Mechanical characterization of large scale soil mix samples and the analysis of the influence of soil inclusions

A. Vervoort, A. Tavallali, G. Van Lysebetten
KU Leuven, Belgium, andre.vervoort@bwk.kuleuven.be, and Gust.VanLysebetten@bwk.kuleuven.be

J. Maertens
Jan Maertens bvba & KU Leuven, Belgium, jan.maertens.bvba@skynet.be

N. Denies, N. Huybrechts
Belgian Building Research Institute, Geotechnical division, Belgium, nde@bbri.be and nh@bbri.be

F. De Cock
Geotechnical Expert Office Geo.be, Belgium, fdc.geobe@skynet.be

B. Lameire
Belgian Association of Foundation Contractors ABEF, Belgium, bart@lameireft.be

ABSTRACT

Since several decennia, the deep soil mix technique is used for ground improvement applications and for the realisation of retaining walls. In recent years, soil mix walls have become an economical alternative to traditional excavation support systems. However, 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. In other words, inclusions of poorly mixed or even unmixed (i.e. soil) material are present. The amount of such inclusions can be less than 1% of the total volume at some sites, but 10% or more is also observed. Some of these inclusions are very small, while in other cases they can have dimensions of several centimetres. It is generally assumed that below a certain volume percentage and/or for small dimensions of the individual inclusions, these inclusions have no negative impact on the behaviour and on the strength of the soil mix material. To quantify the maximum acceptable volume percentages of inclusions, an experimental, as well as a numerical simulation research programme has been initiated in the framework of a Flemish regional research project (IWT 080736) that is carried out in collaboration with the BBRI, the Belgian federation of foundation contractors (ABEF) and KU Leuven. This research aims also to better understand the behaviour of this material and the failure of it.
The experimental part of this research focuses on laboratory experiments. The behaviour in laboratory is certainly affected by the scale and the dimensions of the test samples. Apart from traditional cores (e.g. with a diameter of about 10 cm), large scale tests are being conducted. The large samples tested are rectangular blocks with approximately a square section (about half a meter) and with a height of approximately two times the width. The stress-strain behaviour of the blocks tested so far shows a significant stress drop after reaching its peak strength. The failure is a combination of extension type of fractures and shear failure.
By conducting complementary numerical simulations (2D), one tries to better understand the effect of the inclusions of unmixed material, i.e. the effect of their size, the total surface percentage, the number of inclusions, the relative position, etc. By numerical models, it is relatively easy to consider numerous cases, while experimentally (e.g. by artificial samples) it is much more difficult and time consuming. Three approaches have been used: (i) elastic models are applied, whereby the focus is on the stiffness of the material, (ii) elasto-plastic models, whereby apart from the stiffness the strength is analysed and (iii) a discontinuous approach, whereby individual fracture initiation and growth can be modelled, apart from the stiffness and strength. The most prominent conclusion is that even a small percentage of inclusions has a significant effect on the strength of the material and to a lesser extent on the stiffness. For 1% of unmixed material, the strength is reduced on average by 20%, while for 10% of unmixed material about half of the strength disappears. Another consistent result is that other characteristics than the total surface percentage of unmixed material can have a significant effect, e.g. large sharp-ended individual inclusions have a negative effect on the strength and stiffness.

