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Internal/External Fabric Reinforcement of Sand

Renforcement interne et externe de sable avec les textiles

The stress-deformation behavior of internally/externally reinforced sand masses was investigated experimentally. Internal reinforcement was provided by insertion of fabric layers within the sand; external, by simultaneous encapsulation in a woven fabric or geotextile.

The short term, stress-deformation behavior of sand reinforced in this manner was controlled by the respective modulis and other mechanical properties of the geotextiles and their method of placement. Internally/externally reinforced granular masses, e.g., reinforced "earth pillars" and "trench foundations," merit further investigation as load bearing structures in soft, cohesive soil.

On a expérimenté l'action de contrainte-déformation du sable renforcé à l'intérieur et à l'extérieur. Le renforcement à l'intérieur s'est fait en insérant des couches de tissés dans le sable même. En même temps, à l'extérieur, on a entouré le sable d'un tissé ou d'un géotextile.
A court terme, on a contrôlé l'action de contrainte-déformation du sable ainsi renforcé a l'aide des modules respectifs, des autres caractéristiques mécaniques des géotextiles, et de la méthode avec laquelle ils ont eté installés.
Ces masses granulaires renforcés à l'interieur et à l'extérieur, comme les "piliers de terre" renforcés et les "fondations de tranchée", méritent d'être étudiées davantage car en tant que structures, elles peuvent supporter du poids dans des sols mous et argileux.

INTRODUCTION

This paper describes the results of preliminary research on the stress-deformation behavior of sands which have been internally/externally reinforced with synthetic fabrics or geotextiles. External reinforcement was provided by encapsulating a sand in a woven fabric; internal by inserting layers of either woven or non-woven fabric within the sand. Both types of reinforcement are used conjunctively - a key concept. The ultimate purpose of this research is to determine the feasibility of using internally/externally reinforced granular masses as load bearing structures.

Most fabric reinforcement systems todate consist of interlayered fabric in a granular fill. Fabrics have also been used occassionally for encapsulation and containment (5). In the latter case the fabric acts as both a separation and quasi reinforcement medium. Examples include membrane encapsulated soil for road bases (2, 11) and containment of light weight fill dikes constructed on weak, highly compressible ground (9). The question arises, why not combine both internal reinforcement (intercalated fabric layers) with external reinforcement (fabric encapsulation) in a purposeful and synergystic fashion?

Potential applications of internally/externally reinforced granular masses included above grade structures - embankments and walls; and below grade foundations - "earth pillars" and "trench foundations" (Fig. 1). All these applications entail the use of both encapsulating and intercallated fabrics or geotextiles. Granular fill is shown in these examples; other structural fill materials could eventually be investigated such as lightweight fly ash and saw dust.

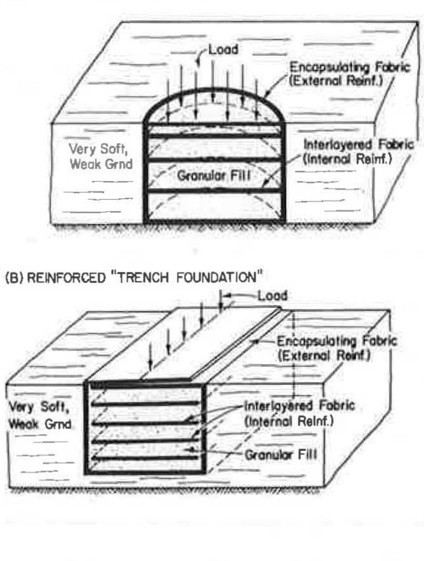

Fig. 1 Internally/externally, fabric reinforced below grade foundations.

The reinforced "earth pillar" concept illustrated in Fig. 1 is an alternative to the stone column - vibro replacement method (3) which has been used to strengthen cohesive soils. In the latter method a combined system of compacted, granular columns in a matrix of native, cohesive soil supports a vertical load which is transmitted through a rigid spread footing. After distribution through a granular blanket, the load is transferred and concentrated initially on the compacted granular cylinders or "stone columns." The cylinders tend to dilate under this increased load and exert a lateral stress on the native, surrounding soil; but this lateral stress (and dilation) are resisted by passive earth pressure. This interaction is repeated until a state of equilibrium is reached. The rigidity and load carrying capacity of the columns depends largely upon the amount of lateral restraint or confining stress that can be mobilized in the surrounding clay.

