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Experimental and numerical investigation on reinforced sand samples

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ABSTRACT: The results of an experimental and numerical study are summarized here concerning the mechanical behavior of reinforced sands. The experimental part of the investigation was carried out using both standard triaxial and plane strain equipments. In the latter case the specimens containing either horizontal reinforcements, or reinforcements inclined with respect to the vertical loading direction. Two alternative finite elements approaches, referred to as "inhomogeneous" and "homogeneous", were adopted for interpreting the tests. The comparison between experimental and numerical results led to some conclusions on the influence of the mechanical properties of the geotextiles, and of their inclination, on the overall behaviour of the reinforced samples.

1 INTRODUCTION

A preliminary and comparative evaluation of two finite element schemes for the analysis of a vertical, reinforced earth wall (Cividini et al. 1997) showed that the available experimental information was not sufficient for a proper mechanical characterization of plane strain earth structures containing inclined reinforcements with respect to the principal stress directions. More recently another numerical study (Molenkamp 2001) confirmed that for testing non isotropic materials, like reinforced soils, the use of a plane strain apparatus is preferable to that of standard triaxial and direct shear devices.

On that basis a laboratory investigation, based on plane strain and standard triaxial compression tests, was carried out on sand samples containing geotextiles reinforcements with various inclinations with respect to the vertical loading direction (Cividini 2002b). A particular procedure was developed for preparing prismatic sand samples containing geotextiles reinforcements with various inclinations with respect to the vertical loading direction (Cividini & Sterpi 2000). The procedure is based on the moist tamping technique and on the subsequent freezing of the samples to allow their setting into the plane strain device.

The experimental investigation leads to a quantitative assessment of the influence of the reinforcement orientation on the overall shear strength and stiffness of the samples.

The numerical analysis of these tests led to a refined formulation for the mechanical response of reinforced sands.

In the following, the testing technique is described and the plane strain results are discussed with particular reference to the influence of the reinforcement orientation on the overall load-displacement curves. Subsequently, the experimental results are compared with those obtained through their numerical simulation based on "inhomogeneous" and "non-isotropic homogeneous" finite element schemes. This comparison leads to some conclusions on the interaction between sand and reinforcements and on the use of plane strain testing devices for the calibration of constitutive laws for reinforced samples.

2 LABORATORY INVESTIGATION

The triaxial tests were performed on cylindrical sand samples having diameter of 7 cm and height of 14 cm. The samples were compacted adopting the so-called "moist tamping" technique reaching a fairly uniform distribution of relative density of about 70%. The prismatic samples for the plane strain tests (Drescher et al. 1990; Cividini 2002b) have dimensions of 4 cm × 8 cm × 14 cm (width × length × height).

The experimental program carried out so far consists of about 50 plane strain tests on the natural sand and on reinforced samples. For sake of briefness only the results of 11 plane strain tests are presented here that refer to samples reinforced with geotextile layers, 2. cm or 3. cm apart from each other. Four of them were carried out to investigate the effects of the inclination β (β = 0°, 15°, 30°, 45°) on Ticino sand samples reinforced with the extensible reinforcement GTX-1 (that is the non-woven polypropylene P-TS10 geotextile, manufactured by Polyfelt Ges. M.B.H., Austria). The remaining tests concern specimens reinforced with GTX-2 (i.e. the non-woven polypropylene-polyethylene T-700 geotextile, manufactured by Terram Ltd., UK), having inclination β from 0° to 90°. The two geotextiles have comparable tensile strengths, but differ in thickness and in stiffness.

A particular mould was designed for preparing samples with inclined reinforcements. The mould can be rotated varying the angle β from 0° to 90°. This permits tamping the sand (having a water content of 4-5%) in horizontal layers even when the reinforcements will not be horizontal during the compression test. At the end of compaction, two steel blades are inserted within the mould to obtain a prismatic specimen. To avoid interference with the blades the reinforcements are cut into elements of suitable dimensions before laying them on the tamped sand layers.

The entire mould is then stored into a refrigerator at a temperature of –80 C for about 24 hours. The ice bridges produced by freezing at the intergranular contacts provide a sufficient apparent cohesion that permits handling the sample at room temperature for the time necessary (about 1 hour) to set up the plane strain cell. Due to the low water content of the sand before tamping, the volume changes caused by the formation of the ice bridges within the pores turned out to be negligible.

To prevent appreciable changes of the relative density during freezing, the difference between the coefficients of thermal contraction of sand and mould should be minimized. This was obtained by using a transparent polycarbonate (Makrolon) for the mould. This material, in fact, is less affected by the temperature changes than other standard materials, like Plexiglas, and allows the visual control of the samples during tamping.