1. INTRODUCTION

The application of deep soil mix technology in Belgium is sharply increasing. Next to soil improvement applications, deep soil mix walls are extensively used for excavation support. The CVR C-mix®, the TSM and the CSM are the three most used types of deep soil mix systems in Belgium. All three are wet deep mixing systems. More details of the execution procedures are given in (Denies et al., 2012). Due to the specific procedure of deep mixing and as a natural material is being mixed, it is to be expected that the entire wall is not perfectly mixed and homogeneous. Hence, soil inclusions are inevitable. In this paper, all inclusions in soil mix material are considered as soft soil inclusions. In other words, inclusions of poorly mixed or even unmixed (i.e. soil) material are present. The amount of such inclusions can be less than 1% of the total volume at some sites, but 10% or even 35% have also been observed. The amount of soil inclusions depends on the nature of the soil wherein the deep mix is performed (Ganne et al., 2012): e.g. in tertiary or quaternary sands, the amount of soil inclusions is less than 3.5 vol%, in silty soils or alluvial clays, it varies between 3 and 10 vol%, and in clayey soils with organic material (such as peat) or in tertiary (overconsolidated) clays, it can amount up to 35 vol% and higher. Some of these inclusions are very small, while in other cases they can have dimensions of several centimetres. It is generally assumed that below a certain volume percentage and/or for small dimensions of the individual inclusions, these inclusions have no negative impact on the strength and on the behaviour of the soil mix wall. To quantify the maximum acceptable limits of volume percentages and inclusions, an experimental, as well as a numerical simulation research programme has been initiated. This research aims also to better understand the behaviour of this material and the failure of it.

The experimental part of this research focuses on laboratory experiments (see paragraph 2). The behaviour in laboratory is certainly affected by the scale and the dimensions of the test samples. Apart from traditional cores (e.g. with a diameter of about 10 cm), large scale tests are being conducted. The large samples tested are rectangular blocks with approximately a square section, with a width corresponding to the width of the in situ wall (about half a meter) and with a height approximately two times the width.

By conducting complementary numerical simulations in 2D (see paragraph 3), one tries to better understand the effect of the presence of the inclusions of unmixed material, i.e. the effect of their size, the total surface percentage, the number of inclusions, the relative position, etc. By numerical models, it is relatively easy to consider numerous cases, while experimentally (e.g. by artificial samples) it is much more difficult and time consuming. Three approaches are being taken: (i) elastic models are applied, whereby the focus is on the stiffness of the material, (ii) elasto-plastic models, whereby apart from the stiffness the strength is analysed and (iii) in comparison to both continuum models, a discontinuous approach, whereby individual fracture initiation and growth can be modelled, apart from the stiffness and strength.

2. LABORATORY EXPERIMENTS

2.1. Large scale tests on rectangular blocks

The main aim of testing large blocks is to get a better idea about the in situ behaviour 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 behaviour 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.

So far, soil mix panels from three construction sites (A, B and C) with different soil types have been tested. For each site an additional soil mix panel has been installed for test purposes only. After being excavated, several types of tests are conducted. One of them is loading a large block cut out from the panel. One horizontal dimension corresponds to the width of the in situ panel, the other horizontal dimension is about the same and the height is approximately two times the width (see Table 1). At sites A and C the soil can be considered as homogeneous (i.e. tertiary and quaternary sand), while at site B the soil is very heterogeneous. Apart from natural loam and sand material, it also contains small particles of construction waste.

The blocks are vertically loaded. The loading is displacement controlled. The loading rate is 0.5 mm/min in order to detail the occurrence and growth of the various fractures. The loading is only stopped after a large vertical displacement has occurred beyond the peak strength, enabling to quantify the post peak behaviour (see Figure 1). The vertical deformation is recorded by four LVDT's with a measurement base of about one fourth of the height, around the centre of each vertical side.

Table 1: Overview of large scale tests and cored samples for the three different sites studied

Site	A: Quaternary sand	B: Mixed soil and construction waste	C: Tertiary sand
Dimensions blocks	61 × 53 × 124 cm	55 × 48 × 90 cm	58 × 53 × 120 cm
Characteristics blocks Uniaxial strength: Young's modulus (tan):	 8.3 MPa 13.6 GPa	 2.1 MPa 2.9 GPa	 4.2 MPa 5.5 GPa
Dimensions cores Diameter: Height:	 113 mm 230 mm	 113 mm 230 mm	 94 mm 200 mm
Characteristics cores UCS: Young's modulus (tan):	 11.1-12.4 MPa 12.5-13.2 GPa	 3.4-4.9 MPa 1.3-2.7 GPa	 5.0-7.6 MPa 5.6-6.9 GPa