In the reinforced "earth pillar" concept (Fig. 1) lateral restraint comes not only from the surrounding soil but also from the encapsulating and intercallated fabric. The increase in confining stress induced by the fabric may equal or exceed the restraint provided by earth pressure from the surrounding soft clay.

The reinforced "trench foundation" works on the same principal but the geometry of the system and method of installation are different. This system avoids the need for a vertical seam or joint on the encapsulating fabric. A "trench foundation" is in essence a trench drain, i.e., a trench which is dug in the ground, lined with a perveous fabric, and backfilled with washed stone. A trench drain is used to intercept groundwater; with some modifications it could also be used to support loads.

A key question in using internally, externally reinforced granular masses as load bearing structures is the amount of lateral confining stress that can be induced by the fabrics. Both the maximum amount and the rate at which the confining stress are mobilized will govern the strength and stress deformation behavior of the reinforced, granular material. Another critical consideration is the potential influence of creep or stress relaxation in the fabrics particularly at high working stresses.

1. MECHANICS OF REINFORCEMENT

1.1 Extensible vs. Non-Extensible Reinforcements

Important differences can be demonstrated (6, 7) in the stress-deformation response of sands reinforced with relatively low modulus synthetic fabrics or natural fibers (PLYSOILS) as opposed to high modulus metallic reinforcement (REINFORCED EARTH®). Tensile modulus and permissable elongations in the reinforcement are important considerations. High modulus steel reinforcement with good frictional contact will greatly inhibit internal soil tensile strains, limit boundary deformations, and increase strength provided the reinforcement does not rupture.

In contrast, low modulus fabrics will not likely limit boundary deformations nor increase strength to the same extent. They have the advantage, however, of being able to undergo high elongation and to continue mobilizing tensile resistance at relatively high strains. Because of their lower modulus, higher elongation at break, and generally high frictional properties (12) they are far less likely to either pull out or break; instead they simply yield or stretch with only limited, local slippage occurring where tangential stress exceeds skin friction at the inclusion-sand interface.

In the case of internally/externally reinforced sands the modulus ratio of the two types of reinforcement is also important. The overall stress-deformation behavior of the reinforced composite will depend upon the rupture strength, tensile modulus, and elongation properties of both internal and external reinforcements. The issue is to identify optimal combinations of internal/external reinforcement properties which lead to desirable stress-deformation behavior, e.g., high peak strength, minimal loss of strength at large strain, and avoidance of overstress in either reinforcing system.

1.2 Equivalent Confining Stress Concept

Different concepts have been advanced to explain the mechanics of earth reinforcement (8). Laboratory studies have been conducted in order to define the basic mechanism. Schlosser and Long (10), Yang (13), and McGown et al. (7) each reported the results of triaxial compression tests on cylindrical samples of dry sand containing thin, horizontal layers of tensile reinforcing material.

The results of these triaxial tests on reinforced sand have been interpreted in two different yet related ways. Yang (13) hypothesized that tensile restraint in the reinforcement induced an equivalent confining stress increase $\Delta\sigma_3$. Thus, from the Mohr-Coulomb formulation for the strength of a cohesionless material, it follows that

$$\sigma_{1_f} = (\sigma_3 + \Delta\sigma_3)N_\phi \qquad (1)$$

where: σ_{1_f} = major principal stress of failure; σ_3 = applied confining pressure on the test specimen; $N_\phi = \tan^2(45 + \phi/2)$; ϕ = friction angle of unreinforced sand.

Schlosser and Long (10) proposed that the reinforcements induced an anisotropic or pseudo cohesion C_R which was a function of their spacing and tensile strength. The strength of the reinforced composite accordingly is given by

$$\sigma_{1_f} = \sigma_3 N_\phi + 2\,C_R\sqrt{N_\phi} \qquad (2)$$

The anisotropic or pseudo cohension (C_R) was computed from a force-equilibrium analysis of a reinforced composite. The following expressions can be derived:

$$\text{Horizontal Reinforcement:}\quad C_R = \frac{\alpha_f}{\Delta H}\frac{\sqrt{N_\phi}}{2} \qquad (3)$$

$$\text{Inclined Reinforcement:}\quad C_R = \frac{\alpha_f[N_\phi\cos^2\beta-\sin^2\beta]}{\Delta H\;2\sqrt{N_\phi}} \qquad (4)$$

where: α_f = force per unit width of reinforcement at failure, kN/m; ΔH = spacing between reinforcements, m; β = angle of inclination of reinforcement counterclockwise from the major principal plane, degrees.

