Proceedings of the 15th European Conference on Soil Mechanics and Geotechnical Engineering
A. Anagnostopoulos et al. (Eds.)
IOS Press, 2011

doi:10.3233/978-1-60750-801-4-977

Soil mix: influence of soil inclusions on structural behaviour

Soil mix : influence des inclusions de sol sur le comportement structurel

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ABSTRACT

This paper first describes the soil mix procedures applied in Belgium. Then, it concentrates on the influence of soil inclusions (un-mixed materials) on the soil mix structural behaviour. Methodologies describing and quantifying inclusions are presented and applied on in situ executed soil mix materials from 18 sites in Belgium. Finally, first results of numerical simulations investigating the influence of soil inclusions on the stiffness of soil mix material are discussed.

RÉSUMÉ

Le présent article donne un aperçu des techniques de « soil-mix » appliquées en Belgique. Il se concentre ensuite sur l'influence des inclusions de sols (non mélangées) sur le comportement structurel du « soil-mix ». Des méthodologies, décrivant et quantifiant la présence des inclusions, sont présentées et appliquées sur des éléments de « soil-mix » exécutés in situ. Ces derniers proviennent de 18 sites en Belgique. Finalement, les premiers résultats de simulations numériques, investiguant l'influence des inclusions de sol sur la raideur du matériau « soil-mix », sont discutés.

Keywords: Sol mix, deep mixing, retaining structure, soil inclusion, structural behaviour

1 INTRODUCTION

Since several decades, the (deep) soil mix technique is known as a ground improvement technique [1] : the ground is in situ mechanically mixed while a binder, based on cement and lime [2], is injected. The results of national and European research programs have been published in multiple reports (such as [3]), while also the European standard for the execution of deep mixing "Execution of special geotechnical works – Deep Mixing" (EN 14679) was published in 2005 [4]. Most of these research projects focus-

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sed on the global stabilisation of soft cohesive soils such as peat, clay, gyttja and silt.

More recently, soil mix is increasingly used for the retaining of soil and water in the case of excavations as a more economical alternative for concrete secant pile walls and even for king post walls (i.e. soldier pile walls). The soil mix cylindrical columns or rectangular panels are placed next to each other, in a secant way. By overlapping the different soil mix elements [5], a continuous soil mix wall is executed. Steel H or I-beams are inserted into the soil mix before curing to resist the shear forces and bending moments in the retaining wall. In general the maximum installation depth of the soil mix walls in Belgium is – so far – about 20 m.

The use of soil mix as ground and/or water retaining structures has some specific advantages. No important vibrations are caused by the execution of soil mix. As the stress relaxation of the soil is limited, soil mix can be executed nearby existing constructions. Contrary to concreted secant pile walls, the execution of the soil mix walls does not suffer from delayed supply (e.g. due to traffic jams) of the fresh concrete. The amount of binder returning to the surface is limited in comparison with jet-grouting.

The main structural difference between these soil mix walls and the more traditional secant pile walls is the constitutive wall material which consists of a mixture of soil and cement instead of traditional concrete. The structural behaviour of soil mix material is governed among others by the type of binder, the volume of injected binder and the nature of the soil. It is also influenced by the presence of soil inclusions (by their number, their volume, their shape, and their scattering in the material). In this paper, all inclusions in deep mix material are considered as soft soil inclusions. Hence, soil inclusions represent the unmixed part of the soil-mix material.

This paper describes firstly the different types of soil mix systems applied in Belgium. The methodology describing and quantifying inclusions is then presented. Finally, the influence of the inclusions on the soil mix stiffness is discussed.

Test results and methodologies with regard to the strength and stiffness properties are referred in [6] in terms of unconfined compressive strength (UCS) and elastic modulus. The methods are validated on a large population of laboratory tests on in situ soil mix material, executed in Belgian soils.

2 SOIL MIX SYSTEMS IN BELGIUM

The CVR C-mix®, the TSM and the CSM are the three most used types of deep mix systems in Belgium. All three are wet deep mixing systems.

