C.R. Coll. Int. Sols Textiles. Paris 1977

SCHWAB E.F.
Royal Institute of Technology, Stockholm, Sweden
PREGL O.
Universität für Boden Kultur, Vienna, Austria
BROMS B.B.
Royal Institute of Technology, Stockholm, Sweden

Deformation behaviour of reinforced sand at model tests measured by the X-Ray technique

ZUSAMMENFASSUNG

Um die Verformungseigenschaften von bewehrter Erde zu untersuchen wurden Modellzugversuche mit einem trockenen gleichförmigen Sand bei lockerer und dichter Lagerung durchgeführt. Als Bewehrung wurde ein Polyester-Gewebe verwendet. Die Verformungen im Sand und im Gewebe wurden mit Hilfe des Röntgenverfahrens gemessen. Der Reibungswinkel zwischen Gewebe und Sand wurde mittels Scherversuche ermittelt. Der aus den Modellversuchen rückgerechnete Reibungswinkel zeigte eine Abhängigkeit von der relativen Lagerungsdichte des Sandes und von der Auflast. Die Versuche haben weiters gezeigt, daß die Bewehrung während des Zugversuches den gesamten Erdkörper oberhalb der Bewehrung beeinflußt. Bei großer Auflast ist auch der Einfluß unterhalb der Bewehrung von Bedeutung. Die Verformungsmessungen haben gezeigt, daß die Bewegungen im Gewebe und im Sand progressiv verlaufen und daß sich die Verschiebungsfelder je nach Lagerungsdichte und Auflast ganz verschieden ausbilden.

INTRODUCTION

The concept of reinforced earth has been applied in Sweden mainly to increase the bearing capacity of embankments constructed on soft soils. Short sheet piles connected by tension rods have economically been used as reinforcement in many cases (Wager, 1968). More recently, a woven polyester fabric has been used as reinforcement. The fabric is woven by the firm AB Fodervävnader, Borås, Sweden and is given the designation of No. 600.

The first time the fabric has successfully been used was at a bridge construction to carry the horizontal forces (Holtz, 1973; Holtz and Massarsch, 1976). The fabric has also been used as reinforcement at a road embankment on very soft organic clay. Experience has shown that large lateral movements can occur in soft soils even at a factor of safety of 2 or more against bearing capacity failure (cf. Schwab, Broms and Funegard, 1976).

Pullout tests have been carried out in the laboratory by Holtz (1973) to study the soil fabric interaction and the zone of influence of the reinforcement. He found that highly nonuniform deformations occurred in the fabric during pullout. The maximum friction angle between the fabric and the sand was found to be in the order of the angle of internal friction of the sand as determined by triaxial tests. Full frictional resistance was developed at small deformations. The zone of influence of the fabric was about 10 cm on either side of the fabric.

Pullout tests have been carried out in large scale by the Swedish Geotechnical Institute. It was found that the friction angle between the fabric and the sand varied between 21^{o} and 29.5^{o} (Lindskog and Erikson, 1974). The strain in the fabric at failure was 3.1%.

Model tests with reinforced retaining walls have been carried out by Lindskog, Bergdahl and Holm (1975) and by Davidson and Ekroth (1975).

The soil-fabric interaction, the zone of influence of the fabric and the mechanism of the development of the frictional resistance in the fabric during loading are of great importance in the design of reinforced earth. The purpose of this investigation was to study these factors by model tests. The tests have been carried out with dry sand at loose and dense conditions and at differrent surcharges. The X-ray technique has been used to measure the small deformations at which the frictional resistance is mobilized.

TEST EQUIPMENT AND TEST PROCEDURE

Model. The model consisted of a 58.2 cm high and 113.5 cm long glass box, Fig. 1. The glass walls were 1.25 cm thick and the width of the box was 15 cm. A vertical steel wall, 29.9 cm high, was mounted 37.8 cm from the end of the box. A surchrge could be applied to the sand by a pressure bag which was connected to an air pressure regulator. A three-component stress transducer was installed in the wall. Eight reference points were attached outside the glass wall.

Reinforcement. A woven polyester fabric has been used at the tests. The properties of the fabric are summarized in Table 1.

