C.R. Coll. Int. Renforcement des Sols. Paris 1979.

TUMAY M.T. et ARMAN A.
Louisiana State University, U.S.A.

ANTONINI M.
Astra Fundaciones, Venezuela

Metal versus fiber fabric earth reinforcement in dry sands - A comparative statistical analysis

Sable sec armé par du métal ou du textile - Analyse statistique comparative

Des études expérimentales utilisant un modèle ont été developpées afin de comparer l'efficacité de l'interaction entre du sable et une armature faite de métal ou de tissu fibreux. Les parois de retention du modèle ont été construites a l'intérieur d'une boite modèle. Du sable a été deposé d'une manière pluviale à des densités relatives determinées d'avance par un depositéur stationnaire spécialement dessiné pour cet emploi. Des armatures ont été mises en place à des niveaux et concentrations requis pendant le dépot a l'intérieur des confins des exigences d'un arrangement statistique et expérimental.

Deux genres de tests ont été exécutes: Dans la première phase des tests de rétraction pour mesurer la réaction latérale sur la surface des parois de retention ont été conduits; ceux-ci consistaient en trois plaques d'aluminium instrumentées par des indicateurs de tension. Une analyse comparative et statistique a été faite des résultats obtenus. Dans la seconde phase, les armatures des parois de retention en terre armée des modèles ont été surtensionnés jusqu'au point de faillibilité en surchargeant le remplissage. Une comparaison des résultats, hauteur du remplissage au point de faillibilité contre la longueur du armature, a été analysée.

En se basant sur les résultats obtenus, il a été conclu que le tissu fibreux presente des avantages sur le métal renforcé utilisé pour la construction de structures en terre armée.

INTRODUCTION

The use of earthwork reinforcement in modern construction was initiated by Vidal (1969). When horizontal reinforcements are introduced into non-cohesive soil, the whole mass exhibits properties similar to cohesion. This cohesion is developed by the friction of the soil grains against the reinforcing members. The beneficial effect of the reinforcement element is to supplement the weak tensile strength in the main material.

In the United States, the basic concept of reinforced earth retaining walls has been verified by laboratory and full-scale field experimental models studied by Lee, et al. (1973, 1975) and Chang, et al. (1974, 1975). The problem of corrosion of the metal affecting the serviceable life of reinforced earth structures is of vital importance in reducing the cost of construction. A search of the literature shows that to date no one has reported on the use of non-woven fiber fabric, a highly non-corrosive material, as earthwork reinforcement.

The purpose of this work was to determine the effectiveness of two different type of reinforcement, metal and fiber fabric. Effectiveness describes the efficiency in mobilizing sand-reinforcement interaction. Two more factors, relative density of the sand and reinforcement concentration (i.e. length of reinforcement), which affect the performance of a reinforced earth structure also were studied. The following tests were executed:

Pull-Out Tests - Mobilization of soil-reinforcement interaction for lateral pressure on a rigid wall, consisting of three strain-gage instrumented plates, was studied under different testing conditions--two type of reinforcement, fiber fabric and aluminum; three reinforcement concentrations, C_r = horizontal reinforcement spacing/length of reinforcement; three relative densities of sand, D_r; two replications of each test. From these tests a comparative statistical analysis was made.

Reinforcement Overstress Tests - Models of reinforced retaining walls with varying reinforcement concentrations of aluminum and fiber fabric, and three different relative densities of sand, D_r, were constructed in stages until failure occurred by surcharging the backfill. From these results a comparison of data of height of backfill at failure versus the length of reinforcement was analyzed.

METHOD

Principle of Reinforced Earth

Reinforced earth is a construction technique formed by the combination of earth (especially non-cohesive soils, and soils with little cohesion) and linear components usually made of steel, acting like reinforcements in the same manner as in reinforced concrete.

Vidal (1969) proved that by the inclusion of the reinforcements into the non-cohesive soils, the whole material exhibits some cohesion developed by the friction of the soil grains against the reinforcing elements. By this friction the soil transmits all the force built up in the earth mass to the reinforcement, placing them in tension, thus giving to the whole mass the capability of withstanding large tensile stresses in a direction parallel to the reinforcements.

The reinforcements are made of thin metal strips attached to flexible skin elements which prevent the soil from running out of the structure and give the desired shape to the front of the wall. The skin elements do not support the total lateral earth pressure usually associated with classical retaining walls; this horizontal pressure is taken by the reinforcements. Small tensile stresses are present on the skin elements, where the reinforcement is attached.

Reinforcement-Soil Interaction

The friction produced by the grains of soil in contact with the reinforcement is show in Fig. 1a. If a difference of tension ($dF = F_1 - F_2$) in the reinforcing member in a length dL between neighboring grains occurs, everything behaves as if the reinforcement is connecting the grains with a tension $F_1 - F_2$. This is possible if this tension $F_1 - F_2$ results from the friction without sliding between the reinforcement and the soil.

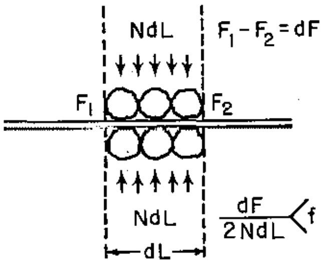

Fig. 1a. Reinforcement-Soil Grains Interaction

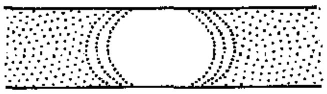

Fig. 1b. Assumed Grain Stress Transfer Between Adjacent Layers of Reinforcement

If the normal stress N acting over a length dL, created by the earth stresses perpendicular to the plane of the reinforcement, and on both sides of the reinforcement has a value of 2 NdL, the friction will take place without slipping, that is,

$$f > \frac{F_1 - F_2}{2NdL} \qquad (1)$$

where f is the coefficient of friction between the soil and the reinforcement.

