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The influences of non-woven fabric inclusions on the stress strain behaviour of a soil mass

Influences des inclusions de matériaux non-tissés sur le comportement d'une masse de sol au point de vue contrainte - déformation

RÉSUMÉ Avec des essais de deformations en plan sur une cellule unitaire et un modèle de semelle, la fonction du renforcement par des materiaux extensibles non tissés dan des systemes de sols pulvérulents, a été étudiée. On montre que, généralement, ces matériaux renforcent le sable quelque peu, mais le plus important, augmentent les deformations jusqu'a' la pointe de resistance et diminuent la perte de resistance apres cette pointe. De même, il est demontré que l'orientation relative de ces materiaux aux deformations principales majeures est critique.

INTRODUCTION

The reinforcement function of fabrics has previously been suggested by Leflaive and Puig (1974), McGown and Ozelton (1973) and others, but little quantitative evidence has been produced to verify that this does operate, particularly with non-woven fabrics. The reinforcement of granular soils with metal strips, rods and meshes has, however, been widely investigated and adopted following the suggestions of Vidal (1969). With metals, the soil reinforcement function has been quantified but the mechanism operating has still to be fully identified. In fact, the placement of either fabrics or metals in soil systems, indeed any materials with different properties from those of the soil media itself, will affect the behaviour of the systems under applied or relieved stress conditions. In many cases, such materials when placed in soils may improve or reduce certain or all of the soil properties. In this respect, the peak strength of the material is not necessarily the determining factor as to whether or not a soil system is improved, often other material properties contribute to this, including its surface shape and texture, flexural stiffness, energy absorption capacity and extensibility, as well as the relative orientation of the insert to the principle strain directions within the system. Therefore materials when placed in soils should not be referred to simply as reinforcements, rather they should be termed "INCLUSIONS" for their influence may not always be one of strengthening.

At Strathclyde University a widely based study of the influence of various types of inclusions in soil systems is being carried out with particular consideration being given to the behaviour of soil systems incorporating fabrics and in particular ICI Fibres melt-bonded TERRAM membranes. These investigations have considered firstly, the stress-strain behaviour of a unit cell of sand when tested under plane strain conditions, with and without a fabric membrane inclusion; secondly, the plane strain load-deformation behaviour of a model footing resting on desne and loose sand and desne sand over loose sand or soft compressible rubber, chosen to replicate clay. Further and larger scale tests on embankments, road pavement structures and retaining walls are also underway, but in this paper only the first two sets of investigations will be referred to in order to illustrate the fundamental principles of the influence of non-woven fabric inclusions on the behaviour of soil masses.

MATERIALS USED

Sands

Leighton Buzzard sand having a particle size range from 0.4 to 1.0 mm and a uniformity coefficient of 1.13 was used in all the various soil systems tested. The maximum and minimum porosities of the sand are 45 and 34.5 per cent respectively when measured in accordance with the recommendations of Kolbuszewski (1948). In some of the plane strain unit cell tests, River Welland fine sand was used. It has a particle size range from 0.006 to 0.175 mm with a uniformity coefficient of 1.53. The maximum and minimum porosities of this fine sand were 51.5 and 38.3 per cent respectively.

Rubber

In some of the model tests on footings, rubber was used in the lower part of the tank to simulate a clay subgrade layer. The rubber had a compressive modulus of 46.5 kN/m^2.

Inclusions

The fabric membranes used were all of non-woven melt bonded construction and composed of 33 per cent nylon and 67 per cent polypropylene in the form of 50 per cent polypropylene homofilaments and 50 per cent polypropylene with nylon sheath hetro-filaments. Three fabric qualities were used in the tests with unit weights of 70, 140 and 280 g/m^2, herein after referred to as T70, T140 and T280 respectively. Some of the measured mechanical properties of the fabrics are given in Table 1.

