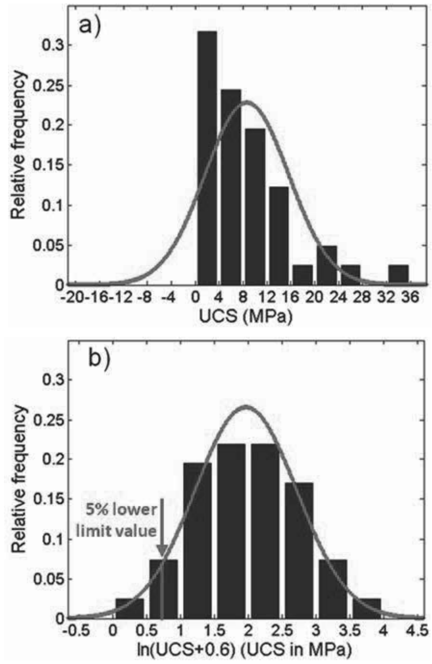

Figure 1. a) Distribution of the UCS values of 41 cores of DSM material from a site in Gent (Belgium) and the corresponding theoretical Gaussian curve. b) Distribution of the logarithm of the UCS values increased with β = 0.6 from the same site and the corresponding Gaussian curve. The vertical line indicates the 5% lower limit value, after Denies et al. (2012).

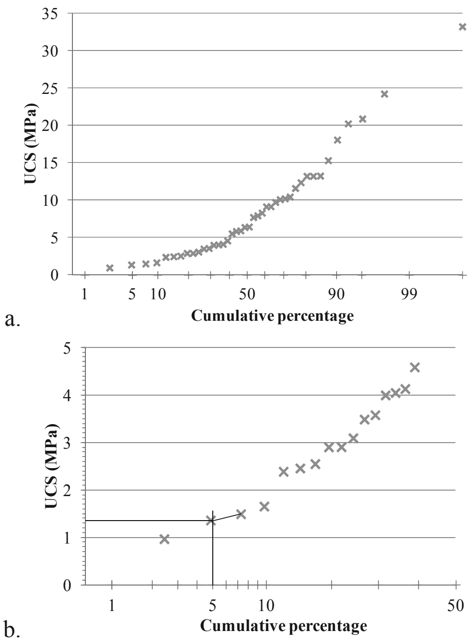

Figure 2. Cumulative frequency curve of all UCS values of the dataset from the site in Gent: a) Full curve. b) Zoom on the part below 50%: presentation of the construction for the evaluation of the 5% lower limit value.

$$f_{c,k} = min\left(f_{m,min}\ ;\ \ \alpha f_{m,mittel}\ ;\ \ 12\,MPa\right) \tag{2}$$

where $f_{m,min}$ is the minimum UCS value and $f_{m,mittel}$ the arithmetic mean UCS value from a series of at least 4 samples. α is determined in function of $f_{c,k}$: α equals 0.6 for $f_{c,k} \leq 4$ MPa and 0.75 for $f_{c,k} = 12$ MPa (linear interpolation is required for intermediate values). This method is described in more detail by Topolnicki and Pandrea (2012).

If the characteristic value $f_{c,k}$ is smaller than 4 MPa, additional creep tests have to be conducted with a load of $f_{c,k}/2$ as described in the annex B of the DIN 4093.

The design strength for calculations with the concept of partial safety factors is then computed as follows:

$$f_{c,d} = 0.85 \frac{f_{c,k}}{\gamma_m} \quad (3)$$

where 0.85 is a factor to consider permanent situations and γ_m is the material safety factor as defined in Eurocode 7 (1.5 for permanent and temporary load cases and 1.3 for accidents). For temporary situations, the design strength is computed without the 0.85 coefficient.

As reported in Topolnicki and Pandrea (2012), if independent and separate design calculations are performed for compressive and shear stresses (i.e. no 3D stress analysis), the maximum allowed compressive stress is 0.7 x $f_{c,d}$ and the maximum allowed shear stress is 0.2 x $f_{c,d}$.

For comparison with the previous version of the DIN 4093 (published in September 1987), Table 1 presents cumulated safety factors on material strength ($f_{m,mittel}$) and equivalent global safety factors (γ_m x $\gamma_{G,Q}$)/(α x 0.85 x (0.7 or 1)) computed with the new DIN 4093 for permanent design situations. An increase in the number of test samples has no effect on the safety factors.