Therefore, if the formula

$$\frac{F}{F.S.} = \frac{dF}{2\ NdL} \qquad (2)$$

is confirmed, friction without slipping occurs, F.S. being the safety factor. This relationship between soil and reinforcement has been satisfied in different reinforced earth designs.

The reinforcements are separated from each other at finite distances, if K is the proportion of reinforcement per unit length

$$\frac{dF}{dL} < 2\ KNf \qquad (3)$$

Only the interaction between the reinforcement and the grains in direct contact with it has been analyzed in the previous paragraphs. Because the reinforcements are placed in horizontal layers, the transfer of forces acting on the reinforcements to the grains not in direct contact with them should be considered. This transmission of forces to the grains of soil which are not in direct contact with the reinforcements is not known with certainty and it was assumed by Vidal to be in some sort of compression arches within the soil as illustrated in Fig. 1b.

Therefore, the friction requirement for the reinforcement of earth is satisfied by checking the formula explained which depends on the stresses in the soil, the geometry of the reinforcements, the coefficient of friction between soil and reinforcement and the change of tension on each reinforcing member.

Reinforced Earth Stresses

Scholosser and Long (1974) have shown that the tension stress in the reinforcing strips is minimum at the face of the wall, therefore, the skin elements are used mainly to prevent the loss of soil, and the tangential stresses transferred by the soil to each face of the reinforcement is

$$\tau = \frac{dT}{dL} \times \frac{1}{2b} \qquad (4)$$

where T is the tension in the reinforcement, L is the length on the reinforcement, and b is the width of the reinforcement.

Schlosser also showed that the shear stress exerted by the earth on the reinforcement at any given point is greater on the lower side of the reinforcement than on the upper side.

A parabolic curve formed by the points of maximum tension in the different layers of strips separates the earth structure into two zones: a) an active zone in which the tangential stresses are directed toward the face of the wall, and b) a resisting zone in which the tangential stresses are directed toward the interior of the wall.

Pluvial Compaction of Sand

The density of packing affects the ability of a sand deposit to carry a load without excessive settlement. In working with models of foundations, the experimenter finds it necessary to replicate the same experimental conditions at will, which requires a method of reproducing a sand deposit over a wide range of densities.

The pluvial compaction of sand is a method used to obtain uniform densities of sand, at determined levels, by allowing the sand to fall as rain to build up the required deposit.

Kolbuszewski (1948) showed experimentally that the factors controlling the density are the intensity of the flow of sand, and the height of fall of the sand grains. He found that for a given height, a decrease in the intensity of flow increased the density, and that for a given intensity of flow a decrease in height of fall decreased the density.

This technique of sample preparation has been used by several investigators, with variations in the mechanism of the sand raining device. Poplin (1968) used two types of movable sand sprinklers: a single-orifice sand sprinkler with a diffuser made of a U.S. standard No. 10 sieve, and a two-dimensional sand sprinkler with a diffuser made of three U.S. standard No. 8 screens. The relative density obtained was from 70 to 90%. Pluvial sand deposition techniques with traversing sand spreaders were used in large scale calibration chambers in 1969 (Chapman, 1974). The University of Florida calibration chamber also makes use of hopper full of sand that travels back and forth over the chamber and lets the sand drop through holes set in plates at the bottom of the hopper (Holden, 1971). Jacobson (1976) used a circular stationary depositor which consisted of a sand silo with its bottom plate perforated in a quadratic pattern. A shutter plate perforated in the same way was placed below the sand silo, and underneath the shutter plate a sand diffuser made of two steel sieves (mesh width 2 mm, distance between sieves 5cm). He found that by using this mechanism, it is possible to produce a one-meter high sand sample with a variation in dry density less than 1%, and with a relative density D_r, from 0.2 to 0.9. Bieganovski and Marcuson (1976) used three types of raining devices, a rotating rainer, a single-hose rainer, and a circular rainer. They found that the circular rainer with a perforated plate was the most satisfactory because any horizontal translation or rocking motion of the rainer would induce differences in density. At the Norwegian Geotechnical Institute, a circular stationary sand depositor for a large calibration chamber has recently been designed and manufactured with the bottom plate perforated in a triangular pattern (Holden, 1976).

MATERIALS, EQUIPMENT AND DENSITY DETERMINATION

Soil Properties

The sand used in this research was a uniform fine sand classified SP by the Unified Soil Classification System; this sand is a commercial blasting sand. Gradation testing repeated on four samples of the sand gave its average grain size, D_{50}, as 0.36 mm, and the uniformity coefficient D_{60}/D_{10}, as 1.7.

Maximum and minimum densities of 109.8 pcf (17.23 kN/m^3) and 94.0 (14.75 kN/m^3) were determined by laboratory tests. The maximum density was determined by compacting the dry sand in a mold 4.6 in. (11.7 cm) high, 4 in. (10.16 cm) diameter, in three layers with 25 blows per layer using a 5.5 lb (2.495 kg) hammer dropping 12 in. (30.48 cm) onto the soil, and then confining the layer and tapping the sides of the mold 20 times with a rubber mallet. The minimum density was determined by pouring the sand into the same mold through a funnel held 1 in. (2.54 cm) above the sand surface. The specific gravity determined for this sand was 2.63.

Reinforcement Characteristics

Testing was performed using two types of reinforcement:

Aluminum strips, 1.5 in. (38.1 mm) wide, and 0.005 in. (0.127 mm) thick with a yield strength of 57.75 lb (256.8 N), and an ultimate stress of 8700 psi (6.03 x 10^4 kPa). These properties were determined by the standard procedure ASTM Tension Sheet Test under the designation B557-74 with a 1.5 x 8 in. (3.81 x 20.32 cm) sample.

