Experimental and Numerical Investigation on the Mechanical Behavior of a Reinforced Sand

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Summary

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. Based on its results a constitutive law was derived for the "composite" material in plane strain conditions. The law was adopted in the finite element analysis of a benchmark structure and the results are compared with those obtained with a standard analysis in which both reinforcements and sand layers were separately introduced.

Introduction

The engineering analysis of a variety of the earth-reinforced structures is customarily carried out in plane strain conditions. This suggests using plane strain triaxial devices for the experimental investigation on the mechanical behavior of the composite soil-reinforcement material.

Here an experimental investigation is first summarized, based on plane strain and on standard triaxial compression tests. A particular technique is illustrated for preparing sand samples containing inclined reinforcements with respect to the horizontal direction. This 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 spacing and slope on the overall shear strength and stiffness of the samples. Based on these results a constitutive law is derived for the composite material in plane strain conditions. Finally, the constitutive law is adopted in the finite element analysis of a benchmark structure.

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 [1] reaching a fairly uniform distribution of relative density of about 70%. The prismatic samples for the plane strain tests [2,3] have dimensions of 4.cm x 8.cm x 14.cm. Due to their small dimensions, the samples were reinforced with a thin polypropylene, nonwoven geotextile.

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For sake of briefness only the results of 6 plane strain tests are presented here. They refer to samples reinforced with four geotextile layers, 3.cm apart from each other. Three of them were carried out to investigate the effects of the lateral pressure σ_3 on samples with horizontal reinforcements, while the remaining three tests concern samples with horizontal ($\beta=0°$) and inclined ($\beta=15°, 30°, 45°$) reinforcements. The angle β was kept within the mentioned limits since the specimen with $\beta=45°$ already shows a shear resistance comparable to that of the natural (unreinforced) sand. To quantify the influence of the lateral stress, three values of the cell pressure (50.kPa, 100.kPa and 200.kPa) were used for the samples with $\beta=0°$.

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 -80C 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.

Some plane strain results are summarized in figs.1 to 3. Figure 1 reports the variation of the axial stress and of the volumetric strain versus the axial strain for the first three tests. The confining effect provided by the horizontal reinforcements leads to a monotonous stress-strain behaviour. In addition, the specimens show a certain amount of dilation for low values of the confining pressure.

The influence of the reinforcement orientation on the axial stress-strain curves and on the volumetric changes is presented in fig.2. A decrease of the overall stiffness and shear resistance is observed with increasing β, while only minor differences exist in the volumetric behaviour.
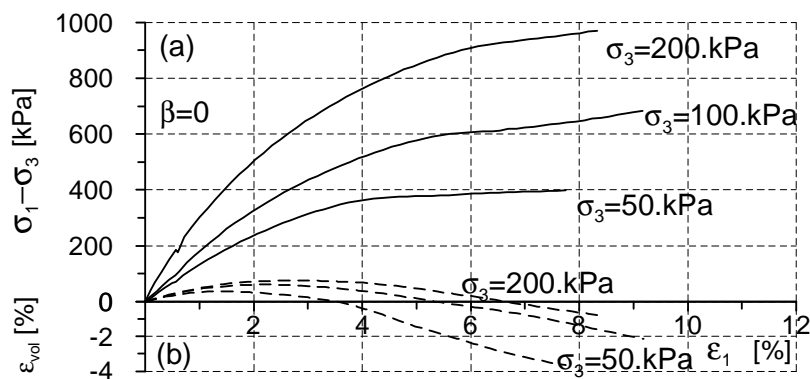
Fig. 1. Plane strain compression tests on samples with horizontal reinforcements: (a) axial stress versus axial strain and (b) volume strain versus axial strain.
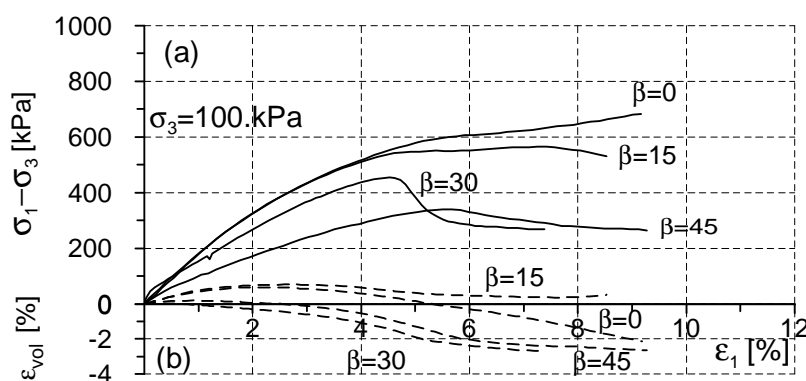