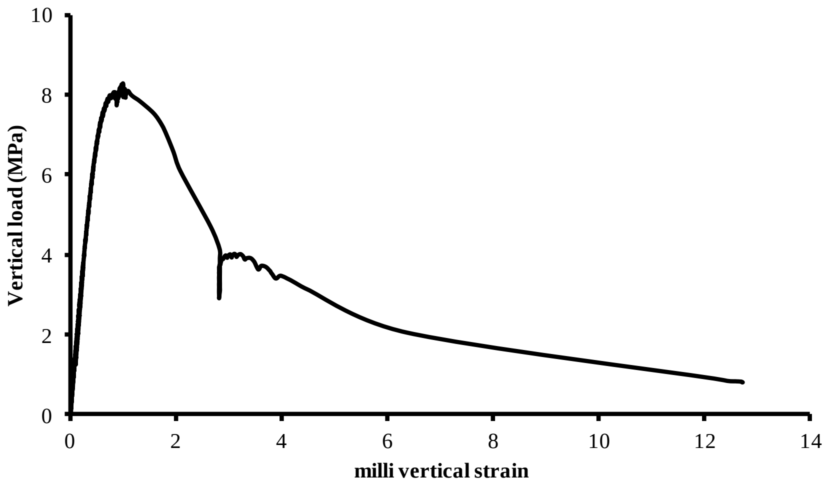
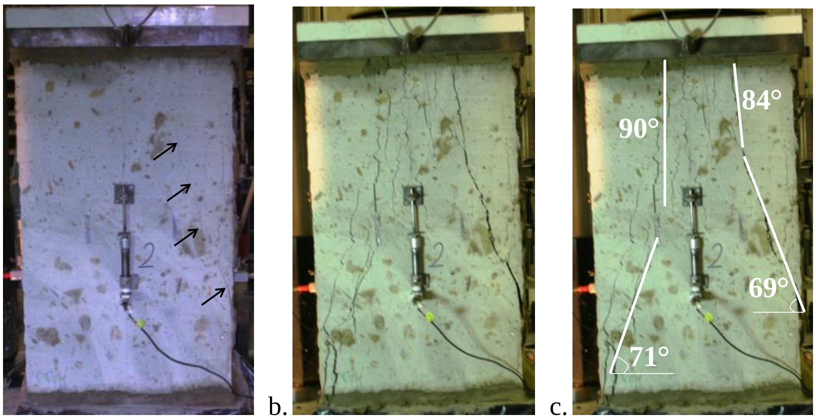


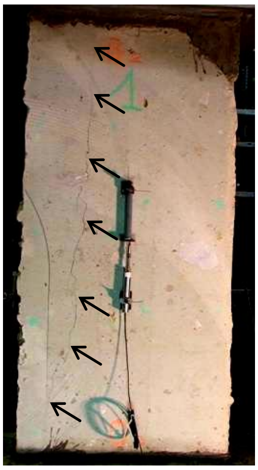
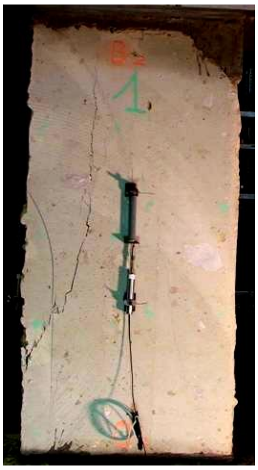
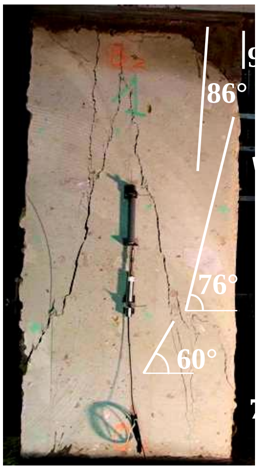
Figure 1: Full stress-strain curve of a large rectangular block from site A