TABLE 1 - MEASURED MECHANICAL PROPERTIES OF THE FABRIC INCLUSIONS

PROPERTY	FABRIC USED		
	T70	T140	T280
Unit Weight	70 g/m^2	140 g/m^2	280 g/m^2
Thickness	0.35 mm	0.55 mm	1.10 mm
Tensile Strength in Plane Strain (Sissons 1977)	2500 N/m	4800 N/m	9200 N/m
Tensile Extension to break in Plane Strain	110%	105%	100%
Grab Tensile Strength (A.S.T.M-D.1682)	290 N	570 N	1130 N
Grab Tensile Extension to Break	140%	120%	150%
Adherance between fabric and sand	ALWAYS GREATER THAN 90% of SAND		

APPARATUS

Unit Cell

Either internal vacuum pressure or external hydraulic pressure was applied as σ_3 a confining pressure to this plane strain apparatus in which a sample 152 x 102 x 102 mm in size was sealed by O-rings onto 152 mm dia. discs attached to the rectangular top and bottom platens. Porous stones were fitted into centred grooves in each platen and connected to external manometers. Two 152 x 127 x 12 mm rigid stainless steel end platens were bolted across the 102 x 102 mm end faces using four 12 mm dia. steel tension rods which thus imposed plane strain conditions ($\varepsilon_2 = 0$). A 5 mm thick glass insert was fitted into each side platen of sufficient dimensions to enable photographs to be taken of the entire sample cross section at different stages of the test and using a stereo viewing technique this later enabled a study of the internal displacement fields to be made.

The samples were deformed by compressing vertically using 5 tonne compression machine at a rate of 0.1 mm/min thus σ_1 was applied by the rigid top and bottom platens, σ_3 was applied by the internal vacuum or external applied pressure and σ_2 was intermediate and developed above σ_3 by using the restriction of the side platens. All platens were lubricated with silicone grease to reduce boundary friction effects. The intermediate principal stress σ_2 was not measured in these tests.

Plane Strain Footing Model

The apparatus consists of a very strong narrow box with internal dimensions of 610 x 260 x 76 mm. Both ends and the base are made of thick hardwood and the front and back are composed of 10 mm glass platens. The glass is again used to permit photography. The whole box is surrounded by a steel reinforcing frame to give further rigidity to the apparatus and the glass plates are supported on their outer faces by perspex packing strips onto the steel frame to reduce to the absolute minimum the lateral movements of the tank.

Strain controlled loading systems either manual or automatic are used and applied at a rate of penetration of the footing of 7.6 mm/min through a proving ring bolted directly onto a smooth steel footing 80 x 76 mm. The deformation of the footing are measured by a dial gauge mounted directly onto the footing and measuring onto the top of the glass.
To reduce side friction between glass and the sand in the model to an absolute minimum latex membranes covered with silicone grease on one side were applied in 120 x 200 mm pieces to cover the entire glass surface.

EXPERIMENTAL WORK

Tests in the Unit Cell

In this series of plane strain tests, the behaviour of sand alone and of sand with the inclusion of a single layer of either T70, T140 or T280 fabric was evaluated. Initially the fabric membranes were placed horizontally at mid-height in the specimens but subsequently the membranes were inclined at various angles with respect to the horizontal, always passing through the centroid of the specimen cross section. The minor principal stresses applied varied from 35 to 207 kN/m^2 and the full range of porosities for each of the sands was investigated. The data so obtained from the test specimens permitted quantification of the influences of horizontal fabric inclusions on the peak shear strengths, the axial strains to this peak and the post peak behaviour. Also the influence of the relative orientation of the membrane could be identified from those tests wherein the inclusions were inclined.

Figure 1 shows the relationship between the maximum angle of friction measured for sand alone and fabric included sand related to the placement porosity of the sand for tests using externally applied pressures of 207 kN/m^2 on River Welland fine sand. Similar data were obtained for other pressures in the range tested and for vacuum pressures with this and Leighton Buzzard sand. Essentially, however, it demonstrates that the inclusions may possibly weaken very dense sand but as the sand becomes looser the improvements derived from the fabric inclusions are much more positive and increase with increasing placement.