Fig. 2. Influence of the reinforcement orientation: (a) axial stress-strain diagrams and (b) volume strains versus axial strain.

The results obtained on reinforced samples are compared in fig.3 with those obtained on the natural sand. In particular, the variations are shown of the first stress invariant, I_1, and of the square root of the second invariant of the deviatoric stress J_2 with the angle β. The data refer to both peak and end-of-test conditions.

The shear resistance of the reinforced samples almost coincides with that of the unreinforced specimens when β approaches 45°. This implies that reinforced earth structures may give substantially different responses to external load increments, depending on the angle existing between the reinforcements and the compressive principal stress.
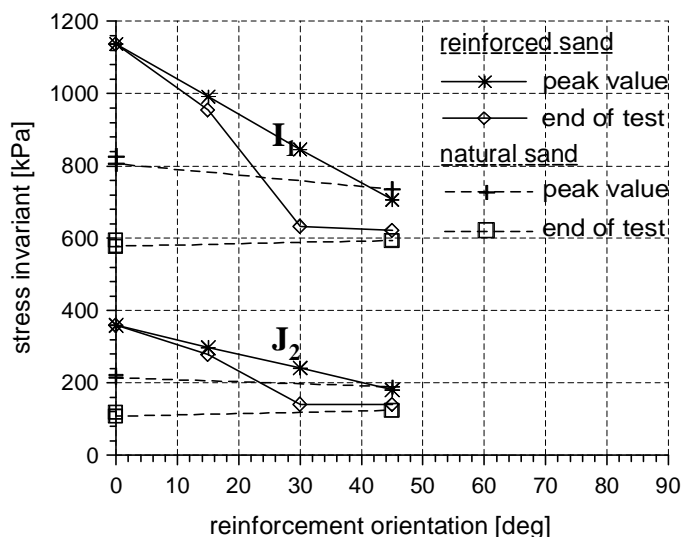
Fig. 3. Stress invariants at the peak condition and at the end of the test: reinforced specimens (solid lines), natural sand (dashed lines).

A Yield Criterion for the Reinforced Sand

The following modified form of Drucker-Prager failure condition was adopted for the non-isotropic composite material equivalent to the reinforced sand,

$$F(\underline{\sigma}, \vartheta) = J_2 + \alpha(\vartheta) \cdot I_1 \cdot K(\vartheta) \quad . \tag{1}$$

The material parameters α, K (depending, respectively, on the frictional and cohesive characteristics), are function of the angle ϑ between the major principal stress and the reinforcements,

$$\alpha(\vartheta) = \left[(\alpha_M + \alpha_m) + (\alpha_M - \alpha_m) \cdot \cos(2\vartheta) \right] \quad , \tag{2a}$$

$$K(\vartheta) = \left[(K_M + K_m) + (K_M - K_m) \cdot \cos(2\vartheta) \right] \quad . \tag{2b}$$

The parameters α_M and K_M in eqs.(2) are determined from triaxial compression tests on sample with horizontal reinforcements while α_m and K_m, that characterise the samples with vertical reinforcements, are assumed equal to those of the natural sand. Eqs.(1,2) are particularly suitable for elasto-plastic analyses based on iterative solution procedures. It is sufficient, in fact, to adopt at each iteration

the values of the parameters α and K determined through eqs.(2) on the basis of the stress state calculated at the end of the previous iteration.