Table 1. Cumulated safety factors on material strength ($f_{m,mittel}$) and equivalent global safety factors in permanent design situation according to DIN 4093 – August 2012 (γ_m = 1.5).

	For α=0.6	*For α=0.75*
With 3D analysis		
Cumulated safety factor	**2.94**	**2.35**
Permanent actions (γ_G=1.35)		
Equivalent global safety factor	**3.97**	**3.18**
Variable actions (γ_Q=1.50)		
Equivalent global safety factor	**4.41**	**3.53**
Without 3D analysis		
Cumulated safety factor	**4.20**	**3.36**
Permanent actions (γ_G=1.35)		
Equivalent global safety factor	**5.67**	**4.54**
Variable actions (γ_Q=1.50)		
Equivalent global safety factor	**6.30**	**5.04**

For comparison, in the previous version of the DIN 4093 (September 1987), the design value was computed as follows:

$$f_{c,d} = \frac{f_{m,mittel}}{5} \quad (4)$$

for samples with UCS values expected larger than 5 MPa and tested according to the DIN 1048 standard for concrete material, or with the help of:

$$f_{c,d} = \frac{q'_u}{3} \quad (5)$$

for samples with UCS values expected smaller than 5 MPa and tested according to the DIN 18 136 for soil material. q'_u is the UCS value computed according to the DIN 18136.

Considering the safety factor of 5 and the reduction factor of 0.7 related to the 3D character of the loading, the previous version of the DIN 4093 resulted in a global safety factor of **7.14**.

For this second approach based on an average value with safety factor, Denies et al. (2012) have remarked that first, the definition of the most suitable mean (arithmetic mean, median, etc.) should depend on the type of the distribution of the dataset. Second, problems may arise with limited number of samples, skewed populations and in the presence of subpopulations.

Figure 3 compares the UCS characteristic value computed with the help of the cumulative frequency curve (CC method) or with respect to the DIN approach. The ratio of the two characteristic values is presented as a function of the number of tested samples for each considered dataset. Minimum 20 samples are necessary in order to conduct the statistical analysis on the cumulative frequency curve. As observed in Fig. 3, the UCS characteristic value is always greater when computed with the help of the cumulative frequency curve (all the values are larger than 1). In Fig. 3, results are given for two different X% lower quantiles: X = 5% and 10%. Indeed, for the first category of approaches (based on the lower limit value), a value for the X% has to be defined. A more detailed analysis is necessary to determine if a 5% lower limit, as often stated in Eurocode 7, is a representative characteristic value for the strength of the soil mix material. Actually, one major issue is the representativeness of the core samples with regard to the in situ executed DSM material.

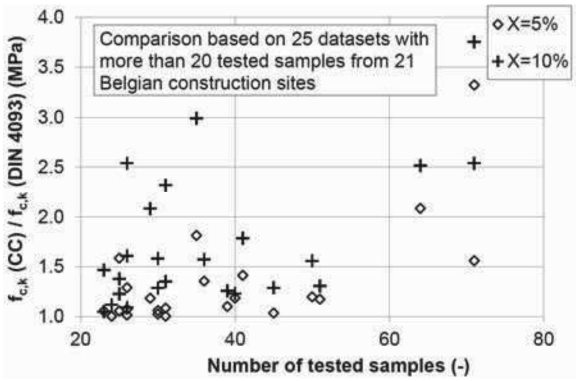

Figure 3. Ratio of the characteristic values ($f_{c,k}$ (CC) and $f_{c,k}$ (DIN4093)) as a function of the number of tested samples.

3 INFLUENCE OF THE UNMIXED SOIL INCLUSIONS

There is mainly the question of the influence of unmixed soft soil inclusions on the mechanical behaviour of the DSM material. Indeed, as a natural material (i.e. soil) is being mixed, it is to be expected that the entire wall is not perfectly mixed and homogeneous: inclusions of unmixed soft soil are present. As a result, Ganne et al. (2010) have proposed to reject all test samples with soil inclusions > 1/6 of the sample diameter, on condition that no more than 15% of the test samples from one particular site would be rejected. This possibility to reject test samples results from the reflexion that a soil inclusion of 20 mm or less does not influence the behaviour of a soil mix structure. On the other hand, a soil inclusion of 20 mm in a test sample of 100 mm diameter significantly influences the test result. Of course, this condition is only suitable if one assumes that there is no soil inclusion larger than 1/6 of the width of the in situ DSM structure. For the purpose of studying this question, 2D numerical simulations were performed at KU Leuven with the aim to quantify the effect of soil inclusions on the DSM strength and stiffness. The following parameters are being considered: size, number, relative position and percentage of soil inclusions. The results of this study are presented in Vervoort et al. (2012) and Van Lysebetten et al. (2013). As illustrated in Fig. 4, they confirm that DSM samples with soft soil inclusions larger than 1/6 have a considerable influence on the deduction of the engineering values. Based on this numerical analysis, the “rule of 1/6” as proposed by Ganne et al. (2010) seems to be justified.