Comparison of Equations (1) and (2) indicates a correspondence between $\Delta\sigma_3$ and C_R, viz.,

$$C_R = \frac{\Delta\sigma_3}{2}\sqrt{N_\phi} \qquad (5)$$

Comparison of Equations (3) and (5) in turn shows the following:

$$\Delta\sigma_3 = \frac{\alpha_f}{\Delta H} \qquad (6)$$

Thus, the unit tensile resistance in the reinforcement ($\alpha_f/\Delta H$) s directly equal to an equivalent confining stress increase ($\Delta\sigma_3$).

The relationships expressed in Equations 3 and 4 assume that failure occurs by breaking of the reinforcement rather than pullout or stretching. The likelihood of breaking a low modulus fabric reinforcement which behaves as an extensible inclusion is slim. Elongations to break in non-woven geotextiles are quite high - often exceeding 50%. In contrast vertical strains at peak stress in a triaxially loaded, dense sand are an order-of-magnitude less. Horizontal strains are even lower; the exact value depending upon the ratio of horizontal to vertical strain during a test. It is the horizontal (lateral) strain which governs the amount of mobilized tensile resistance in horizontal, layered inclusions. This tensile resistance can be computed to a first approximation as follows:

$$\alpha_{\varepsilon_H} = J_{sec_{\varepsilon_H}} \cdot \varepsilon_H = J_{sec_{\varepsilon_H}} \cdot \nu \varepsilon_V \qquad (7)$$

where: α_{ε_H} = force per unit width of fabric reinforcement corresponding to lateral strain in the sand, kN/m; ε_H = horizontal (lateral) strain in the sand; ε_V = vertical strain in the sand at peak stress; $J_{sec_{\varepsilon_H}}$ = secant modulus of fabric reinforcement between elongation O and ε_H, kN/m; ν = Poisson's ratio for sand.

This relation assumes that there is no slip at the sand-fabric interface and that Poissons ratio is a good measure of the horizontal to vertical strain in the sand at failure adjacent the reinforcement.

2. TEST RESULTS

2.1 Reinforcements

Commercially available geotextiles with a range of mechanical and rheological properties were selected for testing. Both woven and non-woven fabrics were included. Fine brass screen or strainer cloth (80 mesh size) was included as well in order to examine the influence of a relatively high modulus reinforcement.

The results presented herein are based on two woven fabrics (Geolon 200 and 400) and two non-woven fabrics (Typar 3401 and 3601) which are believed to be fairly representative of reinforcement geotextiles used in practice. Properties of these fabrics are summarized in Table 1. This information was compiled from data supplied by the manufacturer. The non-woven geotextile is a spun bonded, polypropylene sheet manufactured by E. I. Dupont Company; the woven fabric is made from polypropylene fibers and is manufactured by the Nicolon Corporation.

Table 1 - Geotextile Properties

Trade Name	Thickness (mm)	Grab Tensile (kN/m)	Millen Burst (kN/m^2)	Elongation to Break (%)	Secant Modulus @5% Elong (kN/m)
Typar 3401	0.38	23	1172	62	80
Typar 3601	0.48	39	1813	63	210
Geolon 200	0.46	35x35	2482	20x12	
Geolon 400	0.74	66x44	2896	30x18	180

2.2 Triaxial Tests

The triaxial tests were run on reinforced samples of dry, Muskegon dune sand in a dense condition. Properties of the sand are summarized in Table 2.

Table 2 - Sand Properties

Name	D_{50} (mm)	C_u	φ (degrees)	e_{max}	e_{min}
Muskegon sand	0.23	1.5	39.5	0.73	0.50

Reinforcements were placed in evenly spaced, horizontal layers. Reinforced sand specimens failed by bulging or lateral spreading between reinforcements (Fig. 2).

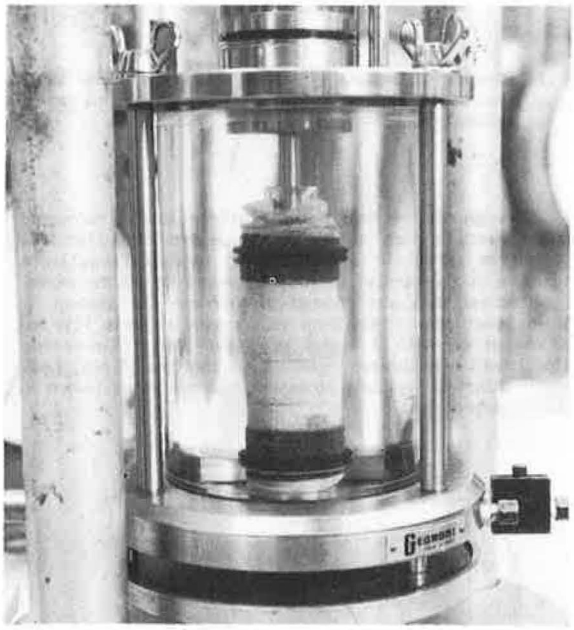

Fig. 2 Deformed shaped of internally reinforced sand tested in triaxial compression.