2.1 CVR C-mix®

The CVR C-mix® is performed with an adapted bored pile rig and a special designed shaft and mixing tool. This tool rotates around a vertical axis at about 100 rpm and cuts the soil mechanically. Simultaneously, the water\binder mixture (w\b weight ratio between 0.6 and 0.8), is injected at low pressure (< 5 bar). The injected quantity of binder amounts mostly to 350 and 450 kg binder/m³, depending on the soil conditions. The binder partly (between 0% and 30%) returns to the surface. This is called ‘spoil return’.

The resulting deep mix elements are cylindrical columns with diameter corresponding to the mixing tool diameter, varying between 0.43 and 1.03 m. When deep mix is used as a retaining structure, the production rate is about 160 m² of deep mix wall per day (single 8 hrs shift).

In order to increase the production rate, a CVR Twinmix® and a CVR Triple C-MIX® can be used. A twinmix has two mixing tools, mixing two overlapping cylindrical columns (total wall element length of 0.8 to 1.2 m) at the same time. The daily production increases till 210 m². A CVR Triple C-mix® has three mixing tools in line, with a total wall element length of 1.5 to 1.8 m. The production rate increases to 300 m² per day.

2.2 Tubular Soil Mix (TSM)

The TSM technique uses a mechanical and a hydraulic way of mixing. Apart from the rotating (around the vertical axis) mixing tool, the soil is cut by the high pressure injection (till 500 bar) of the water\binder mixture with w\b chosen between 0.6 and 1.2. The injected quantity of binder mixture amounts mostly to 200 and 450 kg binder/m³, depending on the soil conditions. Part of the binder (between 0% and 30%) returns to the surface as spoil return.

The resulting deep mix elements are cylindrical columns with a diameter between 0.38 and 0.73 m. The production rate is about 80 m² of deep mix wall per day.

Again, a twin and a triple version exist. The total wall length of the two (three) cylindrical columns of a twin (triple), varies between 0.8 and 1.4 m (1.2 and 2.1 m). In this way, the production rate is increased till about 180 (twin) and 250 m² (triple) of deep mix wall per day.

2.3 Cutter Soil Mix (CSM)

A CSM device is commercially available. It makes use of two cutting wheels that rotate independently around a horizontal axis, cutting the soil. At the same time, the water\binder mixture is injected at low pressure (< 5 bar) with w\b ratio chosen between 0.6 and 1.2. The injected quantity of binder amounts mostly to 200 and 400 kg binder/m³, depending on the soil conditions. Part of the binder (between 0% and 30%) returns to the surface as spoil return.

The resulting deep mix elements are rectangular panels. In Belgium, these panels have mostly a length of 2.4 m and a thickness of 0.55 m, though cutter devices with other dimensions are available. The production rate is about 100 m² to 250 m² per day.

3 DESCRIPTION OF SOIL INCLUSIONS

Due to the specific procedure of deep mixing, soil inclusions are inevitable. The volume of soil inclusions of in situ executed deep mix should be quantified in order to study its influence on the material stiffness.

Two methodologies taking into account soil inclusions are first presented and then illustrated with an overview of in situ results of deep mix material executed in several Belgian soils.

3.1 Methodology of the description of soil inclusions

In order to quantify the volume of soil inclusions, in situ executed deep mix columns and panels are observed. Soil inclusions can be described based on entire sections of deep mix columns/panels as well as on drilled cores.

The two methodologies are the surface percentage (A) and the line percentage (B).

(A) The calculation of the surface percentage of soil inclusions involves five processing steps:

1. Deep mix columns or panels are executed in situ by standard deep mixing procedure.
2. The test columns/panels are (partly) excavated; the column/panel should be sawn to create a statistically representative ‘fresh’ saw-cut section. Alternatively, the saw-cut of a core drill can also be used.
3. The saw-cut surface is photo-graphically digitized to recompose one digital mosaic photo. The pixel resolution is about 0.3 mm.
4. Using commercially available image processing techniques (IPT), soil inclusions are assigned in black on the digital mosaic photo. As the soil inclusions are not always observable, manual verifications are performed on the saw-cut surface.
5. The determination of the surface percentage of soil inclusions consists in the calculation of the amount of assigned (black) inclusions and the total surface of the saw-cut using IPT.

(B) The methodology to calculate the line percentage of soil inclusions involves three processing steps.

The steps 1 and 2 are similar to those of methodology A.