Fabric stips, 1.5 in. (38.1 mm) wide, and 30 mils (0.762 mm) thick, that were cut from a roll of "Mirafi 140", manufactured from polypropylene fibers, referred to in the text as fiber fabric. The fibers, laid in random directions, are bonded into fabric under heat and pressure. Table I contains pertinent physical properties for fiber fabric. The strips used have an ultimate strength of 31 lb (137.9 N) determined by the Standard Method of Testing Nonwoven Fabrics under the designation ASTM D 1117-74 on a 1.5 x 6 in. (3.81 x 15.25 cm) sample.

Table I

GENERAL PHYSICAL PROPERTIES OF NONWOVEN FIBER FABRIC

Fabric Property		Average Value
Weight, g/m^2		140
Thickness, mils		30
ASTM Grab Strength, lb.	Dry Wet	125 100
ASTM Grab Elongation, %	Dry Wet	170 150
ASTM Trapezoid Tear Strength, lb.		65
Air Permeability, CFM/ft^2		250-275
Water Permeability, cm/sec		$1x10^{-2}-3x10^{-2}$
Fabric Width, m		4.5
Fabric Roll Length, m		100

Fig. 2 illustrates a stress-strain curve for both type of reinforcements from the results obtained by the standard procedure tests, the units of stress being given in pounds due to the high elongation of fiber fabric.

Stationary Sand Rainer

According to the theory, one of the factors affecting the total frictional force developed on each side of the reinforcement is the density of the soil. Therefore, in order to study the influence of using three different relative densities of sand, and to be able to replicate these densities, a stationary sand rainer was designed. It consists of a sand bin 21.5 in. (54.5 cm) wide, 34 in. (86.4 cm) long, and 28 in. (71.1 cm) high, made of aluminum plates 0.25 in. (0.64 cm) thick. The bottom plate of the sand silo was reinforced by ribs, and perforated by 113 holes 7/8" (22.2 mm) in diameter in a triangular 24 in. (6 cm) pattern over an area equal to the area of the model box, yielding a porosity of 24.4%. Immediately below the bottom plate, a shutter plate made of 1/8 in. (3.2 mm) thick aluminum was placed, perforated in exactly the same pattern, but with different diameter hole sizes of 11/16, 7/16 and 3/16 (17.5, 11.1 and 4.8 mm) in order to get three different flows of sand which will give the desired densities. The shutter plate is opened or closed instantly by the use of a lever arm.

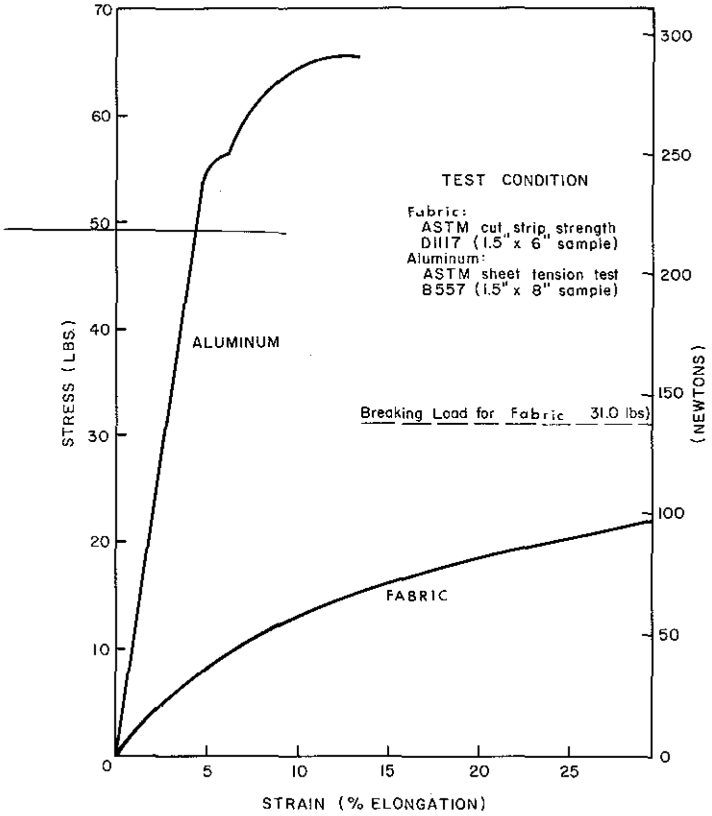

Fig. 2. Stress-strain Diagram for Reinforcements

A sand diffuser was placed below the sand bin, consisting of two steel sieves, mesh opening 0.098 in. (2.5 mm) with distance between sieves set at 2 in. (5.1 cm). The sieves were stretched out by an aluminum frame, and following Jacobsen's (1976) recommendations, they were rotated 45° relative to each other. In order to get a constant falling height of 10 in. (25.4 cm), a crankshaft mechanism was built to lift the diffuser continuously as the sand deposit was rising.

Fig. 3 shows the complete setup of the test to determine the densities. Pictured are the stationary sand rainer in place, the crankshaft mechanism to lift the diffuser, the model box made of plywood with plexiglass in one side to observe the sand rain. Also shown are the supports for the strain-gage instrumented aluminum plates and the hydraulic jacks for the pulling of the reinforcing strips, which will be discussed later.