Table 1. Properties of polyester fabric

No. of threads/m of width	890
Density, g/cm^3	1.38
Tensile strength, kN/m	71.3
Strain at failure, %	14.0
Creep strength, kN/m	35.0

The tensile strength of the fabric is rather high and the creep strength is 50% of the tensile strength. The resistance of ageing and rot of the fabric is good. It is insoluble in organic solvents and very resistent to dilute mineral acids and all organic acids (Holtz, 1973).

Sand. A very uniform washed quartz sand has been used in this investigation. The index properties of the sand are summarized in Table 2.

Table 2. Index properties of the sand

Unit weight of solids, g/cm^3	2.643
Maximum dry unit weight, g/cm^3	1.657
Minimum dry unit weight, g/cm^3	1.478
Minimum void ratio	0.59
Maximum void ratio	0.79
Uniformity coefficient	1.2
Mean grain size, mm	0.85
Angle of internal friction, degrees	
loose state (D_r=19%)	26.0
dense state (D_r=96%)	36.0

The angle of internal friction of the sand has been determined by direct shear tests.

X-ray technique. The method to determine deformations by the X-ray technique consists of recording the images of lead shot markers on radiographs. The lead shot markers, 2 mm in diameter, were embedded in the sand and glued to the fabric. The markers were located orthogonal to the X-ray beam in the midsection of the model box. From successive radiographs it was then possible to establish the displacement vectors for different points in the sand and in the fabric. In the evaluation of the tests the following assumptions were made:

- o the displacement of the markers correspond to the displacement of the surrounding sand and the reinforcement
- o the markers do not influence the properties of the sand and the reinforcement.

The accuracy of the displacement measurements was in the order of 0.2 mm.

Friction between sand and fabric. The friction angle between the sand and the fabric has been determined by direct shear tests. The fabric has been attached to a hard wooden plate which was mounted into the lower part of the shear box. The friction angle was found to be 32.5^{o}. To get a more realistic test condition sand was glued to the plate and the fabric was attached to it. Also at these tests the friction angle was 32.5^{o}. The tests have been carried out at dense condition of the sand. The friction angle between the sand and the fabric was thus about 10% lower than the angle of internal friction of the sand as determined by dirct shear tests.

Test description. Sand has been placed in layers of about 2 cm into the model box. The sand was compacted and the lead shot markers were placed at a distance of about 2 cm at the sand layer, Fig.2. At a height equal to the lower end of the steel wall the fabric, 15 cm wide and about 50 cm long was placed on the sand surface. Then the model box was filled with sand. A clamp has been attached to the reinforcement to which the force transducer and the loading frame was connected. The load has been applied in increments. At a test the following measurements were made:

- o applied force
- o displacement of the fabric just outside the steel wall
- o shear and normal stress at one point at the steel wall, Fig.2.
- o displacements of the lead shot markers by means of the radiographs

Five radiographs were made at each test at a displacement of the fabric of 0, 5, 15, 35 and 75 mm. The midpoints of the reference points and of the markers were measured with respect to a chosen coordinate system and the measurements were evaluated by computer.

