Effect of Soil Dilatancy on Shear Strength of Reinforced Composites

G. E. Bauer
Carleton University, Ottawa, Canada

Y. -J. Zhao
Private Consultant, Vancouver, Canada

ABSTRACT: Direct shear tests were carried out in a large box with geogrids placed at different orientations to the shear plane. The mobilized strength varied greatly with the angle of grid orientation. Soil dilatancy also affected the strength behaviour of the composite. Results from numerical methods agreed well with the corresponding experimental values.

1 INTRODUCTION

Reinforced soil structures, such as the embankment shown in Fig. 1, are subjected to deformation and shear stresses. Before failure can occur along a critical failure plane, indicated as arc AC in Fig.1, the maximum shearing resistance must be overcome. For natural soils this shearing resistance is commonly determined from conventional laboratory tests, such as the direct shear test. The use of a similar test is proposed to estimate the shear strength and the dilatancy behaviour of reinforced composites. The test is considered to be a perfomance test and is applicable to all types of grid and sheet reinforcement and for most backfill materials specified in the construction of reinforced earth structures. The results from such tests then will yield parameters suitable for design applications.

The description of the direct shear test apparatus and some preliminary results were given previously (Bauer and Zhao, 1993). This paper will focus on the effects dilatancy and geogrid orientation have on the shear behaviour of the reinforced composite.

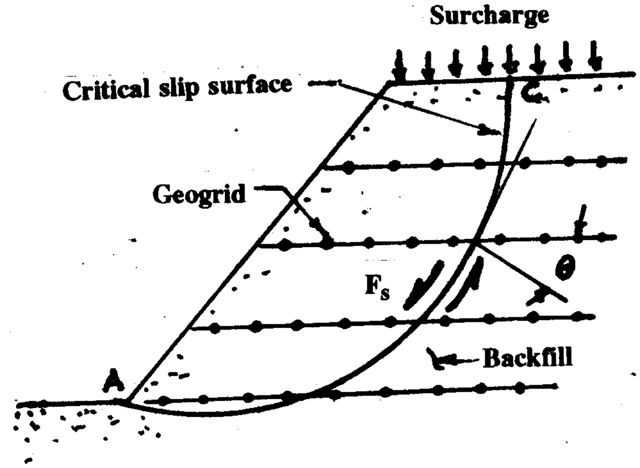

Fig. 1 Direct shear failure of reinforced embankment

For a specified grid orientation, tests with at least three normal stresses were performed (i.e. 23, 28 and 35 kPa). All tests were run with a shear displacement rate of 1 mm per minute. Complete shear force versus displacement relationships were obtained. The vertical movement of the soil (i.e. soil dilation or contraction) was also monitored. In some tests the steel side wall of the box was replaced with a reinforced glass panel in order to observe the displacement of steel markers placed in the soil.

2 TEST DESCRIPTION

2.1 General

Direct shear tests were carried out in a fully automated box as indicated in Fig. 2. The soil was compacted to conditions as specified in the field (i.e., maximum dry density and optimum moisture content) and the geogrid was placed at different orientations to the shear plane.

2.2 Box size

The size of the shear box should be large enough to allow testing of site specific soils and representative geogrid specimens. Large boxes also minimize influences associated with side wall friction, proximity of boundaries and soil particle limitations. Based on these considerations a box having dimensions of 1000 by 1000 by 940 mm was used (Fig. 2). Normal loads were provided by a stack of concrete blocks. The shear force was applied through an hydraulic actuator. The whole system was computer controlled and the results were collected by a data acquisition system. A detailed desription of the testing system was given by Bauer and Zhao (1993).

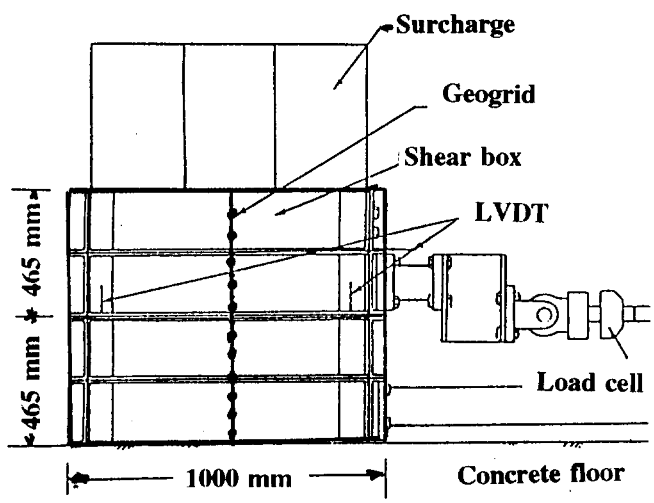

Fig. 2 Overall dimensions of direct shear box

2.3 Geogrid specimen

The size of the geogrid specimens for in-soil tests is governed by the size of the dimensions of the box. All grid specimens were 975 mm wide and the length varied accordind to the orientation of the mesh within the box. Two geogrids were investigated, an extruded uniaxial polyethylene mesh (TENSAR UX 1500) and a knotted polypropylene grid (CONWED 9027). The physical properties of these meshes were given by Bauer and Zhao (1993).