Finite Element Analysis of a Reinforced Earth Structure

Some results are shown of the finite element analyses of a vertical earth wall reinforced with oriented polyethylene grids (OPG). The calculations [4] were performed using the described yield criterion (non-isotropic analysis) and by separately discretizing the sand layers and the reinforcements (inhomogeneous analysis).

Both two-dimensional, plane strain and three-dimensional analyses where performed. Fig.4 shows the 3D mesh. The grid for the 2D analyses is merely a vertical section of the 3D mesh. The sand is discretised through 8 node isoparametric *brick* elements in the 3D mesh and through 4 node quadrilateral elements in the 2D calculations. The reinforcements are introduced by means of 4 node membrane elements and of 2 node truss elements in the 3D and 2D analyses, respectively. In the 2D case, the mesh used for the non-isotropic analyses does not contain the truss elements discretising the reinforcements.
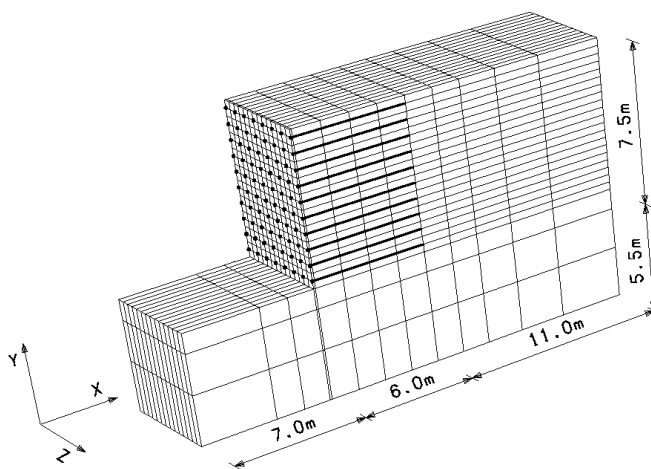

Fig. 4. Finite element mesh used for the 3D analyses of the reinforced earth wall.

The horizontal displacements of the wall obtained from 2D and 3D analyses are shown in fig.5. In these calculations the construction of the wall is modelled through a series of 10 steps, each of which corresponds to the placement of one reinforcement and of one sand layer. The results of calculations show that the non-isotropic approach leads to results similar to those derived from a more detailed inhomogeneous analysis.
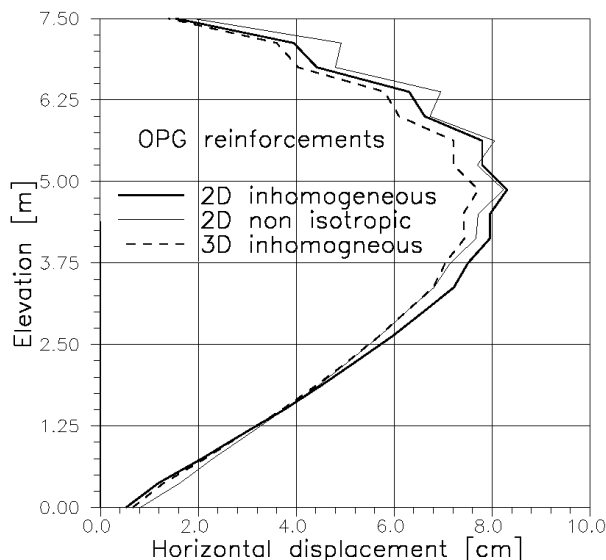
Fig. 5. Horizontal displacements of the vertical wall at the end of construction from 2D and 3D analyses.

Conclusions

A non-isotropic yield criterion has been derived from the results of laboratory on sand samples containing inclined reinforcements. The criterion was then applied to the analysis of an earth-reinforced structure. The comparison between these results and those obtained with standard calculations, where sand layers and reinforcements are separately introduced, shows that the non-isotropic approach predicts an overall structural behaviour similar to that obtained with standard, and more cumbersome, calculations.

References

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