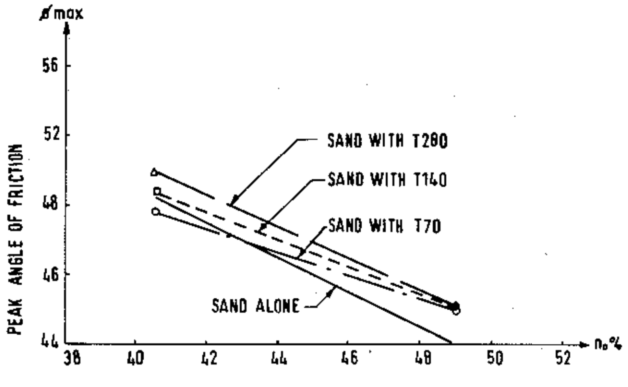

Fig. 1. The relationship between placement porosity and peak angle of friction for River Welland sand tested at 207 kN/m^2. (Al-Hasani 1977)

Figure 2 presents the axial strain to the peak stresses plotted in Figure 1 and indicates quite clearly the significantly increased peak axial strains that are exhibited by the fabric included sand. Once again this result was found for the other test conditions and the other sand.

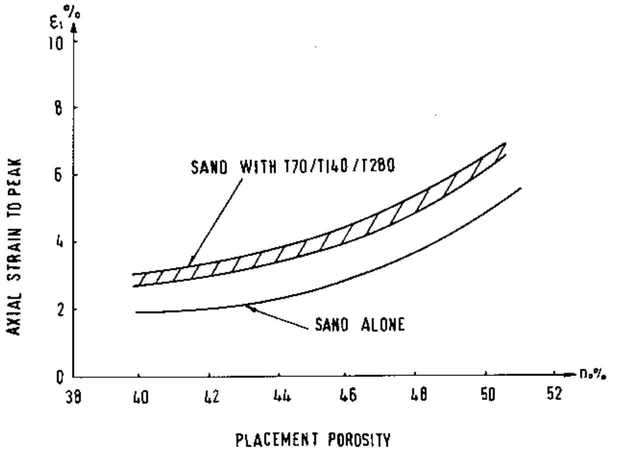

Figure 2. Axial strain to peak related to placement porosity for River Welland sand tested at 70 kN/m^2. (Al-Hasani, 1977)

The descent of the stress-strain curve from the peak to a residual or constant volume value, as the axial strain increases, may be expressed in terms of a Brittleness Factor, (Bishop,1967). In this investigation the Brittleness Factor is taken as the ratio of the peak less the constant volume to the peak deviator stress, expressed as a percentage. In Fig. 3 this is plotted against the placement porosity and the considerable reduction in the Brittleness Factor for the fabric included system, particularly at lower placement porosities, is entirely evident.

For higher placement porosities the sand alone was of course not itself exhibiting a significant peak and so the improvement due to the fabric inclusions was much less.

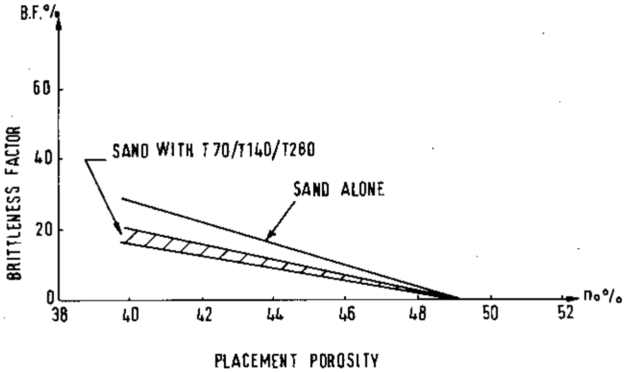

Fig. 3. Brittleness Factor related to placement porosity for River Welland sand tested at 70 kN/m^2. (Al-Hasani 1977)

Thus from this series of tests there emerges a pattern, in so far as the horizontal fabric inclusions were found to improve the peak strength of the sand somewhat, particularly for higher initial placement porosities of the sand, sub more significantly they increased the peak axial strains and reduce the brittleness of the unit cell tested.

For the same system but with the fabrics oriented with respect to the horizontal at various angles, the pattern of fabric influences on the sand behaviour varied markedly. Peak strengths, strains and brittleness factors were all modified and most significantly there emerged a definate anisotropy of these properties. Fig. 4 shows a plot of the measured peak strength against the inclination of the fabric layer. It should be noted that the minimum values shown are less than for sand alone indicating again that the fabrics may weaken the sand in certain specific circumstances.