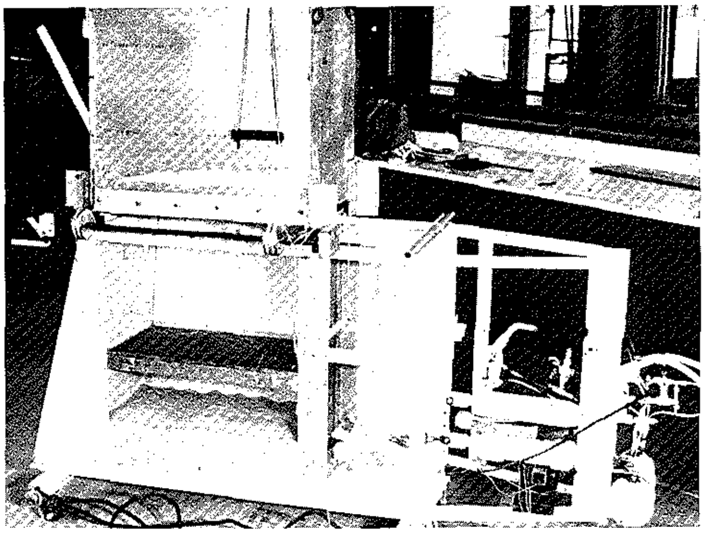

Fig. 3. Complete Test Equipment

Density Determinations

The dry density was varied by changing the perforated shutter plates. The average dry density of the sand was calculated dividing the net weight of the sand specimen by its corresponding volume in the model box, which was determined by measuring the height of the sand specimen, since the area (3.86 ft^2 [0.36 m^2]) of the box was known. The net weight of the sand rained was determined by a load cell, which was made of aluminum plate 0.5 in. (1.27 cm) thick, with strain gages attached to it. It was previously calibrated by an Instron Universal Testing Machine (Model TT-D), to ensure ± 5 lbs (approx. 0.5% of total weight) repeatability.

After the sample was prepared, a Nuclear Moisture-Density Device (Troxler Model SCM-227) was used to check the uniformity of the sand at three different points of the sand surface. Test results showed that all the specimens prepared were uniform; variations in density were equal to or less than 0.6%.

In this study the sand specimens were classified according to their average relative densities as dense sand (D_{r1} = 91.5%), medium sand (D_{r2} = 72%) and loose sand (D_{r3} = 38%). For each average of the

Table II

SUMMARY OF PARAMETERS RELATED TO DENSITIES AND RANGE OF REPRODUCTION

Description	Loose	Medium	Dense
Shutter plate diameter hole, in. (mm)	11/16 (17.1)	7/16 (11.1)	3/16 (4.8)
Dry density, pcf (kn/M^3)	99.4 (15.60)	104.7 (16.43)	108.23 (16.98)
Relative density, D_r (%)	37.8	72.0	91.5
Uniformity variation at three points of sand surface (%)	0.6	0.3	0.2
Angle of internal friction, ϕ, (degrees), from triaxial tests	34.5	38.5	41.5

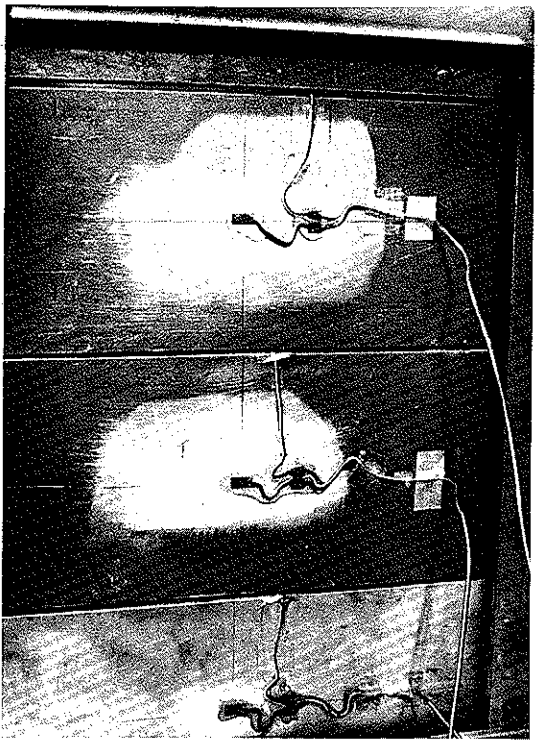

Fig. 4. Strain-gage Instrumented Aluminum Plates

relative densities obtained by the pluvial compaction of sand the angle of internal friction, ϕ, was determined by a triaxial compression test. Table II shows the range of reproduction in percentage for each of the relative densities.

According to Jacobsen (1976), in order to obtain a uniform sand specimen the vertical difference between the highest and lowest point of the sand surface should not exceed 5-10 cm (2-3.9 in.). The largest difference (3.8 cm [1.5 in.]) was observed in the loose sand specimens. Surface of denser specimens exhibited much smaller differences.

TESTING

Reinforcement Pull-Out Test

Models of reinforced earth retaining walls were constructed within a 18 in. x 48 in. x 36 in. (46 x 122 x 91 cm) plywood box with plexiglass in one side. Sand was pluvially deposited at predetermined relative densities as explained earlier. Three strips of reinforcement, spaced horizontally 6 in. (15.25 cm) center to center and with predetermined lengths, were placed during deposition at two levels--6 and 12 in. (15.25 and 30.5 cm)--from the bottom of the sample box.

The face of the retaining wall consisted of three strain-gage instrumented aluminum plates 0.25 in. (6.35 mm) thick, 6 in. (15.25 cm) high, and 16.5 in. (42 cm) long (see Fig. 4). The plates were resting on a knife-edge frame made from aluminum angles to provide a simply supported beam action. An opening of 1/8 in. (0.30 mm) was provided between the plates for the reinforcement strips to pass through without friction for manipulation outside the wall.