3 EXPERIMENTAL RESULTS

Some plane strain results are summarized in Figure 1. The diagrams present the influence of the reinforcement orientation β on the axial stress-strain curves. The data show that the GTX-1 and the GTX-2 reinforced samples have different load carrying capacity, however in both cases a decrease of the overall stiffness and shear resistance is observed with increasing β. The shear resistance is lower than that of the natural sand when β exceeds 30°.

This implies that reinforced earth structures may give substantially different responses to external load

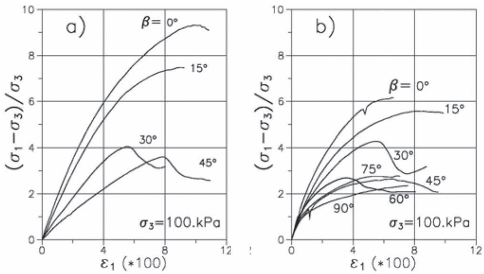

Figure 1. Influence of the reinforcement orientation for samples prepared with GTX-1 (left) and with GTX-2 (right) geotextiles, (σ_1, ε_1 axial stress and strain, σ_3 cell pressure).

increments, depending on the angle existing between the reinforcements and the compressive principal stress.

The observed overall resistance is likely to depend on the frictional resistance between the reinforcement and the sand. In particular, the structure of the GTX-1 geotextile, quite deformable along its thickness, leads to a relatively high degree of interlocking with sand grains, thus increasing the surface frictional resistance of the reinforcements. Such interlocking, however, is less pronounced for the GTX-2 geotextile, characterized by smoother surfaces and low compressibility along its thickness (Cividini 2002b).

4 MODELLING OF THE SHEAR RESISTANCE AT THE SAND-GEOTEXTILE INTERFACE

The described experimental results indicate that the overall behaviour of a reinforced soil depends on various mechanical and geometrical parameters that characterise both its basic components (soil and geotextile) and their assemblage. In particular, the results of the plane strain tests permit deriving some further conclusions on the frictional characteristics of the sand/geotextile interface, without making recourse to direct shear tests (e.g. Seo et al. 2004).

In general terms, the numerical simulation of the tests can be based on two finite element schemes, referred to as "inhomogeneous" and "homogeneous" approaches (e.g. Cividini et al. 1997). When the first one is adopted the sample is discretized introducing separately the reinforcements and the soil layers between them. In the second case the inhomogeneous medium is made equivalent to a continuous homogeneous nonlinear and nonisotropic material characterised by a suitable constitutive law.

4.1 *"Inhomogeneous" approach*

An elastic-ideally plastic behaviour is adopted for the geotextile, while a strain-softening model governs the stress-strain response of the interface and of the sand layers. In fact, the tests on the natural sand show a marked loss of strength after the peak load condition has been reached.

The strain-softening law, implemented in the finite element program SoSIA2 for non linear **So**il-**S**tructure **I**nteraction **A**nalysis of **2**D problems (Cividini & Gioda 1992) is based on the assumption that a peak yield condition exists until the irreversible strains attain a given limit. Then, with increasing plastic strains, a linear reduction of the shear strength parameters occurs, until an ultimate failure condition is reached.

The numerical results obtained under this assumption indicates that the adopted model leads to a satisfactory quantitative interpretation of the plane strain compression tests on reinforced sand, as shown by the diagrams in Figure 2 concerning in particular results from tests with different inclinations of the GTX-1 reinforcement.

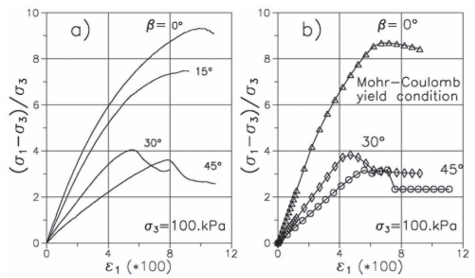

Figure 2. Influence of the reinforcement orientation β on the stress-strain relationship of samples with GTX-1 geotextile: experimental data (a) and their numerical simulation (b), (σ_1, ε_1 axial stress and strain, σ_3 cell pressure).

In fact this model is able to reproduce both the ductile behaviour of sample with horizontal reinforcements and the strain softening behaviour of samples containing inclined geotextile layers.

It is worthwhile observing that the comparison between numerical and experimental results allows also calibrating the relationships governing the variation of the deformability in elasto-plastic constitutive laws. For sake of briefness, this aspect is not discussed here and additional comments are presented in (Cividini & Sterpi 2000; Cividini 2002a).