Typical results of triaxial tests are plotted in Fig. 3 for sand reinforced with increasing numbers of layers (N=1, 3, & 5) of the synthetic, non-woven fabric Typar 3601. Results of reinforcement tests with the brass strainer cloth (N=3) are shown for comparison as well. Strength increased with increasing concentration of reinforcement. The break in the curves corresponds to a critical confining stress; below this critical stress the reinforcements tended to slip or pullout as opposed to stretching. This behavior corroborates earlier triaxial test results reported by Yang (13) and Schlosser and Long (10). The critical confining stress was typically about 98 kPa (14 psi) for the synthetic fabrics tested and 214 kPa (31 psi) for the brass strainer cloth. Above this confining stress, failure envelopes all tended to parallel the envelope for the unreinforced sand. These results indicate that the friction angle of the sand was unaffected by the reinforcement.

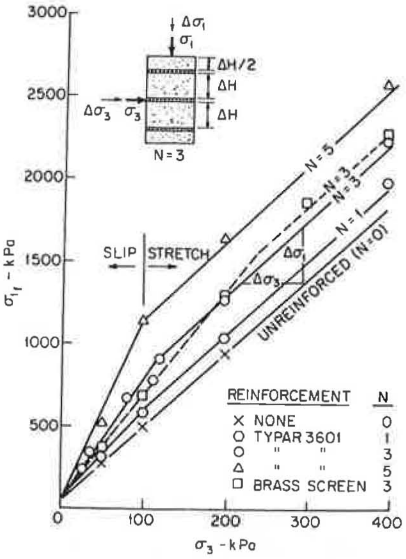

Fig. 3 Results of triaxial tests on Muskegon dune sand reinforced with different numbers of layers of fabric reinforcement.

Although reinforcement with synthetic fabrics increased ultimate strength, they tended to reduce overall stiffness of the sand as shown in Fig. 4. This tendency was more pronounced as the number of reinforcement layers increased. The reinforcements also tended to increase the amount of strain to reach peak stress from 4% for sand alone to 11% for sand reinforced with 5 layers of Typar 3401. Geotextile reinforcement also limited significantly the loss of post peak strength which is typically observed in dense sands tested in triaxial compression.

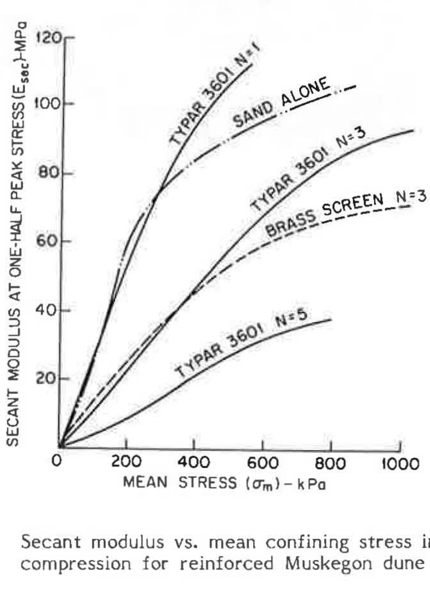

Fig. 4 Secant modulus vs. mean confining stress in triaxial compression for reinforced Muskegon dune sand.

The equivalency between confining stress increase ($\Delta\sigma_3$) and mobilized unit tensile strength in the reinforcement ($\alpha\varepsilon_H/\Delta H$) predicted by Equations 3 to 7 is compared in Fig. 5. The two variables are shown plotted vs. one another for a number of different test runs. The reinforcement induced confining stress was obtained directly from experimental data. The mobilized unit tensile strength in the reinforcements was computed according to Equation 7 using the stress-deformation relationship for the fabric (Table 1), spacing between reinforcements, and an assumed ratio of $\varepsilon_H/\varepsilon_V$ = 0.25. The latter is simply a typical value of Poissons ratio for a dense sand. A rough correspondence exists; a slightly lower strain ratio would improve results particularly for the Typar 3601 reinforcement which has a higher modulus, and which tends to restrict lateral strain more. An interesting consequence of this correspondence is that at failure or peak stress in the sand only a small fraction (≤10%) of the tensile strength of the fabric is apparently mobilized. This same result was observed earlier by Gray and Ohashi (4) during direct shear tests on dense sand reinforced by low modulus, natural fibers.