The peak uniaxial strength of the three sites is significantly different, 2.1 MPa for site B, 4.2 MPa for site C and 8.3 MPa for site A. The Young's or elastic modulus varies accordingly. The tangent modulus at 50% of the UCS peak value is respectively 2.9 GPa for site B, 5.5 GPa for site C and 13.6 GPa for site A. The fractures occurring during loading are in one way similar for the three blocks, but also different (see different pictures in Photo 1). All induced macro-fractures have a strike which is roughly parallel to the original soil-wall contact. Further investigation has to clarify if this is related to the mixing procedure. For all three blocks the first macro-fracture is only observed very close to the peak. Most of the final macro-fracture pattern is induced during the post-peak behaviour. For the block from site A, first a vertical fracture is observed (close to the maximum strength; photo a). It is probably due to the splitting of the block (extension type of fracture). When the load reaches about half the maximum load after the peak, the part delineated by the vertical fracture buckles (photo b). The test is continued and a new vertical macro-fracture is induced, again parallel to the wall of the soil mix panel. This fracture is combined with some inclined fractures at the bottom and top part of the block (photo c and d), probably due to the non-central loading of the remaining part of the block. For the block of site B, the failure pattern is mainly characterised by two macro-fractures, which are inclined at the bottom and are more vertical towards the top. Probably, the main mode is shear rather than extension or splitting. Apart from these two fractures, parallel fractures are also observed. For the block from site C, the first visible fracture is a vertically orientated fracture which inclination decreases slightly toward the bottom of the block (photo a). After the peak strength is reached, the inclination of the new induced fractures is about 60° to 80°. Two large (probably shear) fractures are observed (photos b, c and d). It is remarkable that at the top of the block all fractures are (sub)vertically orientated.

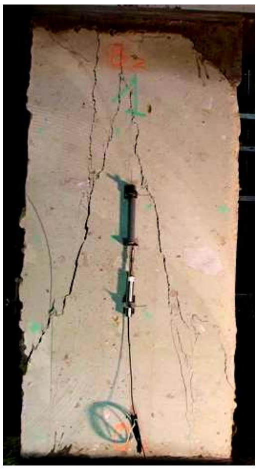
Site A



Site B

a.  b.  c. 

d.



Site C

Photo 1: Pictures taken from the loaded block from the three sites, illustrating the occurrence of fractures during loading

2.2. UCS tests on core samples

As in the long term it is not possible to test each time a block of such dimensions, conventional cores have also been tested. The cores have a diameter of 94 to 113 mm and a height of 2 to 2.5 times the diameter. The vertical deformation is measured by strain gauges with a length of about one fourth of the total height (i.e. the same measurement base as for the large blocks). For site A, the tests result in a UCS value between 11.1 and 12.4 MPa (in comparison to the block strength of 8.3 MPa). For site C, the difference between the cores and the block is similar: 5.0 to 7.6 MPa for the cores in comparison to 4.2 MPa for the block. For site B, with much more heterogeneous material, the difference is on average about a factor 2: UCS values of 3.4 to 4.9 MPa, while the block has a strength of 2.1 MPa. For typical rock material, one would expect a reduction by a factor 2 or 3 for a block which is about 5 times larger (Bell, 1992). The reason why this is not observed at site A and C is probably the fact that the soil mix material is relatively more homogeneous than most rocks.

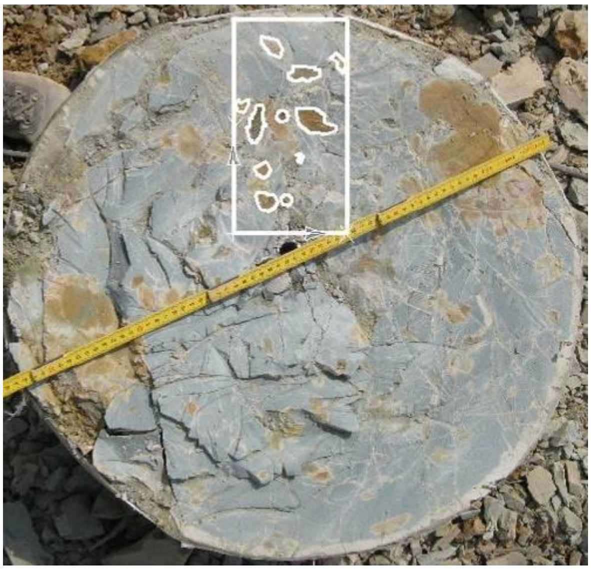
3. NUMERICAL SIMULATIONS

3.1. Description of 2D model

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 how the number of inclusions, their sizes, their shapes and their relative positions influence the soil mix material behaviour. However, it is not possible to analyse in detail this influence by observations only. That is the reason why laboratory tests and numerical simulations have to complement each other. Sensitivity analyses can be conducted more easily in numerical modelling.