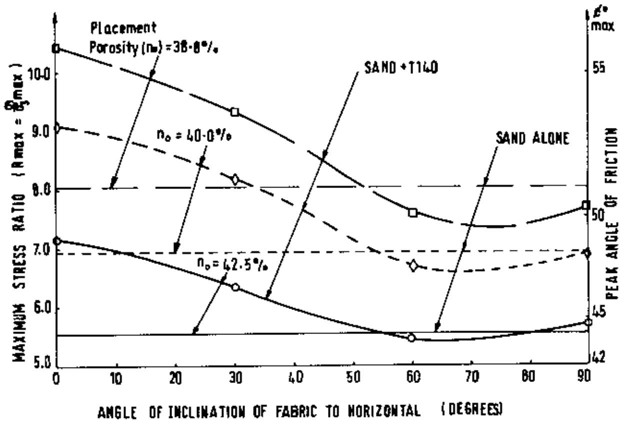

Fig. 4. The anisotropy of Leighton Buzzard sand containing T140 fabric and tested at 70 kN/m^2. (Al-Hasani, 1977).

Tests with the Model Footing

Three groups of tests were conducted in this apparatus. The first group was with a single inclusion of either T70, T140 or T280 at various depths within a single layer of dense or loose sand. The second group was with two separate inclusions of the fabric within either a layer of dense or loose sand and the third group involved single inclusions of the fabrics placed at the interface of dense sand over either loose sand or rubber with the depth of dense sand varied between tests.

In presenting the results and assessing the incluence of inclusions, the following parameters have been used:

a) Depth Ratio $(d/_B)$ = $\dfrac{\text{depth of inclusion}}{\text{width of footing}}$

b) Spacing Ratio $(S/_B)$ = $\dfrac{\text{Spacing of inclusions}}{\text{width of footing}}$

c) Settlement Ratio $(\Delta/_B)$ = $\dfrac{\text{Settlement of footing}}{\text{Width of footing}}$

d) Improvement Factor (at any settlement ratio) (I_f)

$$= \frac{\text{Vertical footing stress with inclusions}}{\text{Vertical footing stress without inclusions.}}$$

From the tests conducted on loose Leighton Buzzard sand with and without the inclusion of a single layer of T140 the relative load deformation characteristics of the footing resting on these systems were obtained, Fig. 5(a). The greatly beneficial effect of including the fabric is obvious but also apparent is the fact that this effect influenced by the depth at which the fabric membrane is placed. Figure 5(b) demonstrates this, showing the Depth Ratios against the Improvement Factors calculated from the data for various settlement. This also serves to demonstrate that the beneficial effects of the fabric are dependent on the degree of settlement of the footing much greater benefit accruing from the larger settelements.

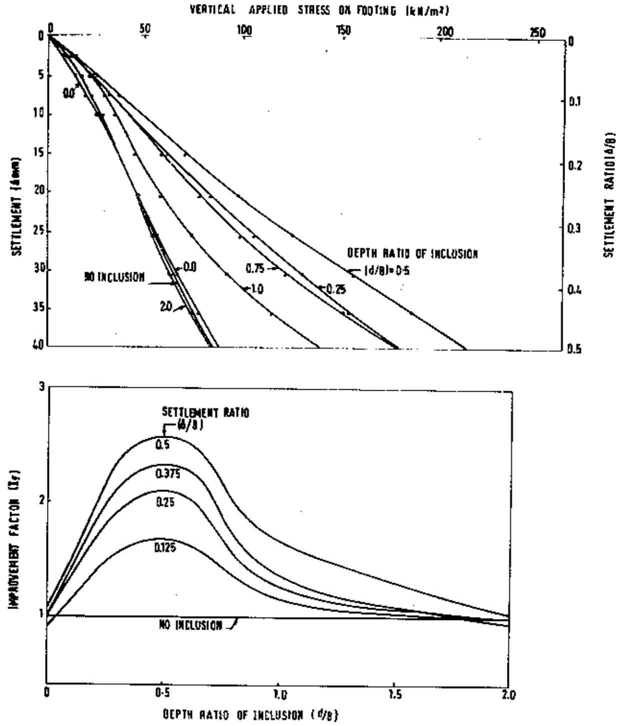

Fig. 5. The applied stress and settlement of the model footing with fabric at different depth related to the sand alone condition. (Alkirwi, 1976).