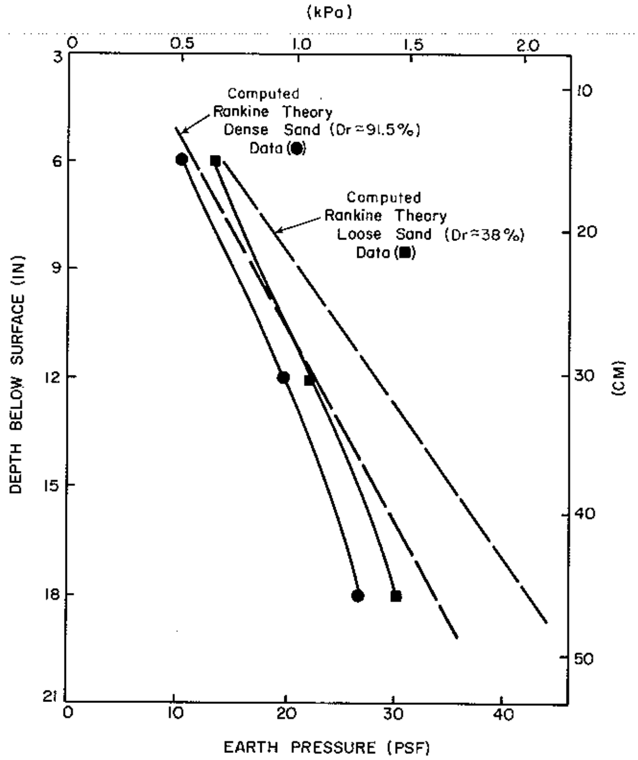

Fig. 5. Comparison of Lateral Earth Pressure Data for Loose and Dense Sand Without Reinforcements

Each aluminum plate, with strain gages attached, was individually calibrated twice under varied, uniformly distributed loads. The plates, supported on horizontal knife edges, were loaded with water contained in a plastic bag. Pressure-strain curves obtained from these calibrations were used to measure the lateral reaction mobilized by the sand-reinforcement interaction as a result of pulling out the reinforcing strips.

Three specimens, one for each relative density of the sand, were prepared without reinforcement to evaluate the lateral earth pressure developed on the back of the facing elements. Fig. 5 shows a comparison between the data found for loose and dense sand at the center of the instrumented plates, and the theoretical values by the Rankine method. It is seen that the total lateral earth pressure obtained are lower than the theory predicts, and the difference increases as the depth below the surface increases. The medium sand values, which are not shown, follow the same pattern. These small values were expected because of the arching effect caused by the boundaries of the model box. The increase in difference as the depth increases was explained by Terzaghi (1936). It is also attributed to friction developed between the bottom of the specimen and the bottom of the model box.

The pulling load was applied by two hydraulic jacks anchored at the steel frame of the model box. Load measurement was made by a standard load ring placed between the hydraulic jack and the frame used to pull the reinforcement. Lateral reaction on the strain-gage instrumented aluminum plates was measured by a digital strain indicator (see Fig. 6).

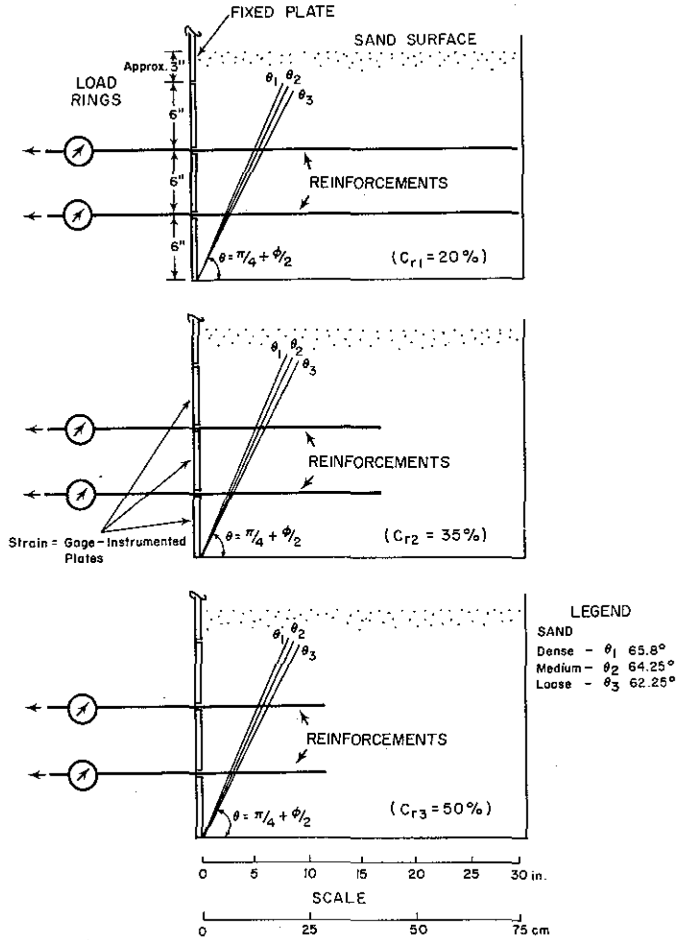

Fig. 6. Reinforcement Pull-Out Test

The aluminum reinforcements were pulled until sliding occurred, or until the reinforcements showed no tensile resistance. The peak shear stress and the normal stress on the aluminum strips were calculated to determine the skin friction angle, δ, between the sand and aluminum for each average of the relative density, D_r, of the sand used. Results showed that the tangent of the skin friction angle for the aluminum strips was about 0.43 times the tangent of the angle of internal friction, ϕ, of the sand, which agrees with the values found by Potyondy (1961).