The starting point for the model is a real 2D section with dimensions of 120 × 240 mm, in which 11 inclusions are observed, corresponding to about 11% surface area (see Figure 2.a). 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. The basic model representing 10% inclusions is presented in Figure 2.b. Apart from changing the number and the size, also the shape of the inclusion was varied. Hence, some of these models contain inclusions with a more rounded shape or inclusions with sharper corners.

Three approaches with increasing complexity are conducted. First, a linear elastic continuum model is used (paragraph 3.2), followed by a perfect elasto-plastic behaviour for the same continuum model (paragraph 3.3). Both approaches are based on FLAC simulations. Finally, a discontinuum UDEC model is used to simulate the fracturing process in detail (paragraph 3.4).

a. 

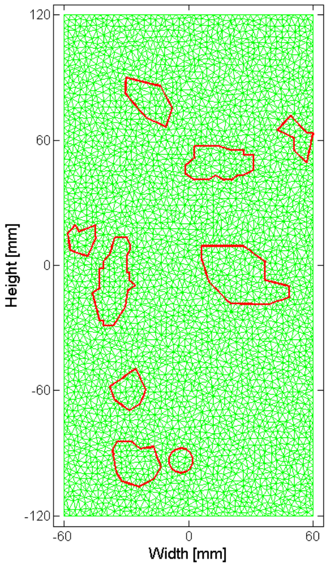
b. 

Figure 2: a. Section through a soil mix column; in this section a rectangular sample with dimensions of 120×240 mm is selected; b. Mesh generated for the discontinuous simulations (red lines indicate the soil inclusions)

3.2. Linear elastic simulations

The mixed part in each model corresponds to a material with a Young's modulus, E, and a Poisson's ratio of respectively 11.6 GPa and 0.3, while for the soil inclusions (unmixed material) these values are 0.165 GPa and 0.4. The resulting Young's moduli for the complete set of models are presented in Figure 3.a, as a function of the % surface area of soil inclusions. The presence of 1% of weak inclusions results in an average reduction of about 3% of the stiffness, while 10% of inclusions results in a 30% reduction (on average) 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 given percentage, the variation of the Young's modulus is mainly related to the shape of the inclusions. Sharp corners strongly reduce the Young's modulus, while rounded shapes (e.g. circle) are less harmful to the stiffness of the material. Figure 3.b illustrates the influence of the shape for 30 different models corresponding to 10% of inclusions. Of course, size and number of the inclusions play also a role.

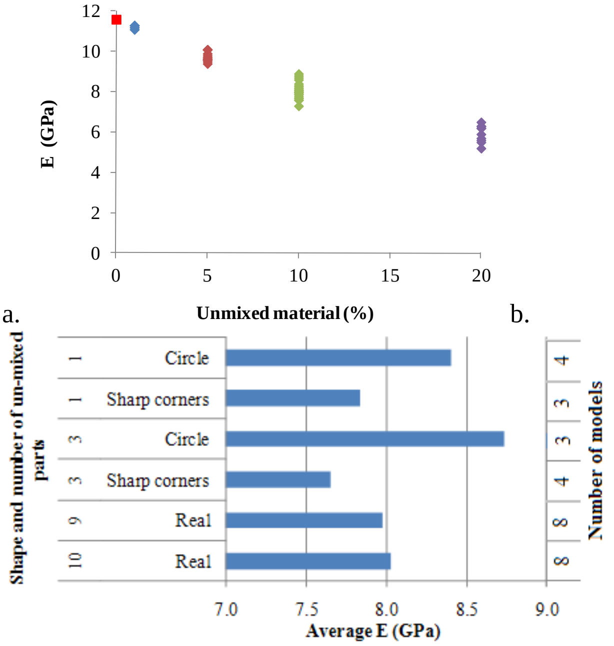


Figure 3: a. Variation of Young's modulus as a function of the percentage of unmixed material (surface area); b. Effect of the number of inclusions and their shape on the average Young's modulus for 30 numerical models (10% unmixed material)