From the tests on the other Fabrics, T70, and T280 an entirely similar pattern emerged wherein the maximum Improvement Factors were obtained at Depth Ratios of between 0.4 and 0.6 for all Settlement Ratios with the greatest values obtained at the larger settelements. The quality of the fabric used as the inclusion did have an effect on the values measured but this was subordinate to the influence of the Depth Ratio as is seen in Table 2. Also obtained to date are the data from similar tests carried out with dense Leighton Buzzard Sand. The pattern of the dependency of the measured Improvement Factors on the Depth Ratio and Settlement Ratio is as with the loose sand but the measured values are all significantly reduced. Indeed in some cases where a fabric membrane was placed at a Depth Ratio of between 0.8 and 2.0 in the dense sand slight weakening of the system was found.

TABLE 2. MEASURED IMPROVEMENT FACTORS FOR SINGLE FABRIC INCLUSIONS IN LEIGHTON BUZZARD SAND.

FABRIC QUALITY	DEPTH RATIO	SETTLE-MENT RATIO	IMPROVEMENT FACTOR FOR LOOSE SAND
T70	0.5	0.125 0.25 0.50	1.49 1.80 2.25
	1.0	0.125 0.25 0.50	1.25 1.28 1.65
T140	0.5	0.125 0.25 0.50	1.65 2.05 2.55
	1.0	0.125 0.25 0.50	1.15 1.25 1.65
T280	0.5	0.125 0.25 0.50	1.85 2.25 2.80
	1.0	0.125 0.25 0.50	1.55 1.60 2.00

Using two separate layers of fabric within loose or dense sand also provided consistent sets of data with much less improvement in the dense sand than in the loose sand. The test programme in this group of tests was based on placing one layer of the membrane at a specific depth and varying for each test the depth of the other layer from the surface to a depth of twice the other width (d/B = 2.0). By repeating this for various depth of the fixed layer over the same depth range, the full variety of depth combination was explored. The load-deformation data from each test was then analysed as before and the benefit of the fabric included sand condition over that without fabric was calculated in terms of the Improvement Factor as before. For fixed Depth Ratios of the first layer at variable Depth Ratios of the second layer a number of plots of Improvement Factor against Depth Ratio of the second layer were constructed. Figure 6 shows the data for T140 fabrics in loose Leighton Buzzard Sand. As with the single layer the Settlement Ratio had a significant effect on measured values but most importantly was the Depth and Spacing Ratios of the two layers. For maximum improvement at any Settlement Ratio, the two layers should lie within the Depth Ratios of 0.25 and 1.0 and with an optimum Spacing Ratio of 0.5. Similar findings emerged for the other two fabrics tested and with dense sand. Also the Improvement Factors measured were almost all greater than the simple aggregation of the previously measured Improvement Factors for single inclusion systems, which infers an interaction of the influence of the two layers of inclusions.

Tests on more complex soil systems, such as dense over loose Leighton Buzzard sand and the same dense sand over rubber, the latter used to replicate the elastic response of medium to soft clay but with only a single layer of fabric at the interface between the soil layers, served to illustrate further the complexity of the influence of fabric inclusions in soils. Taking the base conditions in these tests to be the load deformation response of the loose sand or the rubber, the Improvement Factors due to the laying of a dense sand layer over these was established as shown for a particular Settlement Ratio in Figs. 7 and 8. Thereafter the improvement from the same dense sand layers but with a layer of either T70 T140 or T280 fabric at the soils interface was measured and is again shown in Figs. 7 and 8.