When pulling out the fiber fabric reinforcement, it was not possible to determine if sliding was taking place in all the tests done with this material because of the high values of grab strength and grab elongation. In order to have comparative values of the skin friction for both types of reinforcement, the direct shear test method was used to determine the coefficient of friction between fabric reinforcement and soil.

The tangent of the skin friction angle determined by the direct shear box was about the same as the tangent of the angle of internal friction of the sand for the fiber fabric, and about 0.63 times for aluminum.

		REINFORCEMENT 1			REINFORCEMENT 2		
		C_{r1}	C_{r2}	C_{r3}	C_{r1}	C_{r2}	C_{r3}
D_{r1}	REP. 1	1111	2111	3111	1211	2211	3211
	REP. 2	1121	2121	3121	1221	2221	3221
D_{r2}	REP. 1	1112	2112	3112	1212	2212	3212
	REP. 2	1122	2122	3122	1222	2222	3222
D_{r3}	REP. 1	1113	2113	3113	1213	2213	3213
	REP. 2	1123	2123	3123	1223	2223	3223

A. TYPE OF REINFORCEMENT (1. ALUMINUM, 2. FABRIC)
B. RELATIVE DENSITY OF DRY SAND, D_r (1. 91.5 %, 2. 72 %, 3. 36 %)
C. REINFORCEMENT CONCENTRATION, C_r (1. 20%, 2. 35%, 3. 50%)

$$C_r = \frac{\text{REINFORCEMENT SPACING IN HORIZONTAL PLANE}}{\text{LENGTH OF REINFORCEMENT}}$$

3 STRIPS SPACED 6 IN. (15.25 CM) CENTER TO CENTER WITH LENGTHS OF 12, 17.1, AND 30 IN. (30.5, 43.2, AND 76.2 CM)

D. EXPERIMENTAL REPLICATION (TWICE)

Fig. 7. Factorial Grid for Pull-Out Test

Statistical Design of Experiments

The testing program was designed as a factorial model to collect and analyze data in an attempt to investigate the comparative and combinational effects of three different factors and their probable interactions. Statistical relationships could then be obtained between the lateral reactions on the strain-gage instrumented aluminum plates and these factors as well as the pull-out forces on the reinforcements. These factors studied were: a) type of reinforcement, b) relative density of sand, and c) reinforcement concentration.

A representation of factorial combinations that places each combination into a position falling into the columns and rows of the related levels is shown in Fig. 7.

It should be mentioned that the term "reinforcement concentration" in this study was defined as the ratio of reinforcement spacing in horizontal plane to length of reinforcement, Lee (1973), but as the spacing was held constant, it gives direct indication of "length of reinforcement".

Reinforcement Overstress Test

Models of reinforced earth retaining walls were constructed within the same plywood box used for the pull-out testing. The fact of the wall was changed; it consisted of three skin elements made from 0.015 in. (0.38 mm) thick aluminum sheet and formed to a semielliptical shape 6 in. (15.25 cm) high and 16.5 in. (42 cm) long. A sketch of this experimental

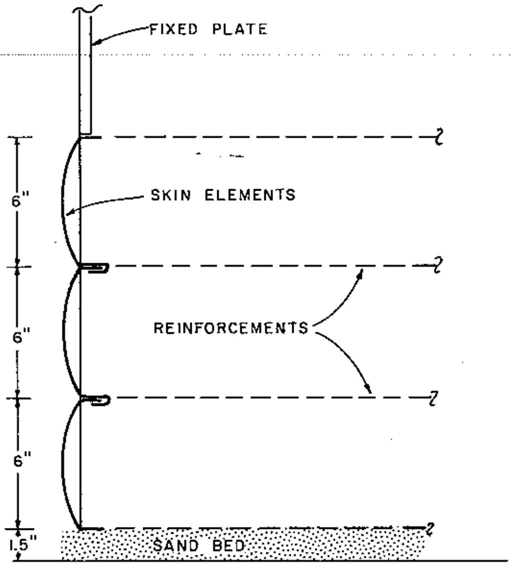

Fig. 8. Reinforcement Overstress Tests

setup is shown in Figure 8. The skin elements were previously assembled with the strips already attached to eliminate any possible disturbance caused by handling the joints. Four levels of strips were used: one level at each extreme of the skin elements and one at each joint.

In order to provide a similar sliding condition as that in the field, a layer of sand 1.5 in. (3.8 cm) thick was pluvially deposited in the bottom level of the box. Then the skin elements were placed in position with the bottom level of strips laid over the initial sand bed. Additional sand was added up to the top edge of the bottom skin element. Precautions were taken to hold this skin element in place with a temporary support. (This support was a steel angle anclored by sliding bolts passing through horizontal slots in the plywood side of the sample box. This arrangement allowed the removal of the support without disturbing the wall face.)

Next, the second level of strips was placed flat over the sand surface. Three more inches of sand were then deposited to embed this second level. The temporary support was then removed and placed to hold the top edge of the second skin element. Sand was again deposited to the top of this skin element. The same procedure was repeated for the third skin element and the two remaining levels of strips.

The walls were backfilled with three different relative sand densities (38%, 72% and 91.5%) obtained by the same stationary sand rainer described earlier. Varying length of both types of reinforcement, aluminum and fiber fabric, were tested for each relative density. The horizontal spacing was kept constant at 6 in. (15.25 cm). The vertical spacing was kept constant at 6 in. (15.25 cm), which was the height of the skin elements.

The same construction process used for all tests was continued until the wall failed. In some tests, the wall failed before the height of the backfill was equal to the total height of the wall. Because the dimensions of the sample box limited the maximum backfill depth to 24 in. (61 cm), some tests did not result in a wall failure.