3.3. Elasto-plastic simulations

A strain-softening model is applied, based on the Mohr-Coulomb criteria. The cohesion and tension cut-off fall back to zero after the onset of plastic yield. The elasto-plastic model is calibrated, based on UCS, Young's modulus and failure behaviour. After calibration, the Young's modulus of the basic model equals 7.8 GPa (this is very close to the Young's modulus of the basic model in elastic simulations, which is equal to 8 GPa). The UCS value for the basic case corresponds to 5.3 MPa.

Figure 4.a illustrates the large effect of the unmixed percentage on the UCS of the simulated models. For 1% of unmixed material the strength is reduced on average by about 20%. For 10% of inclusions the UCS is reduced on average by about 50% and for 20% even by about 70%. As for the Young's modulus, one observes also a significant variation for a given percentage of soft inclusions. For example, for the models with 10% inclusions, the UCS value varies between 4.5 and 6.3 MPa, while the smallest value for 5% is 5.5 MPa. In other words, other parameters than the surface percentage of weak material are also important. This is illustrated in Figure 4.b for the models with 10% unmixed material. This figure shows that sharp-ended heterogeneities generally cause smaller UCS values than rounded inclusions, at least for the same number of inclusions or the same size of inclusions. An increase in the size of the inclusions, for the same percentage of weak areas, reduces the UCS significantly. For example, models with only one, sharp-ended heterogeneity present the lowest average UCS value (4.6 MPa), while the highest average UCS (6 MPa) is found in models with three rounded inclusions, representing 10% of the sample surface.

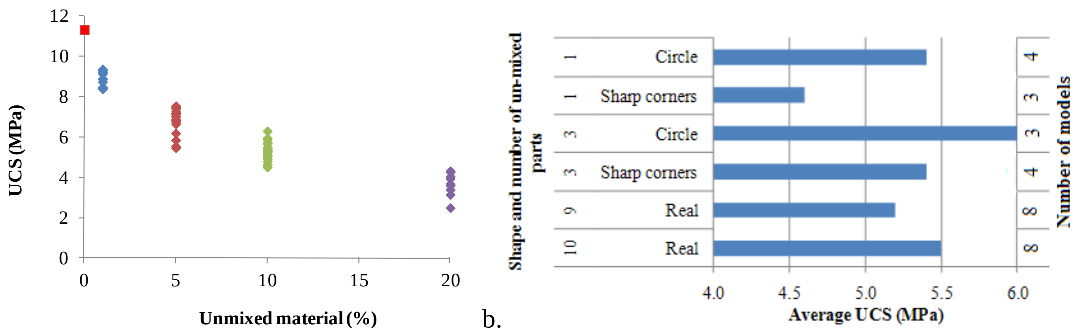


Figure 4: a. Variation of UCS values as a function of the percentage of unmixed material (surface area); b. Effect of the number of inclusions and their shape on the average UCS value for 30 numerical models (10% unmixed material)