2.4 Geogrid orientation

In a reinforced soil structure the critical shear plane is transgressing the horizontally placed geogrids at different angles of orientation (Fig.1). This angle tends to become 90^0 at the bottom of the embankment and close to 0^0 at the top. (Note that the orientation is measured from the normal of the shear plane to the alignment of the geogrid). It stands to reason then that the mobilized strength should be different for different angles of intersections. In order to investigate this aspect, tests were carried out with geogrid placement at 90, 45, 30 and 0 degrees to the normal of the shear plane. At 90^0 orientation the grid is placed along the horizontal shear plane (sliding test) and at 0^0 the geogrid and the shear plane intersect at right angles. It should be noted that the grids were anchored at the bottom of the box and were folded along the top surface of the sand in order to prevent pullout during shear.

3 SAND PROPERTIES

A uniform coarse sand having a mean grain diameter of 0.35 mm was tested in conjunction with the two geogrids. The maximum dry density was 19.8 kN/m^3 (modified Proctor) with a corresponding moisture content of 11%. The sand was compacted into the box in 150 mm lifts at a density of 18.8 kN/m^3 and 8% moisture corresponding to 95% of modified Proctor density. The peak and residual friction angles were 46.0^0 and 36.8^0, respectfully.

4 TEST RESULTS AND DISCUSSION

4.1 Shear strength

The mobilized shear stress versus horizontal shear displacement is given in Fig. 3. This figure shows the results of 15 tests. Each curve represents, in a normalized form, the results of three tests. It is observed from these results that the orientation of the geogrid with regard to the shear plane has a marked effect on the strength of the composite. The maximum increase, as compared to the natural sand, occurs when the grid is oriented at 30^0 to the normal of the shear plane (i.e. the angle between the shear plane and geogrid is 60^0).

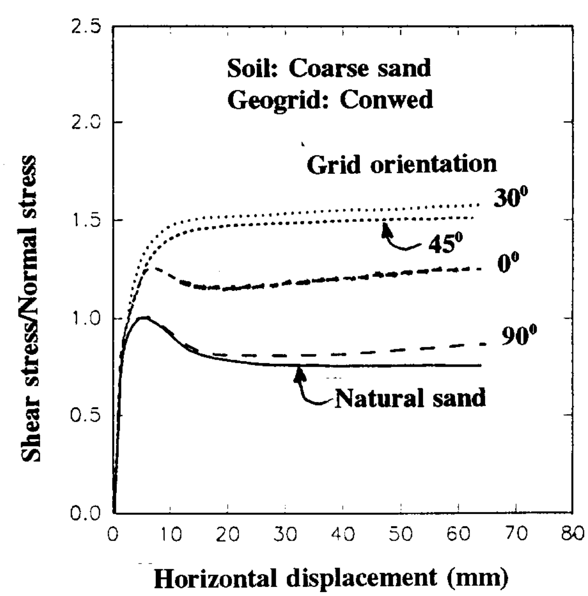

Fig. 3 Shear stress - displacement response

The strength of a granular soil is generally presented by the classical Mohr-Coulomb equation as

$$\tau = \sigma \tan \Phi \qquad (1)$$

For a reinforced granular composite the shear strength is given as (Bauer and Zhao, 1993)

$$\tau_R = \sigma \tan \Phi_R + c_R \qquad (2)$$

where the subscript R refers to the properties of the reinforced soil. σ and Φ are the normal stress and the soil friction angle, respectfully. The term c_R is known as the "apparent cohesion" or "reinforcing effect". Zhao (1993) has found that the natural and reinforced angles of friction are approximately equal for the several granular soils and different geogrids investigated. Bauer and Zhao (1993) have proposed a numerical model relating c_R to the soil poperties and the grid orientation

$$c_R=K(\cos\theta\tan\delta/\cos\Delta\theta)[\sin(\theta+\Delta\theta)+\cos(\theta+\Delta\theta)\tan\Phi] \qquad (3)$$

where K is a constant to be determined from the physical soil and geogrid properties, θ is the orientation of the grid, Φ and δ are soil and soil/geogrid friction angles respectfully.

Fig. 4 shows the theoretical and experimental data for the strength increase (c_R) with grid orientation. The relationships are plotted for both peak and residual soil friction angles of the sand. The correlation between the measured strength increase and the model prediction is quite good. One can, therefore, use the numerical relationship, knowing the physical properties of the given soil and the geogrid, to predict the shear strength increase for various grid orientations. In order to obtain a global value for the shear strength mobilized along a critical failure plane, such as AC of the embankment shown in Fig.1, one should sum up the differen strength components associated with a particular grid orientation.