For lengths of reinforcement less than 11 in. (28 cm) for aluminum and 8 in. (20.3 cm) for fiber fabric, the wall failed when the temporary support was removed from the top edge of the bottom skin element. Therefore, in later tests, the wall was built with longer reinforcement.

DISCUSSION OF RESULTS

Reinforcement Pull-Out

The values of the lateral reaction exerted on the plates forming the retaining wall, and the values of the pulling force applied to each level of reinforcements obtained from the experimental data were subjected to Analysis of Variance for evaluation (Peng, 1967).

For comparative analysis, the lateral stress on the strain-gage instrumented aluminum plates for pull-out tests did not include the static earth pressure as shown in Fig. 5, only the change in stress resulting from tensile forces on the reinforcement was analyzed. This was achieved by subtracting in instrumentation the initial values of the lateral reaction on the plates from the final values obtained after pulling out the reinforcements.

Fig. 9 shows the reduction effect in earth pressure on the back of the wall by the inclusion of a reinforcement concentration of 20%, 30 in. (76.2 cm) long, before pulling out the reinforcement, in medium sand. Fig. 10 shows a typical curve of the lateral reaction on the middle plate versus the pulling force applied to the reinforcement. It can be seen that for the same values of the pulling force applied to the reinforcements, the lateral reaction on the plate is higher for the fiber fabric than for the aluminum reinforcement, showing that the fiber fabric is more efficient that the aluminum in mobilizing sand-reinforcement interaction.

Table III

PRIORITY ORDER OF FACTORS CONSIDERED IN SAND-REINFORCEMENT INTERACTION

Type of Statistical Analysis	Nested Factor	Priority Order of Factors
No Nesting	None	1. Type of reinforcement
		2. Reinforcement concentration
		3. Relative density of sand
Nesting Under Type of Reinforcement	Aluminum	1. Reinforcement concentration
		2. Relative density of sand
	Fiber Fabric	1. Relative density of sand
		2. Reinforcement concentration
Nesting Under Relative Density of Sand	D_{r_1} = 91.5%	1. Type of reinforcement
		2. Reinforcement concentration
	D_{r_2} = 72%	1. Type of reinforcement
		2. Reinforcement concentration
	D_{r_3} = 38%	1. Type of reinforcement
		2. Reinforcement concentration

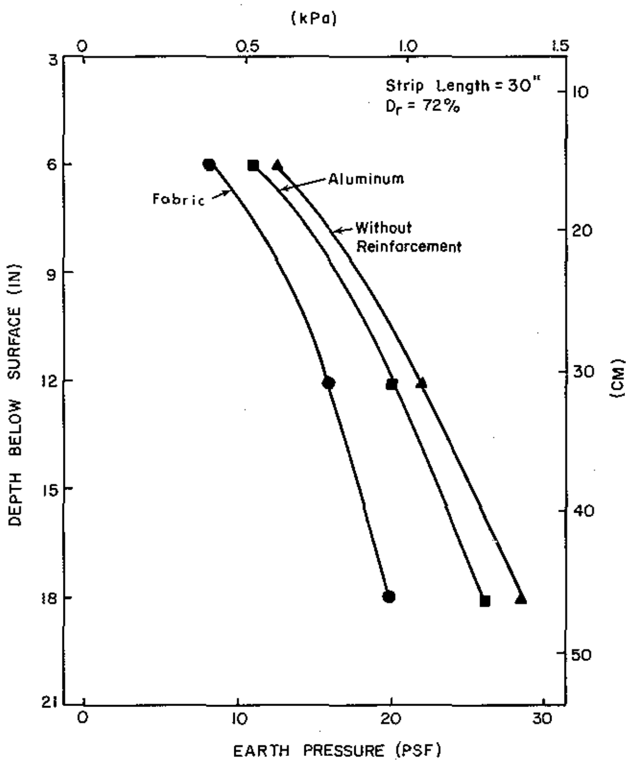

Fig. 9. Comparison of Data for Medium Sand With and Without Reinforcement (on fixed wall)

The lateral reaction was measured and analyzed for each of the three strain-gage instrumented aluminum plates. But an exhaustive analysis of the lateral reaction on the middle plate was made because this plate was between two levels of reinforcements; therefore, it was the only plate that could show the assumed arching effect induced in a soil mass between two layers of reinforcement. The data showed that the lateral reaction exerted on this plate as a result of pulling the strips out was higher than the top and bottom plates.

The statistical computer program used allowed detailed analysis of the data by nesting technique. For example, by nesting the type of reinforcement (1--aluminum, 2--fiber fabric), it was possible to evaluate the priority order by which the other two factors (relative density and reinforcement concentration) affected the levels of the nested factor.

Table III summarizes the order of importance of the factors analyzed in mobilizing sand-reinforcement interaction.

The effectiveness of the reinforcement in mobilizing sand-tie interaction can be evaluated graphically by plotting the mean values of the lateral reaction data obtained from the analysis of variance outputs. Fig. 11 illustrates a relationship between all the factors and its levels, affecting the lateral reaction on the middle plate. It shows the effect of changing the relative density of the sand for each type of reinforcement used. With fiber fabric the grabbing effect improves for all the reinforcement concentrations, and as the density of the sand decreases this grabbing effect decreases more rapidly for short lengths of reinforcements. Thus, it can be said that for the fiber fabric the sand-reinforcement interaction depends more on the length of the reinforcement, when low densities of sand are used, than with high densities of sand. With aluminum strips, by increasing the density of sand, the increase in friction effect is almost negligible for short lengths of reinforcements (high reinforcement concentration). Then, improvement in mobilizing sand-reinforcement interaction depends more on the reinforcement concentration (reinforcement lengths) than in the density of the sand.