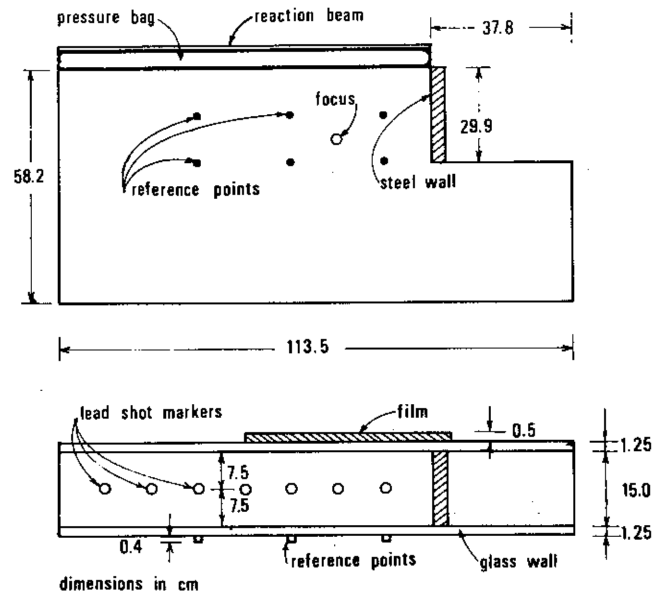


Fig. 1 Model box used in this invesigation

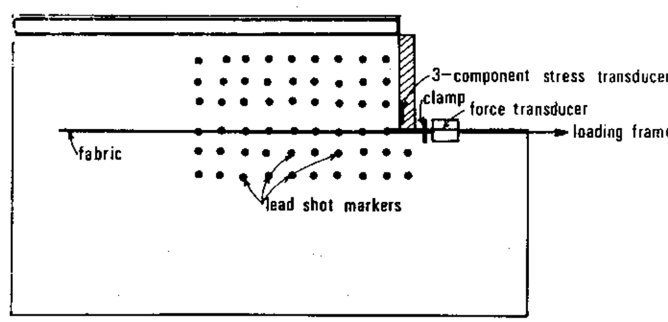


Fig. 2 Test arrangement at pullout tests

TEST RESULTS AND DISCUSSION

Only some typical test results of the pullout tests are presented in this report.

In Fig. 3 the finite element grid is shown. The joints in the grid correspond to the midpoints of the lead shot markers. In Fig. 4 the applied force, the shear and normal stress has been plotted against the displacement of the fabric. The peak values occurred almost