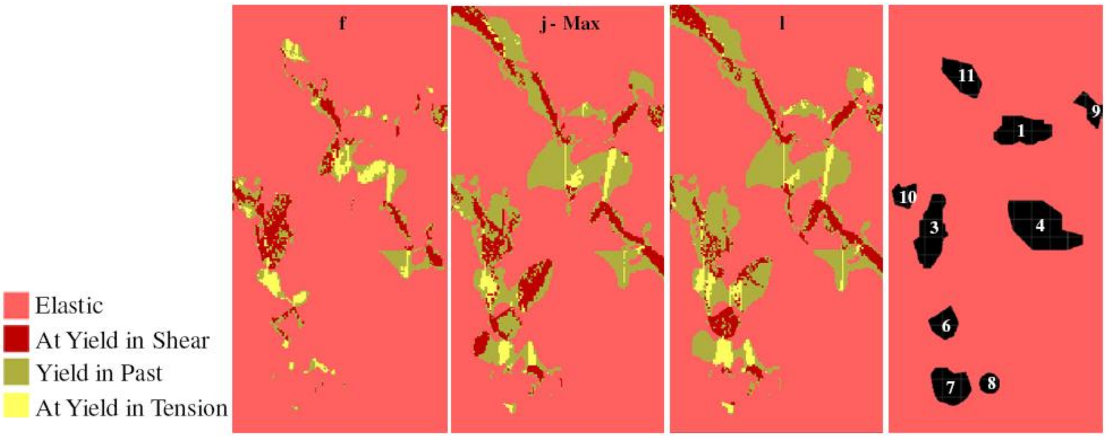


Figure 5: Occurrence of plastic deformation at the moment just prior to reaching the UCS value (left), at the peak value (middle) and just after the peak (right). The extreme right picture illustrates the position and size of the soft inclusions (in black)

The occurrence of plastic deformation during the elasto-plastic simulations for some of the loading steps around the maximum UCS peak value is presented in Figure 5. On this figure, a V-shape failure is visible corresponding to shear, but also some vertical tensile fractures can be observed.

3.4. Simulations of fracturing

The discontinuous simulations are done in UDEC, a 2D numerical program that is based on the discrete element method (Van Lysebetten, 2011). The studied medium is divided into a network of discrete blocks which are tightly bounded together by contacts. In the concept of this study, the blocks only deform elastically, while the contacts are assigned a Mohr-Coulomb shear criterion. Initially, the sample is considered as intact material in which the contacts act as potential fracture paths. Once the failure criterion of a contact is reached, it is considered as a physical crack. The behaviour of the entire model is determined by the material and contact properties. Of course, different properties are assigned to mixed and unmixed material. Note that the contact properties are determined by calibration, since they cannot be measured physically. Though simulations in UDEC and FLAC are based on different concepts, the discontinuous and elasto-plastic simulations provide rather comparable results (especially in relative terms). The surface area percentage of unmixed material affects the strength and stiffness of a sample in a very similar way for both simulations. Similar conclusions can be drawn with regard to the effect of the shape and the number of inclusions on the stiffness for models with 10% unmixed material.

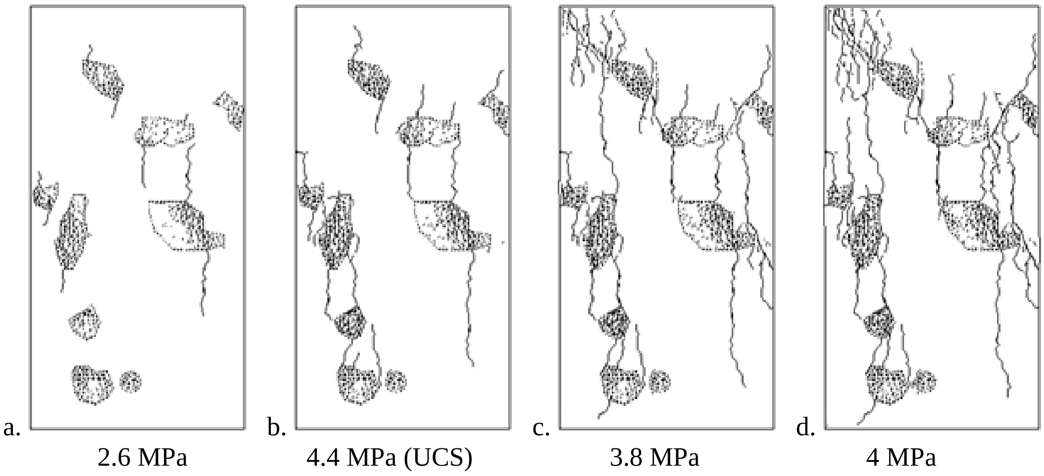
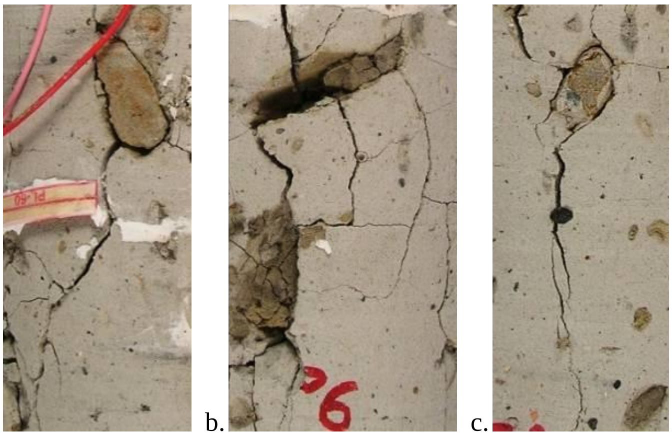