3. Parallel lines with an interdistance of minimum 7 cm are drawn on the deep mix material. The cumulative length of soil inclusions along the line is manually measured. The line percentage is calculated as the proportion of this cumulative length to the total line length.

The observed line and surface percentages can be considered as unbiased estimations of the volume percentage of soil inclusions in the deep mix material [7].

3.2 Overview of observed soil inclusions

Figure 1 gives an overview of the quantified soil inclusions in soil mix material, executed on 18 job sites, in different types of Belgian soils (quaternary and tertiary sands, silt, alluvial clay, stiff clay and clay with peat). In Figure 1, soil inclusions are quantified using:

- method A, applied on saw-cuts of in situ executed deep mix columns or panels,

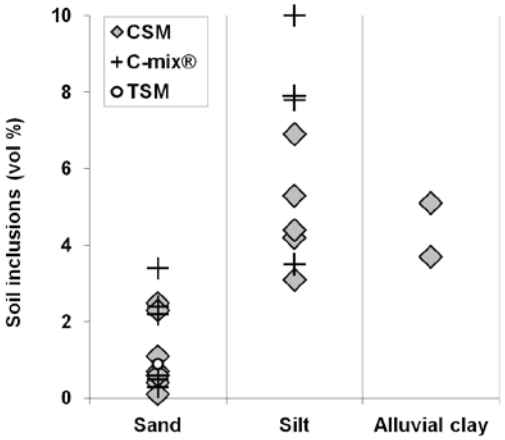

Figure 1. Percentage of soil inclusions in soil mix material, executed on 18 sites in Belgium.

- method A, applied on the saw-cuts of drilled cores of in situ executed deep mix columns of panels,
- method B, applied on the saw-cuts of drilled cores of in situ executed deep mix columns of panels.

The amount of soil inclusions depends on the nature of the soil, wherein the deep mix is performed:

- in quaternary of tertiary sands, the amount of soil inclusions in deep mix material varies between 0 and 3.5 vol%,
- in silty soils or alluvial clays, it varies between 3 and 10 vol%,
- in clayey soils with organic material (such as peat) or in tertiary (overconsolidated) clays, it can amount up to 35 vol% and higher (not represented in Figure 1).

4 INFLUENCE OF SOIL INCLUSIONS ON THE ELASTIC MODULUS OF SOIL MIX MATERIAL

Soil inclusions or volumetric parts which are not well mixed are an integral part of soil mix material. Various observations allow deriving certain conclusions on the way that the number of inclusions, their sizes, their shapes and their relative positions influence the soil mix material behavior. However, it is not possible to analyse in detail this influence by observations only. That is the reason why the laboratory tests and numerical simulations complement each other. Sensitivity analyses can be conducted easily in numerical modelling. Here, the results of linear elastic simulations using a continuous code (FLAC) are presented.

The starting point for the model is a real 2D-section with dimensions of 120 x 240 mm², in which 11 inclusions are observed, corresponding to about 11% surface area. From this, 69 different models were generated. The % surface area of inclusions was changed by varying the number and size of the inclusions resulting in 1, 5, 10 and 20% inclusions. Apart from changing the number and the size, the shape of the inclusion was also varied. Hence, some of these models contain inclusions with a more rounded shape or inclusions with sharper corners. In Figure 2, the mesh of a 10% model with the original shape and size of the inclusions is presented.

The mixed part in each model corresponds to a Young's modulus E and a Poisson's ratio of respectively 11.6 GPa and 0.3, while for the soil inclusions (un-mixed material) these values are 0.165 GPa and 0.4. The resulting Young's moduli for the entire models are presented in Figure 3, as a function of the % surface area of soil inclusions.

The presence of a mere 1% of weak inclusions results in about a reduction of 3% of the stiffness.

Figure 2. Mesh of the reference model (10% of surface area is composed of soil inclusions and the original observed shapes are used).

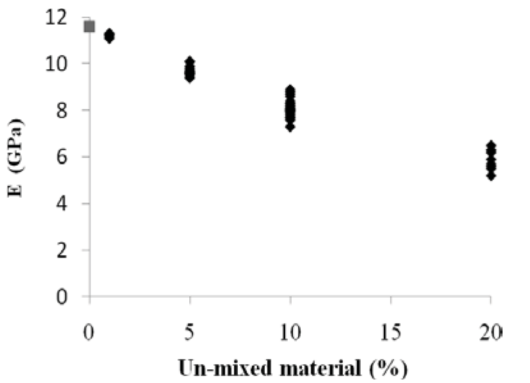

Figure 3. Variation of the Young's modulus as a function of the percentage surface area corresponding to the soil inclusions.