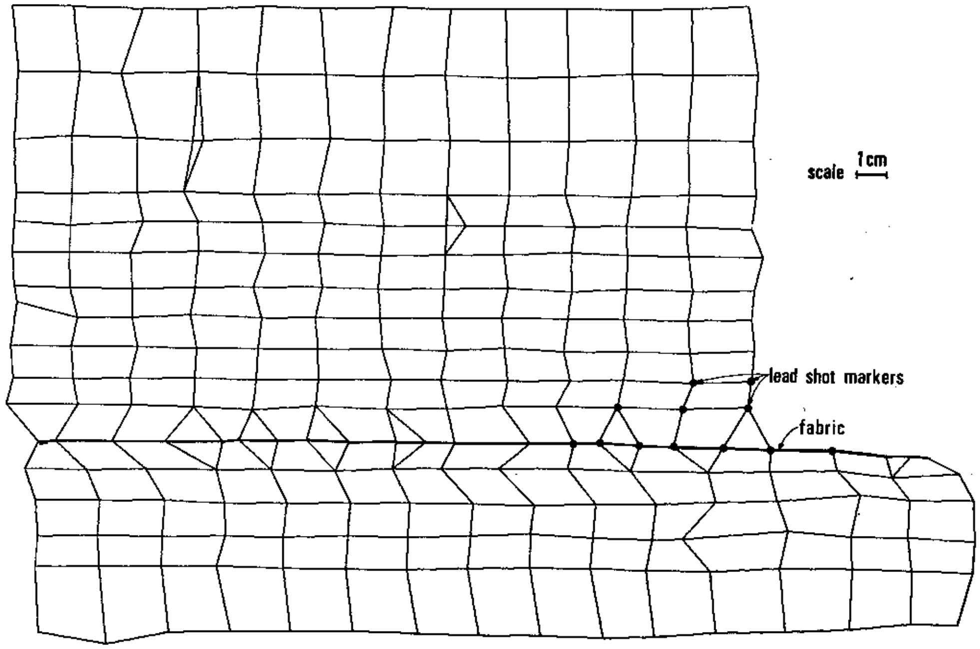


Fig. 3 Finite element grid

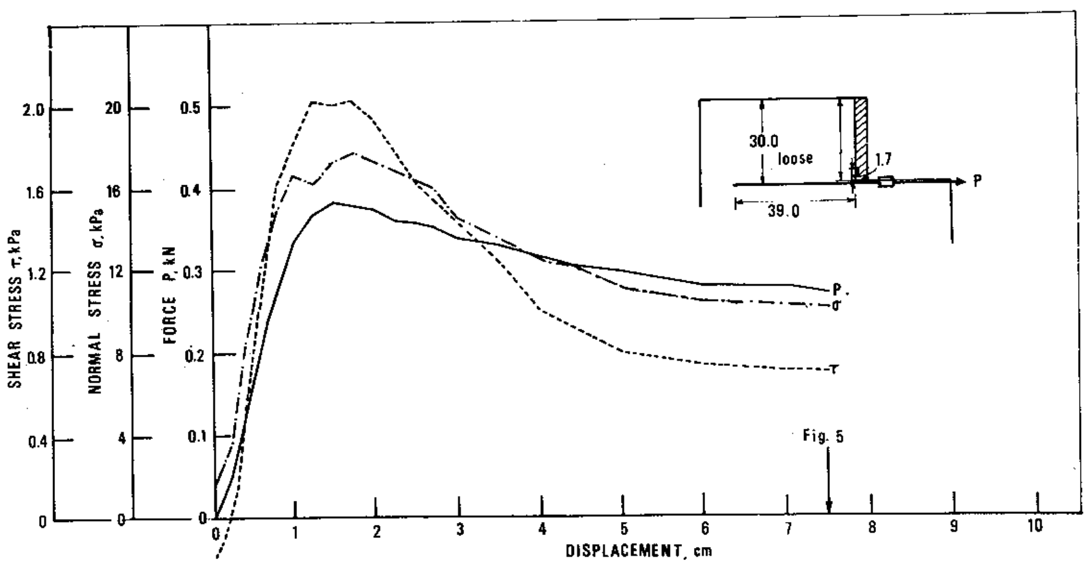


Fig. 4 Relationship between applied force, shear and normal stress and displacement for a test with loose sand without surcharge

simultaneously at about 15 mm displacement or 5% strain of the fabric. The previous radiographs showed, however, that the displacement in the fabric increased gradually towards the end of the fabric. The peak value of the force corresponds to an average frictional resistance which has been mobilized successively along the fabric. After the peak values have been reached they decreased gradually with increasing displacement of the fabric. The residual value of the applied force is about 70% of the peak value. The normal stress at the wall measured at the start of the test corresponded to the earth pressure at rest. Due to the displacement of the fabric passive earth pressure was mobilized against the wall. The direction of the shear stress was at the start of the test downwards due to the settle-

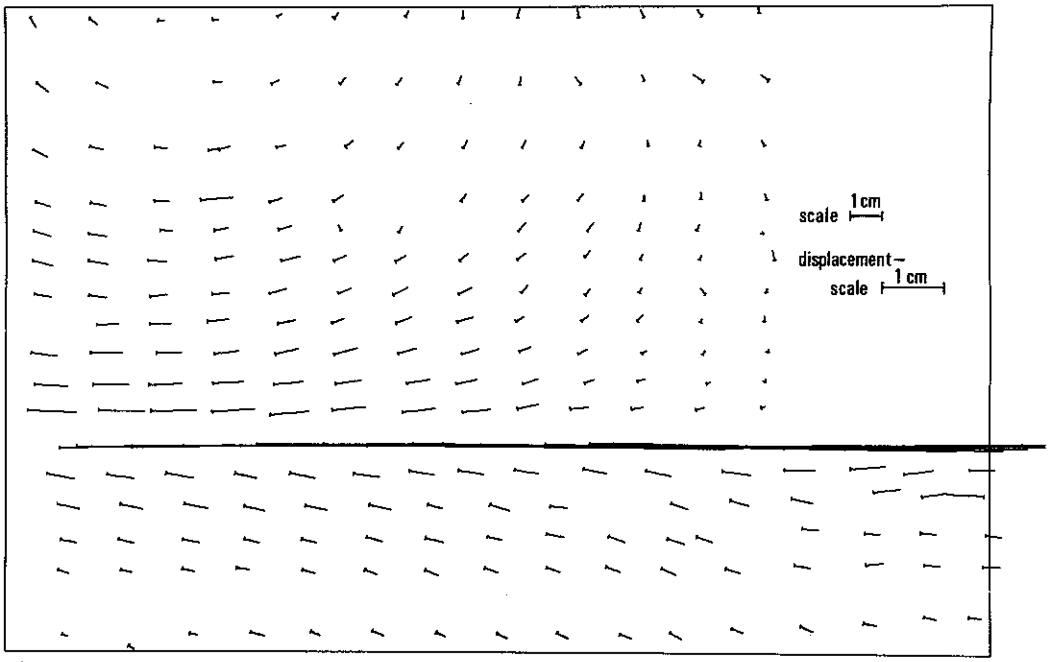


Fig. 5 Displacement vectors of pullout test with loose sand without surcharge at a displacement of 75 mm of the reinforcement

ments during installation of the sand. When the fabric was displaced horizontally against the wall the shear stress changed into the opposite direction. The measured shear stress at failure was small, about one tenth of the normal stress.