Figure 6: Evolution of the fracture pattern of the basic model during the simulated UCS test in UDEC. a. Fracture pattern before the peak strength is reached; b. At a stress level corresponding to the peak strength; c and d. At lower stress levels after peak strength is reached.



a. b. c.

Photo 2: Details of induced fracture patterns in uniaxially loaded samples, cored from the rectangular block originating of site B (see Table 1), the width of the photos is about 2 cm

The evolution of the fracture pattern of the basic model during a UCS test is shown in Figure 6. Generally, the resulting fracture pattern is very similar to the results of the elasto-plastic simulations (see Figure 5). The shear zone that extends from the upper left corner of the sample to the lower right part is clearly visible for both methods, as well as the vertical fractures at the top and bottom of the inclusions. Nevertheless, some important differences can be observed. For example, failure occurs more locally along discrete fractures in the discontinuous simulations while the elasto-plastic simulations show larger zones of plastically deformed elements. Moreover, shear failure seems to occur earlier in the elasto-plastic simulations, at the moment that UDEC still simulates exclusively tensile fracturing.

In general, one can say that the discontinuous character of the UDEC simulations approaches better reality and, hence, are more suitable, if one wants to study the fracture initiation and growth in detail. Photo 2 shows some details of fracture patterns of uniaxially loaded samples cored from the rectangular block that originates from site B (Table 1). In these samples relatively large inclusions (unmixed soil) are visible. Very similar failure patterns as simulated in UDEC (Figure 6) are observed in the vicinity of inclusions, especially the vertical fractures at the top and bottom of the inclusions.

4. DISCUSSION OF EXPERIMENTAL AND NUMERICAL RESULTS

The experiments on large blocks and cores, as well as the three types of numerical simulations indicate some important trends. The influence of weak soil inclusions on the strength and stiffness of the soil mix material is significant. The reduction of the stiffness and strength is much more than what one would expect from a weighted average of the material properties (mixed and unmixed material) based on the percentage of both material types. Apart from the percentage of unmixed material, the shape, the number, the size and relative position of the inclusions are important parameters too. Hence, they have to be taken into account when conducting a detailed study. For both the continuous and discontinuous simulations, similar trends are observed for the effect on the stiffness and strength. However, the discontinuous simulations better distinguish between tensile and shear fracturing, and indicates more accurately the onset of fracturing. This means that they will be better suited to extrapolate a calibrated model, e.g. for the study of the scale effect or for other loading configurations (e.g. bending instead of uniaxial compression loading). Within this framework, the simultaneous testing of the conventional core material and the large rectangular blocks helps to better understand the possible failure of soil mix material and are really necessary as input for further numerical simulations.

In the future, more experiments are planned, so that as many soil types as possible can be investigated, resulting in a better understanding of the scale effect and the influence of heterogeneities on the mechanical behaviour of the soil mix material.

5. ACKNOWLEDGEMENTS

This research program is financially supported by the Agency for Innovation by Science and Technology of the Flemish Region IWT (BBRI, 2009-2013). The results of the discontinuous simulations are part of the thesis by Gust Van Lysebetten to obtain a M.Sc. in Geotechnical and Mining Engineering at the KU Leuven (2010-2011).

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