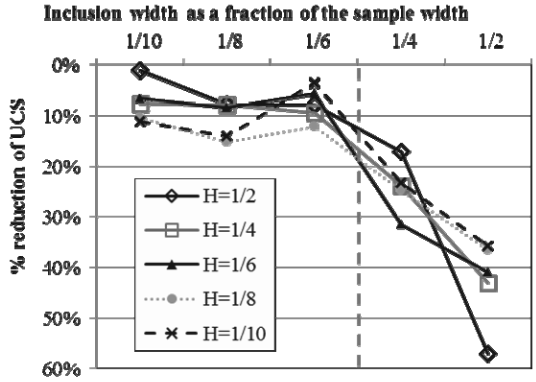

Figure 4. Influence of the dimensions of the soil inclusions on the UCS of soil mix material. Results of 2D numerical simulations performed with the help of the Universal Distinct Element Code UDEC of Itasca®. Details of the model are available in Van Lysebetten et al. (2013). H is the ratio between the height of the soil inclusion and the sample diameter.

4 INFLUENCE OF THE SCALE EFFECT

Apart from traditional core samples (with a diameter around 10 cm), large scale UCS tests were conducted on rectangular blocks with approximately a square section, with a width corresponding to the width of the in situ SMW (about half a meter) and with a height approximately twice the width (Vervoort et al. 2012). The results of all the tests performed in KU Leuven are presented in Fig. 5 for various soil conditions and different execution systems: the CSM and the TSM.

As observed in Fig. 5, a linear relationship is observed between the test results obtained from the typical core samples 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. It is to note that similar conclusion was observed for DSM columns in Japan (CDIT 2002).

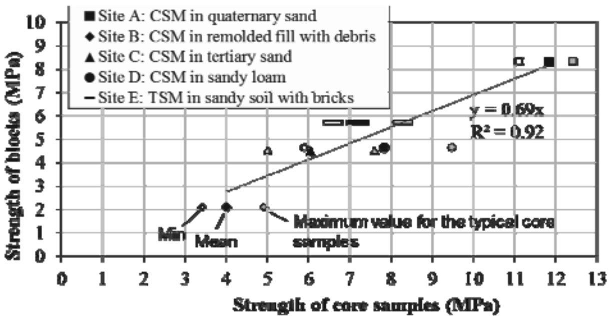

Figure 5. Scale effect: relationship between the results of UCS tests on typical cylindrical core samples (10 cm diameter) and on large rectangular blocks tested in KU Leuven (after Vervoort et al. 2012).

5 CONCLUSIONS

Based on the results of the BBRI 'Soil Mix' project, a Belgian design methodology for the DSM structures is currently developed. On the one hand to determine the UCS characteristic value of the DSM material and on the other hand to design the SMW as a retaining wall according to the requirements of the Eurocode 7. According to the results presented in this paper, the calculation of the UCS characteristic value should consider:

- the number of tested core samples,
- the possibility to use a statistical approach (based on the cumulative curve) or an approach such as in the DIN,
- the determination of the X% lower quantile for DSM material (in case of statistical calculation),
- the presence of the unmixed soft soil inclusions potentially considering the rule of 1/6 (Ganne et al. 2010),
- the scale effect (with regard to the full-scale factor of 0.7),
- the possibility of 3D analysis,
- and the time effects (with the help of creep test or based on experience with similar technique and soil conditions).

The curing and creep phenomena are currently investigated within the framework of the BBRI 'Soil Mix' project. Indeed, while SMWs were previously used only for temporary excavation support, permanent retaining and bearing applications with soil mix are increasingly applied in Belgium. For the evolution of the UCS value with time, it is suggested to consider the value of the UCS at 28 days as the value of reference for the strength of the DSM material.

6 ACKNOWLEDGEMENTS

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