The friction angle between the sand and the fabric calculated from the measured force and the force due to gravity is about 38^{o}, which is a reasonable value, as the angle of internal friction can be very high at low normal stresses.

The displacement vectors of the lead shot markers after a displacement of 75 mm are shown in Fig. 5. The deformation behaviour can clearly be seen. Near the steel wall the sand moved primarily in an upwards direction. At some distance from the wall the sand moved horizontally against the wall. The deformation of the sand near the wall was small, about 1 mm. At a distance which corresponds about to the height of the wall the deformations were about 10 mm. Near the wall the deformations were about the same over the whole height of the wall. At some distance, however, the deformations decreased with increasing distance from the fabric. Below the reinforcement the deformations in the sand were about the same along the fabric. The deformations decreased with increasing distance from the fabric.The entire mass of soil above the fabric is affected by the reinforcement during pullout.

In Fig. 6 the relationship between force, shear and normal stress and displacement is shown for a test with dense sand and without surcharge. The peak values were reached at a displacement of approximately half of the displacement when the sand was loose. The peak force was about 25% higher than for the test with loose sand. The calculated friction angle is about 41^{o}.

The normal stress became zero after a displacement of about 30 mm. This can be explained by the fact that some sand grains were squeezed through the space between the steel wall and the fabric.

The displacement vectors after a displacement of 15 mm of the fabric are shown in Fig. 7. It can be seen that the sand above the reinforcement moved primarily in upward direction. The same tendency was observed at a displace-