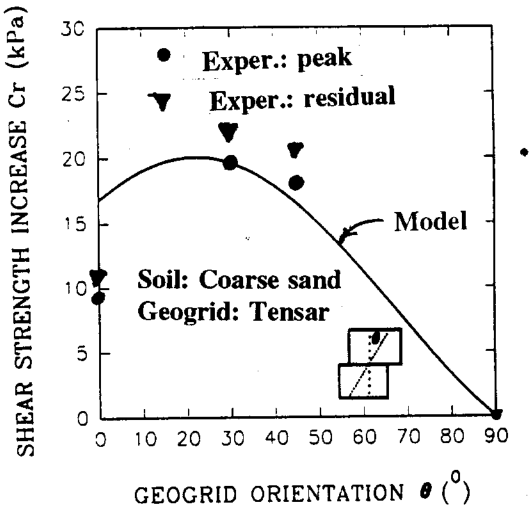

Fig. 4 Shear strength increase versus grid orientation

4.2 Soil dilatancy

Dense granular soils will dilate (i.e. expand in volume) when sheared. This phenomenon is generally expressed by the angle of dilatancy as

$$\Psi = \tan^{-1} (\Delta Y/ \Delta X) \qquad (4)$$

where ΔY and ΔX are the incremental vertical and horizontal displacements of the expanding soil. These quantities are commonly measured in a direct shear test. If no slip between soil and reinforcement is assumed than the dilatant soil strain must manifest itself in mobilized tensile strains of the reinforecement. Using a flow rule analysis (Jewell,1980) a continious relationship between horizontal shear displacement and the correspoding shear stress can be formulated. Zhao (1993) has extended this analysis include also the orientation of the geogrid. The governing equation was given as

$$S/N = [\tan\Phi - (\Delta Y/\Delta X)][1+(T_R/N)\cos(\theta+\Delta\theta)] + (T_R/N) \sin (\theta+\Delta\theta) \qquad (5)$$

where S is the resulting shear force, N is the known normal force and T_R is the mobilized tension in the reinforcement which can be calculated from the soil strain expressed in equation (4).

Figs. 5, 6, 7 and 8 show the experimental results for shear force versus shear displacement for the four geogrid orientations together with the corresponding data from the numerical prediction. The model predicts quite well the peak or maximum values in shear strength and gives a fair prediction for the complete strength versus displacement response.

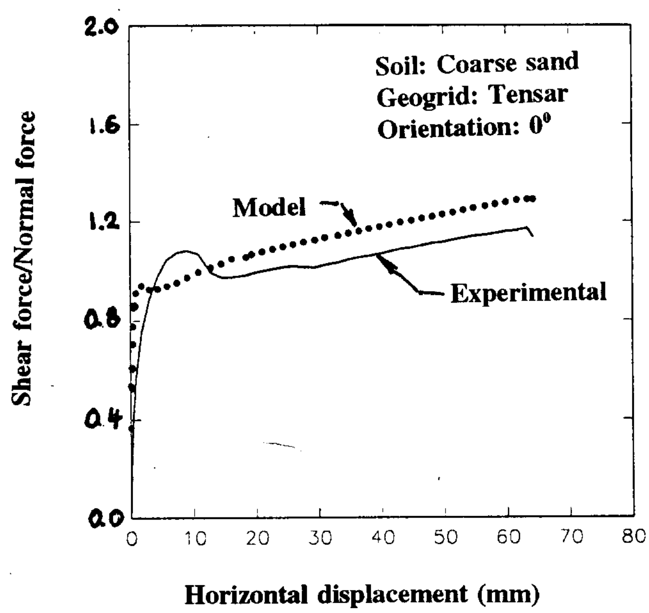

Fig. 5 Experimental and numerical results (θ = 0)

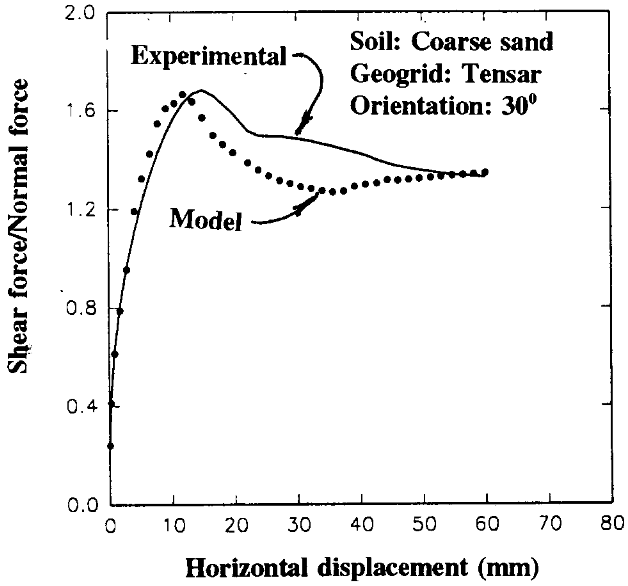

Fig. 6 Experimental and numerical results ($\theta = 30^0$)