4.2 *"Homogeneous" approach*

In the framework of the approach, discussed in some details in Cividini (2005), for modelling of the shear resistance at the sand-geotextile interface the stress state along the reinforcement direction is evaluated considering the specimen as a "homogeneous" (or reference) element. Due to the anisotropy of the reinforced samples the evolution of the stress state depends on the angle β between geotextile layers and the horizontal direction. This effect is clearly shown by the diagram in Figure 3a since, for the plane strain tests on GTX-2 reinforced sand samples, the lines, representing the variation of the normal and shear stresses σ_r, τ_r for the different reinforcement orientations, are not bounded by a circle.

For completeness, Figure 3a shows also the peak and ultimate resistance envelopes for the sand-geotextile interface, obtained from direct shear box tests carried out in general accordance with the procedure of code EN ISO 12957-1. From the experimental viewpoint, it can be observed that when the reinforcement orientation is equal to 45° and to 75° the stress state is in practice bounded by the ultimate (or residual) resistance curve characterising the sand-geotextile interface, while for the intermediate value of 60° the peak resistance is almost attained.

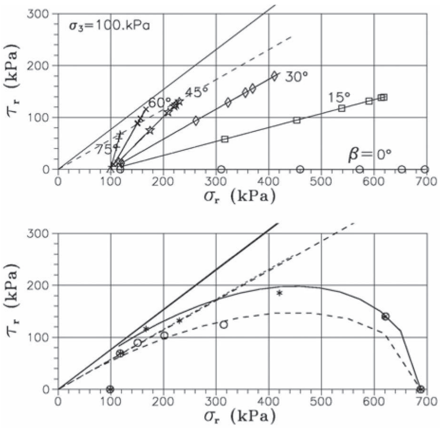

Figure 3. Influence of the reinforcement inclination β on the stress state at the geotextile/sand interface: (a) stress path from plane strain tests on GTX-2 reinforced sand and (b) numerical interpolation of the peak (open symbols) and of the end-of-test (dots) data.

For the numerical representation of the stress state reached on the reinforcement at the overall peak and at the end-of-test conditions, the basic form of the Hierarchical Single Surface **HiSS** (Desai 2001) constitutive law was chosen among the various isotropic hardening constitutive laws presented in the literature. Written in terms of the stress components σ_r and τ_r along the geotextile, the HiSS yield surface allows an acceptable approximation of both sets of experimental data, as shown by the solid and dashed interpolation curves indicated in Figure 3b. Only the data from the sand sample containing vertical reinforcements are not properly represented.

To avoid this effect, it seems necessary to improve the interpolation curve, perhaps by shifting its vertex. Alternatively a simpler provision consists in bounding the presently proposed interpolation curve with a vertical cut-off line having abscissa equal to the confining pressure adopted in the laboratory tests.

Finally, Figure 3b shows that the HiSS ultimate curves, obtained for the asymptotic stress state condition, almost coincide with the peak and ultimate lines obtained on the basis of the direct shear test results. It is important to note that the HiSS model parameters were calibrated by curve fitting of the σ_r, τ_r experimental data and that only subsequently the two HiSS ultimate lines, associated to the obtained interpolation curves, were drawn.

The above observations indicate that the shear resistance at the interface between reinforcement and sand can be evaluated on the basis of the results from plane strain tests.

Even if the results here presented concern a limited amount of data, obtained at constant confining pressure, they show that the interface resistance has a relevant effect on the overall mechanical resistance of the sample. This suggests broadening the experimental and numerical study carried so far.

5 CONCLUSIONS

The experimental and numerical results here discussed concern an ongoing research on the mechanical behaviour of reinforced sands, containing geotextile reinforcements with various inclinations with respect to the vertical loading direction.

First the results of a series of plane strain compression tests have been illustrated. They show the marked influence of the reinforcement slope on the overall stiffness and shear resistance of the "composite" material. Subsequently, the experimental results have been compared with those obtained from a series of finite element analyses based on "inhomogeneous" and "homogeneous" schemes. The inhomogeneous analyses indicate that the overall load-displacement response of the reinforced sample is influenced by the strain softening behaviour of the interface only in the case of inclined reinforcements.

As to the homogeneous approach, the numerical results show that the HiSS model provides an acceptable approximation of the experimental data. In fact the HiSS model can properly take into account of the shear resistance that develops at the interface between soil and geotextile.

On these bases it can be concluded that the described experimental investigation and its numerical modelling represent two necessary and interlaced steps towards a deeper understanding of the mechanical behaviour of reinforced sands and towards the stress analysis of actual engineering problems.

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