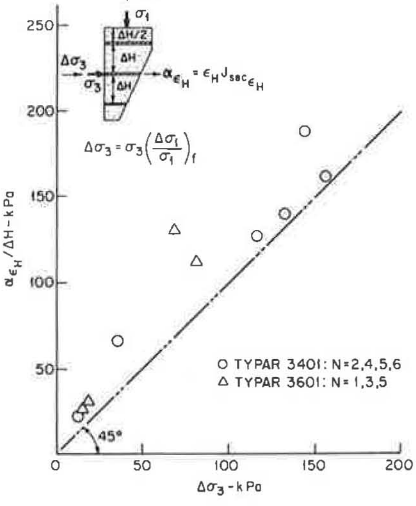

Fig. 5 Comparison between induced confining stress increase and mobilized unit tensile strength in the reinforcements.

Anisotrop ic reinforcement cohesion (C_R) was computed from experimental data using Equation 5. This cohesion is shown plotted vs. a reinforcement thickness/spacing parameter ($\Sigma T_g/\Delta H$) in Fig. 6. The number of layers of reinforcement are indicated adjacent each data point. This method of plotting makes it possible to examine and compare the influence of type of reinforcement, number of layers, reinforcement thickness and spacing. It also permits comparison with results of internal reinforcement cohesion computed from uniaxial compression tests on internally/externally reinforced sands and with theoretical predictions from finite element model studies.

2.3 Uniaxial Compression Tests

Quasi uniaxial compression tests were run on 127-mm high x 61-mm diameter specimens of dry Muskegon dune sand

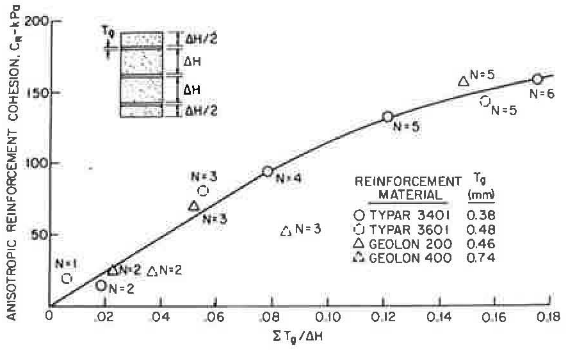

Fig. 6 Anisotropic reinforcement cohesion vs. thickness/ spacing parameter for Muskegon dune sand reinforced with woven and non-woven geotextiles.

encapsulated (externally reinforced) in a woven fabric (Geolon 400). Another series of tests were run on samples that were both encapsulated and internally reinforced with horizontal layers of different reinforcing fabrics (Typar 3401, 3601, and brass strainer cloth). These tests simulate loading of a reinforced "earth pillar" (Fig. 1). A typical deformation pattern in an internally/externally reinforced sand column near failure is shown in Fig. 7. Failure usually occurred as a result of localized bursting of the encapsulating fabric. When bursting occurred adjacent the seam this resulted in lower compressive strengths.

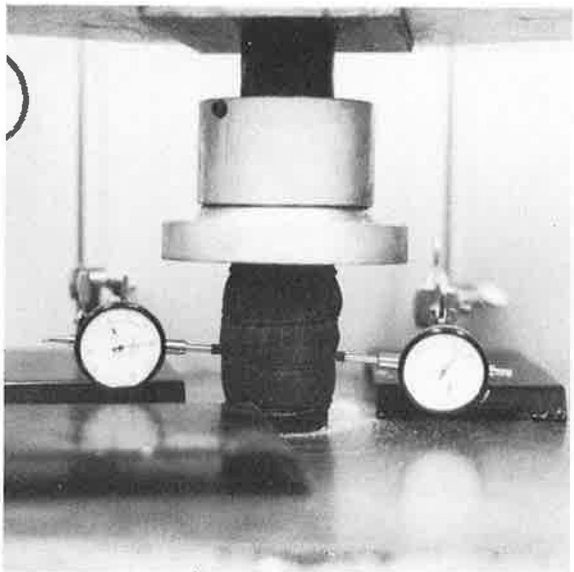

Fig. 7 Deformed shape of internally/externally reinforced sand tested in "uniaxial" compression.