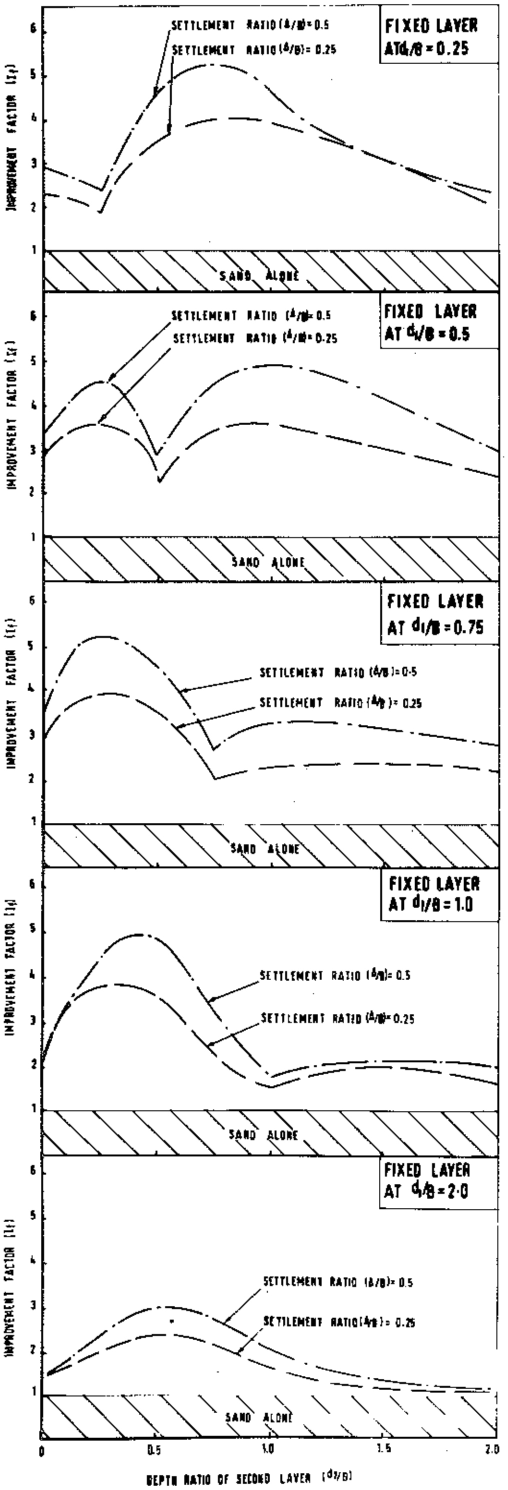

Fig. 6. The Influence of Two Separate Layers in Loose Sand (ALKIRWI, 1976)

As with previous tests in the apparatus, the Settlement Ratio influenced the measured values but not the pattern of them. The over-riding factors controlling the measured improvement were the nature of the sub-soil and possibly the friction or the adhesion between the sub-soil and the fabric. In these tests the top of the rubber layers was lubricated with silicone grease to reduce the friction/adhesion to almost zero and this appeared to have a great influence.

The deformation mechanisms observed operating during application of the surface loading, varied between those tests with loose sand sub-soils and those with rubber. Essentially the former exhibited deformations consistent with local shear failure whereas the latter was a punching shearing failure. However, in both these cases and in the previous single soil layer system tested the inclusion of fabric was noted to alter the deformation patterns and principally to increase the volume of sand mobilised during the surface straining. This redistribution of material strains would appear to be the fundamental mechanism which permits the development of additional surface bearing capacity.

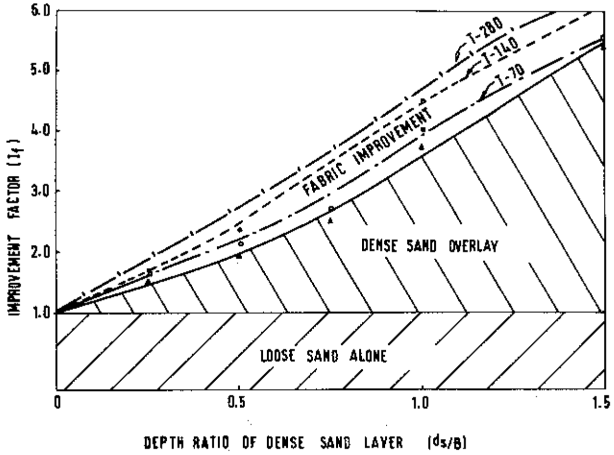

Fig.7. Improvement for Dense Sand and Fabrics over Loose Sand. (ALVAREZ, 1976)