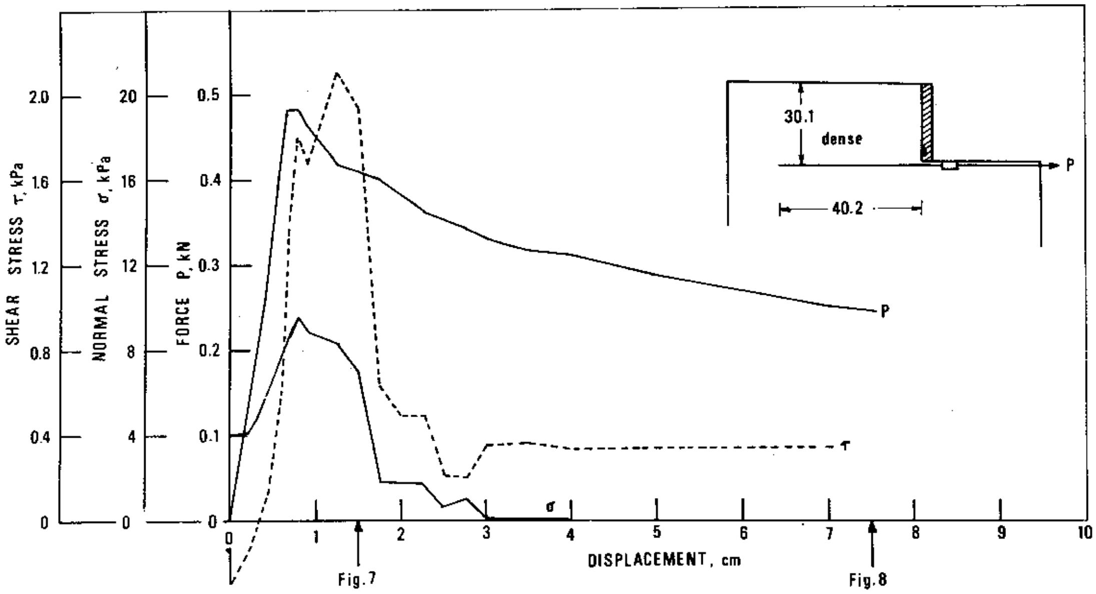
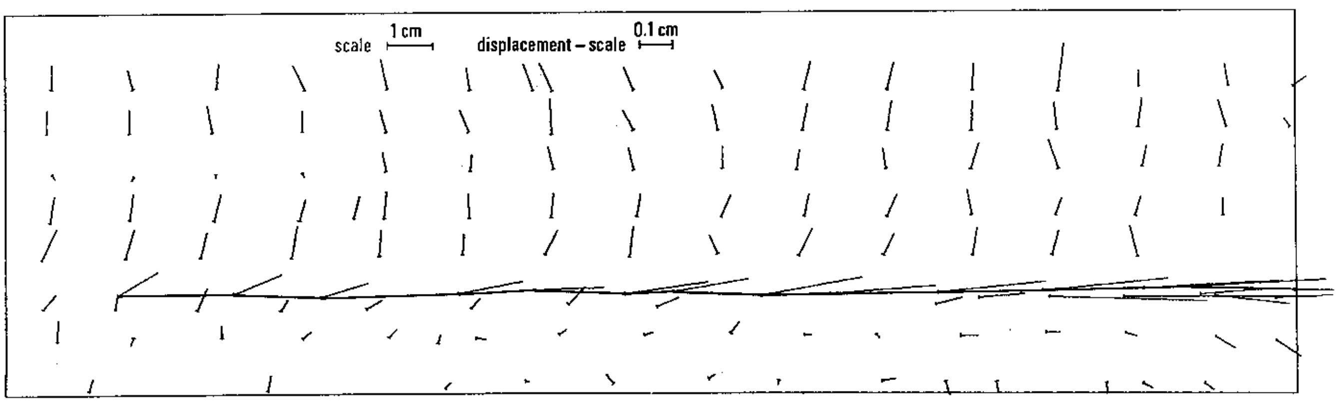
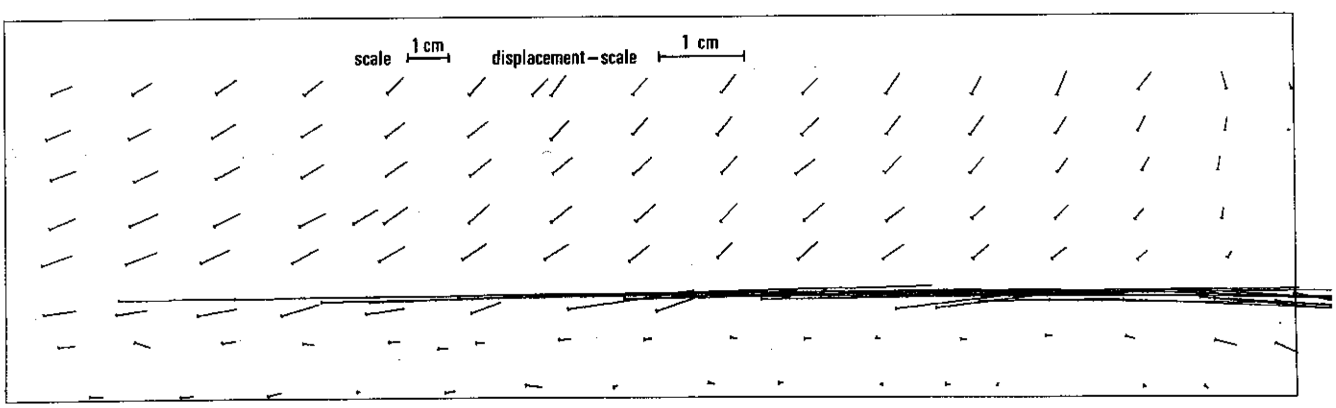


Fig. 6 Relationship between force, shear and normal stress and displacement for a test with dense sand without surcharge





Figs 7 and 8 Displacement vectors of pullout test with dense sand without surcharge at a displacement of the reinforcement of 15 and 35 mm, respectively

ment of the fabric of 5 mm. This deformation-behaviour can be expected in dense sand due to the volume increase during shearing at low deformations. It is interesting to note that the heave of the sand corresponds approximately to the mean grain size diameter of the sand. The displacements of the sand below the fabric were erratic. The displacement vectors after a displacement of 35 mm are shown in Fig. 8. In front of the wall the sand moved