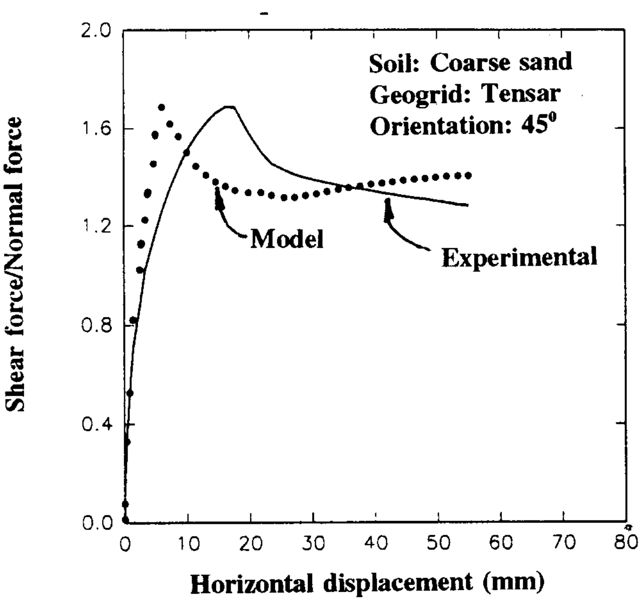

Fig. 7 Experimental and numerical results ($\theta = 45^0$)

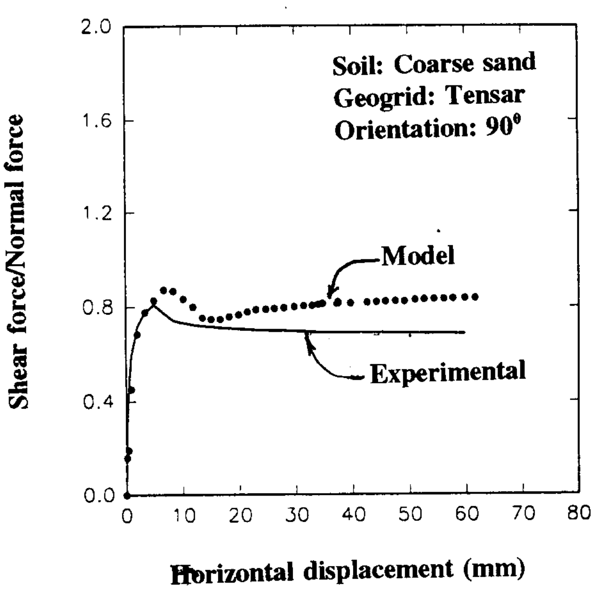

Fig. 8 Experimental and numerical results ($\theta = 90^0$)

5 CONCLUSIONS

In most reinforced soil structures the orientation of the shear plane the geogrid varies along a critical failure plane (Fig. 1). The maximum strength within the composite is developed when the this angle is about 60^0. When the direction of shear and the alignment of the geogrid is in the same plane, the strength of the reinforced composite is approximately equal to the natural sand. Therefore, in order to carry out a proper stability analysis for a reinforced soil structure, one should take into consideration the variation of strength with geogrid orientation along the the failure plane. The results from the proposed numerical model agree well with the experimental ones.

Tensile strength in the reinforcement is only mobilized when the soil dilates during shear. This increase in strength can be simulated numerically using constitutive relations from soil dilatancy and flow rule. The prediction for peak or maximum strength values agree well with the experimental data. The model will also give a fair correlation with the experimental values with regard to strength versus displacement relation.

REFERENCES

Bauer, G.E. and Zhao, Y. (1993) Evaluation of shear strength and dilatancy behaviour of reinforced soil from direct shear tests. *Geosynthetic Soil Reinforcement Testing Procedures,* ASTM, STP 1190, Philadelphia, 138-151

Jewell, R.A. (1980) Some effects of reinforcement on the behaviour of soils. *Ph.D. thesis,* Cambridge University, Cambridge, England

Zhao, Y. (1993) Strength and deformation behaviour of geogrid reinforced soils. *Ph.D. thesis,* Department of Civil Engineering, Carleton University, Ottawa, Canada

ACKNOWLEDGEMENT

Financial support for this investigation was provided by the Natural Science and Engineering Research Council of Canada (NSERCC), Conwed Plastic and Tensar Corporation. This assistance was greatly appreciated.