The presence of 10% of inclusions results on average to a reduction of 30% of the stiffness. It can also be observed that for a certain percentage the variation in Young's moduli is relatively large, but there is no real overlap between the four percentages considered. For example for 10% inclusions, the E-modulus varies between 7.3 and 8.9 GPa, while the smallest value for 5% is 9.4 GPa and the largest value for 20% is 6.5 GPa.

For a fixed percentage, the variation of the Young modulus is mainly related to the shape of the inclusions. Sharp corners strongly reduce the Young's modulus, while the rounded shapes (e.g. circle) are less harmful to the stiffness of the material. Figure 4 illustrates the influence of the shape for 30 different models corresponding to 10% of inclusions. Of course, size and number of inclusions play also a role. It is assumed that once individual fractures are being simulated the effect of the shape will even be larger.

5 CONCLUSIONS

In Belgium, the soil mix technique is used more and more as a practical solution for the retaining of soil and water in the case of excavations. If it represents an interesting economical alternative

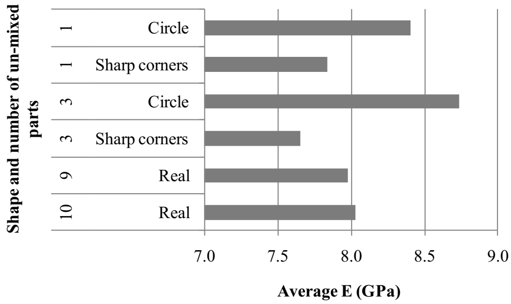

Figure 4. Variation of average Young's modulus as a function of the shape of the inclusions (10% surface area corresponding to the soil inclusions).

for concrete secant pile walls, it remains a lot of uncertainties relating to its structural behaviour and notably concerning the influence of soil inclusions on its stiffness.

In the framework of the research program "Soil Mix" that the Belgian Building Research Institute (BBRI) carries out in collaboration with the Catholic University of Leuven and the Belgian Association of Foundation Contractors (ABEF), numerous tests on in situ soil mix material have been performed. A good insight has been acquired with regard to strength and stiffness characteristics that can be obtained with the CVR C-mix®, the TSM and the CSM procedures in several Belgian soils. A methodology and an interpretation method to determine the strength and stiffness characteristics of soil mix material have been proposed and validated [6].

The present paper focuses on the influence of soil inclusions on the soil mix structural behaviour. The surface percentage (A) and the line percentage (B) methodologies, quantifying soil inclusions, are described and illustrated by in situ results from 18 sites in Belgium. The amount of inclusions in soil mix material depends on the nature of the soil. In the present study, soil mix materials executed in situ in quaternary and tertiary sands, silt, alluvial clay, stiff clay and clay with peat are considered (figure 1).

Once the presence of soil inclusions is quantified, numerical modelling is used to characterize its influence on the stiffness of the soil mix material. Numerical simulations clearly highlight the influence of the amount and the characteristics of soil inclusions on the Young modulus of the soil mix material (figures 3 and 4).

Within this research program, the tests to determine strength and stiffness characteristics and numerical simulations will continue. In parallel, numerous tests dealing with porosity, permeability, long term behavior (e.g. creep) and adherence with steel reinforcement have been launched.

If soil mix walls were previously used only for temporary excavation support, permanent retaining and foundation applications with soil mix are increasingly applied in Belgium. Hence, the durability aspects of the soil mix material have to be treated.

In the second half of the research program, the soil mix material should be investigated in terms of its alkalinity properties, with the help of pH long term measurements, in order to control its level of corrosion protection. The viability of the process in presence of polluted soils should be also considered.

Based on the results of this research program, a design methodology for the soil mix structures, accounting for the presence of the heterogeneities and soil-inclusions, the scale effects and the time-effects such as curing time and creep shall be developed.

ACKNOWLEDGEMENT

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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