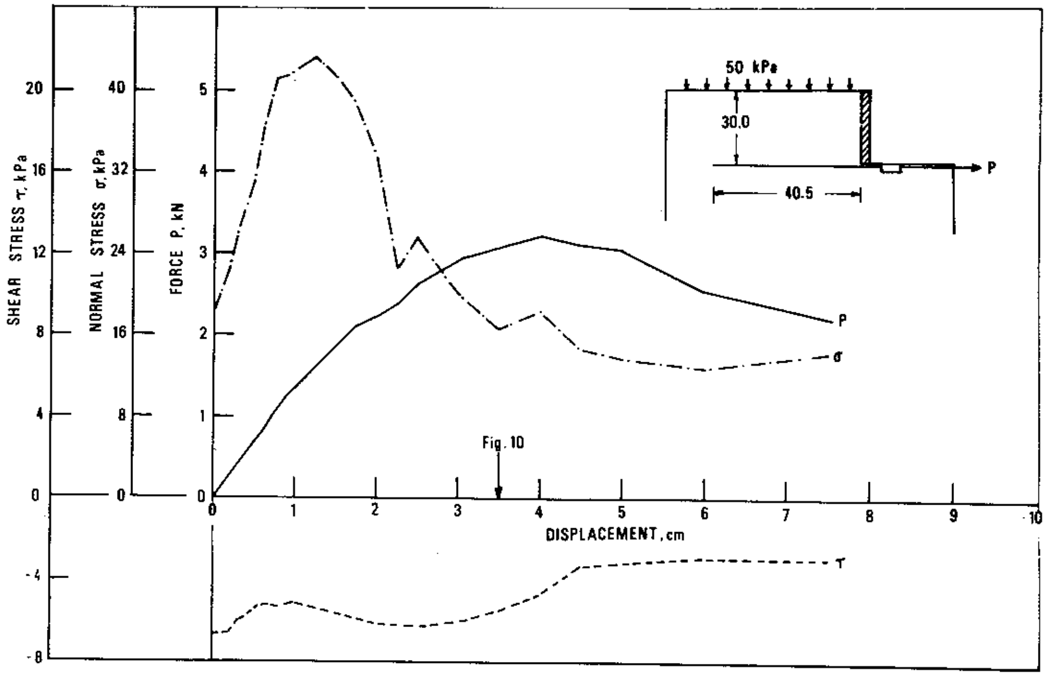


Fig. 9 Relationship between force, shear and normal stress for a test with dense sand at a surcharge of 50 kPa