The confining stress increase induced by encapsulation alone ($\Delta\sigma_3$) was calculated from Equations 3 with the external or applied confining stress (σ_3) set equal to zero. The major principal stress at failure (σ_{1f}) was equal to the uniaxial compressive strength (q) in this case. The induced confining stress (834 kN/m^2) was only equal to one fourth of the burst strength of the fabric (Table 2). The need to glue a vertical seam in the fabric may have contributed to premature failure and incomplete mobilization of fabric burst strength. Conversion to plain strain testing conditions which simulate loading of a reinforced "trench foundation" (Fig. 1) may eliminate this problem. In this case the seam (overlap) will be on top of the reinforced mass directly beneath a distributed load.

Apparent reinforcement cohesion (C_R) from encapsulation was calculated using Equation 5. Additional reinforcement cohesion from internal reinforcement was calculated using Equation 2. These results are summarized in Table 3.

Table 3 - Results of Uniaxial Compression Tests on Internally/Externally Reinforced Sands.

Reinforcement	N	q_1	q_2	$(\epsilon_v)_f$	Extl. C_R	Intl. C_R
Encapsulation Only (Geolon 400)	0	3827	-	0.26	896	-
+ Typar 3401	2	-	3978	0.25		35
" 3401	4	-	4482	0.27		153
" 3401	5	-	4744	0.22		214
+ Typar 3601	3	-	5392	0.25		365
" 3601	4	-	4454	0.22		146
" 3601	5	-	5033	0.26		282

N = no. of reinforcements; q = compressive strength (kPa); C_R = reinforcement cohesion (kPa); $(\epsilon_v)f$ = axial (vertical) strain at failure.

Internal reinforcement cohesion varied with the number of reinforcing layers and ranged from 35 to 365 kPa whereas the external reinforcement cohesion was 896 kPa. The internal reinforcement cohesion was the same order-of-magnitude as reinforcement cohesions claculated from results of triaxial tests (see Fig. 6).

The internal reinforcements did not greatly increase the ultimate compressive strength of the cylindrical sand specimens (see Table 3). Their main influence seemed to be on the stress-deformation response (Fig. 8). Internal reinforcements increased the stiffness of the sand by constraining lateral deformation and limiting overstress in the encapsulating fabric. This influence was particularly pronounced at high strains. Increasing the number of internal reinforcements increased stiffness. A much more linear stress-strain relationship was observed in these internally/externally reinforced composites almost up to failure — in spite of the fact that failure occurred at quite large strains (ϵ_v > 20%). This behavior is opposite that observed with internal reinforcements alone (Fig. 4). In the latter case an increase in layers of reinforcement (N > 1) resulted in a loss of rigidity. The former response suggests, therefore, a synergistic type of interaction between internal and external reinforcements in a sand.

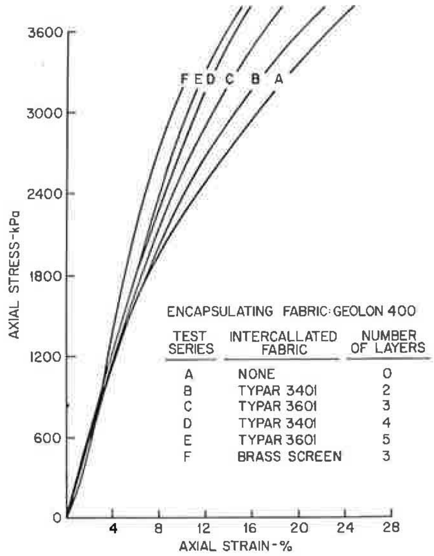

Fig. 8 Stress-deformation behavior of internally/externally, fabric reinforced Musekgon dune sand.

3. CONCLUSIONS

Preliminary test results indicate that conjunctive reinforcement of granular columns with both external (encapsulating) and internal (layered) geotextiles can both strengthen and stiffen the column significantly. Stress-deformation response of such a reinforced composite can be controlled to a large extent by selection and placement of fabrics with appropriate moduli and other properties.

Internally/externally reinforced granular masses show promise of being used as load bearing structural units in soft, cohesive soils. Reinforced "earth pillars" and "trench foundations" are possible alternatives in this regard to the vibro replacement - stone column system in such soils.

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