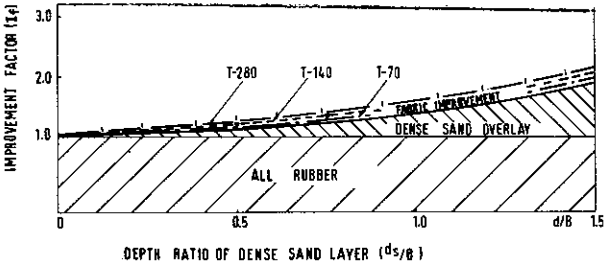

Fig.8. Improvement for Dense Sand and Fabrics over Rubber (ALVAREZ, 1976)

CONCLUSIONS

From the unit cell tests on both sands, using a wide range of applied pressures, it has been shown that where the non-woven fabrics were placed along the major principal plane they generally increased the strength of the system, although where the sands were placed at their minimum porosity, a slight weakening was observed. The peak strength of the fabrics appeared to have some influence, but system strengthening was not directly proportional to it. More important than the strengthening was the fact that the strains to the peak strength were increased and the brittleness of the system post-peak was markedly reduced. Such behaviour is, in fact, in stark contrast to the influences of metals and fabrics of low extensibility which inhibit strains, (Al-Hasani 1977). Thus the fabric included systems tested are considered to have particular characteristics and have therefore been termed "Ply-soil" systems to indicate their capability of accepting deformations without disruption above those which the soil media alone could accept. From the cell tests wherein the fabrics were inclined to the major principal plane, i.e. to the horizontal, it was found that a definate anisotropic pattern of behaviour could be established. At certain inclinations, essentially where the fabrics were inclined at an angle close to that of the shear failure plane, weakening of the system at all porosities of the sands was observed. This was a results of the soil-fabric friction being a little less than soil-soil friction and high-lights the importance of the surface properties of the inclusions.

The model footing tests on dense or loose sand, in general bore out the findings of the unit cell tests, particularly when the load-deformation behaviour of the footing was considered in association with the internal deformation patterns observed through the glass sides of the model. In almost all cases, as with the unit cell, the inclusion of fabric increased the strength of the system. Only for very specific conditions with dense sand, was weakening observed. Indeed the most critical factor tested appeared to be the positioning of the fabric membrane in the system, the Depth Ratio. When the internal major principal strain directions within the sand without inclusions, are considered it is evident that the best performance of fabric included systems occurs when the fabric membrane lies across those strain directions and least improvement or weakening occurs when the fabric lies along them. Thus the Depth Ratio is essentially comparable to the fabric inclination in the unit cell.

In those tests wherein dense sand overlaid loose sand or rubber, the critical influence of the Depth Ratio was borne out. In addition the differences in Improvement Factors due to the inclusions at the interface of the dense sand with the loose sand and the rubber sub-soils were shown to be in keeping with the relative improvements due to the dense sand overlays alone. The deformation mechanisms without fabric were different, therefore the influences of fabric inclusions were different. The very low friction/adhesion at the fabric-rubber interface was also thought to be an important factor in these tests. Lastly, the tests with double fabric inclusions showed that the deformation modifications induced by an individual layer might interact with those induced by another individual to produce a greatly enhanced overall improvement, but as might be expected there was a critical positioning for the two layers in the system. Consideration again of this positioning leads to the same conclusions as before with respect to the relative orientation of the inclusion to the internal principal strains.

Thus the inclusion of highly extensible non-woven fabrics in various essentially granular soil systems have been shown to somewhat strengthen but more particularly alter the deformation behaviour of the system and possibly make them subject to less disruption at higher strains. Thus best advantage from the use of extensible non woven fabrics would appear to be in soil sytems which can accept or will inevitably be subject to large strains, such as roads or embankments on very soft clays or peats. It should be emphasised that in some cases further and possibly more important benefits may be realised from the separation and filtration functions of these fabrics.

Identification of all the fabric properties contributing to the strengthening of soil systems has yet to be achieved but from these tests surface friction and possibly the entire stress-strain behaviour of the fabric inclusion, not just peak strength, appears to be important. Above all else the importance of the location and orientation of the fabric in soil systems has been identified.

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