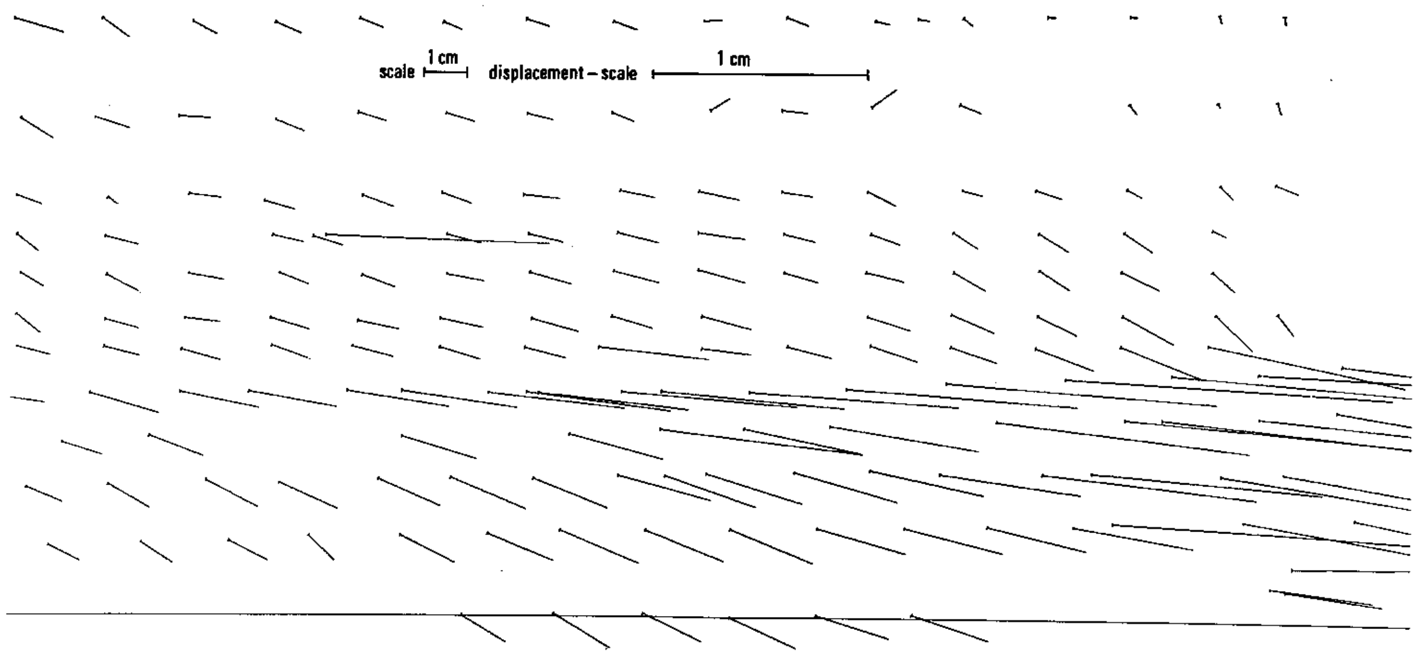


Fig. 10 Displacement vectors of a pullout test with dense sand at a surcharge of 50 kPa at a displacement of 35 mm of the fabric

vertically upwards and the displacements were small. At some distance from the wall the displacements were both horizontally and vertically. As the deformations at low displacements were primarily vertically upwards the horizontal deformations occurred at large displacements of the fabric.

In Figs 9 and 10 the results of a test with dense sand at a surcharge of 50 kPa are shown. It can be seen from Fig. 9 that the peak force was reached at relatively large displacements of the fabric, at about 40 mm. or 10% deformation. As the deformation of the fabric decreased gradually with increasing distance from the wall, the failure strain has probably been reached in the fabric near the wall. The peak normal stress occurred at a displacement of about 10 mm. A large downward directed shear stress was measured at the start of the test due to the relative high surcharge. Even at failure the direction of the shear stress was downwards. The friction angle calculated from the measured values is 26^{o}, which a reasonable value for this test where failure occurred progressively and where the normal stress was relatively high.

In Fig. 10 the displacement vectors after a displacement of the fabric of 35 mm are shown. The movements of the sand were horizontally and downwards due to the high surcharge. Large deformation occurred in that case also below the reinforcement.

CONCLUSIONS

The following conclusions can be drawn from this investigation:

- The friction angle between the fabric and the sand is about 10% lower than the angle of internal friction as determined by direct shear tests.
- The friction angle between sand and fabric calculated from the results of the pullout tests depends to a large extent on the deformation of the fabric, the relative density of the sand and the surcharge. The calculated friction angle varied between wide limits.
- The deformation at which the maximum frictional resistance was mobilized depends on the relative density of the sand and on the surcharge. When the sand was loose the peak values were larger than for the case with dense sand.
- The pullout tests indicate that the entire mass of sand above the reinforcement is affected by the reinforcement during pullout. Below the reinforcement the zone of influence depends on the relative density and on the surcharge.
- The shear and normal stress increased with increasing force. At the start of a test the normal stress against the wall corresponded to the earth pressure at rest. The direction of the shear stress was downwards and changed into an upwards direction during loading. At high surcharges the shear stress was always downwards.

ACKNOWLEDGEMENT

This investigation has financially been supported by the Swedish Council for Building Research, AB Fodervävnader, Boras, Sweden, and by the Royal Institute of Technology, Stockholm. The tests have been carried out at the University of Agriculture, Geotechnical Department under the supervision of Mr. M. Fuchs The computer program has been written by Mr. G. Petschl. The fruitful discussions with Mr. O. Wager are greatly appreciated.

REFERENCES

DAVIDSON, S. and EKROTH, N., 1975, Försök med vävförankrad stödmur, Diploma thesis, Dept. Soil a. Rock Mechs., Royal Inst. of Techn., Stockholm, 43 p.

HOLTZ, R. D., 1973, Laboratory studies of reinforced earth using a woven plastic material, Report (order No. 20505), Swedish Geotechn. Inst., 58 p.

HOLTZ, R. D. and MASSARSCH, K. R., 1976, Improvement of the stability of an embankment by piling and reinforced earth, 6th Europ. Conf. Soil Mechs a. Found. Engng., Vienna, Vol. III/1 p. 473-478.

LINDSKOG, G. and ERIKSSON, A., 1974, Rapport angaende fältförsök med polyesterväv som jordarmering, Report (order No. 50436), Swedish Geotechnical Institute, 32 p.

SCHWAB, E. F., BROMS, B. B. and FUNEGARD, E., 1976, Comparison between calculated and measured settlements beneath a test fill on soft soil, Väg- och vattenbyggaren, Stockholm, No. 8-9, p. 58-61.