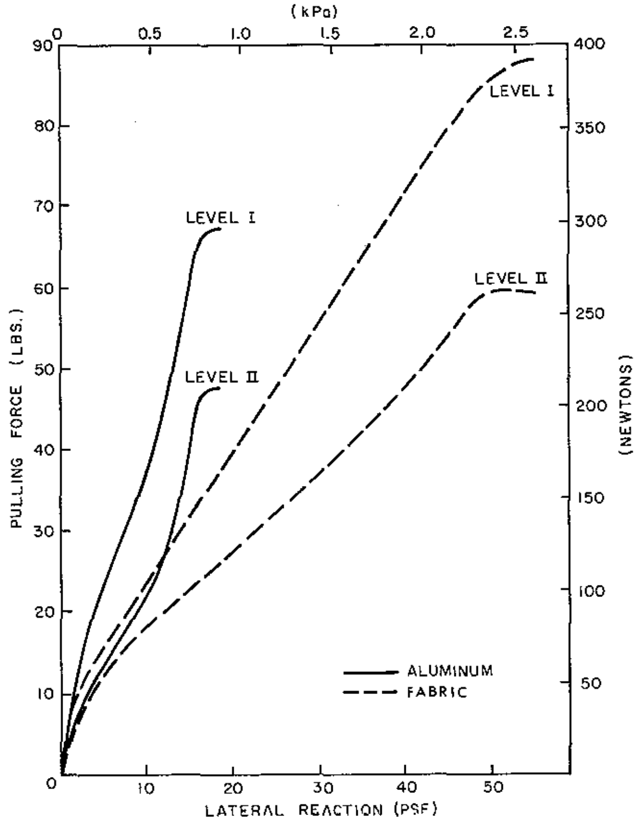

Fig. 10. Typical Curve on Lateral Reaction on Middle Plate vs. Pulling Force on Reinforcements (D_r = 91.5%, D_r = 20%)

The advantage of using fiber fabric as reinforcement can be seen, since this reinforcement produced a greater stress on the plate before failing. Due to the high grab strength of this material, the ratio of the lateral reaction exerted on the plate by the fiber fabric reinforcement to the lateral reaction on the plate by the aluminum is about four except for loose sand.

Fig. 12 also shows a complete relationship between all the factors affecting the lateral reaction on the middle plate. In this figure the effects of changing the reinforcement concentrations for each relative density of sand can be evaluated for both types of reinforcement. It should be mentioned again that the negative slope of these curves is a result of the reinforcement concentration being inversely proportional to the length of the reinforcement. When fiber fabric is used, an increase

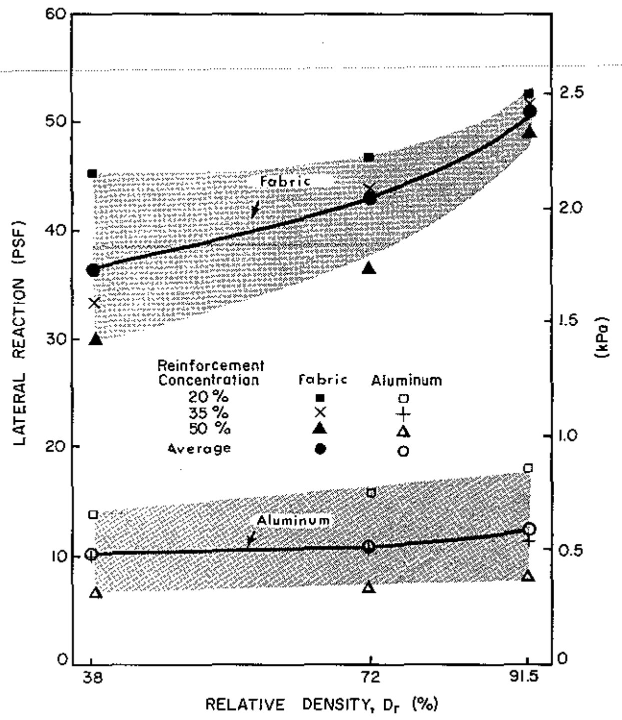

Fig. 11. Relationship Between Lateral Reaction on the Middle Plate, Relative Density of Sand, and Type of Reinforcement

in length will increase the lateral reaction for all the relative densities of sand, but for a dense sand this increase is less than for the medium and loose sand. Therefore, as the density of the sand decreases this grabbing effect becomes less dependent on the length of the reinforcement. With the aluminum reinforcement, an increase in the length of the reinforcement will increase the interaction with the sand. Also, for a reinforcement concentration of 50% by changing the density of the sand, no significant improvement in friction is developed, but as the length of the reinforcement increases, the sand-tie interaction increases with use of higher densities of sand.

It can be seen that the stresses on the plates increase linearly with the length of the strip. The ratio of the lateral reaction on the plate by the fiber fabric to the lateral reaction by the aluminum strips is about 3 for C_r = 20%, 4.2 for C_r = 35%, and 5.6 for C_r = 50%. The decrease in this ratio as the length of the reinforcement increases is attributed to the small friction developed between the sand and the aluminum when pulling out small lengths of aluminum strips.

Analyses were also made of the forces applied to pull out the top and bottom reinforcements. For the two levels of reinforcing strips the curves follow a similar pattern.

Reinforcement Overstress

To be able to compare both categories of tests made in this research, the skin elements forming the face of the retaining walls were made to the same height, 6 in. (15.25 cm), as the strain-gage instrumented plates used in pulling out the reinforcements. Also, the horizontal spacing between reinforcements was kept the same, 6 in. (15.25 cm) for both types of tests.

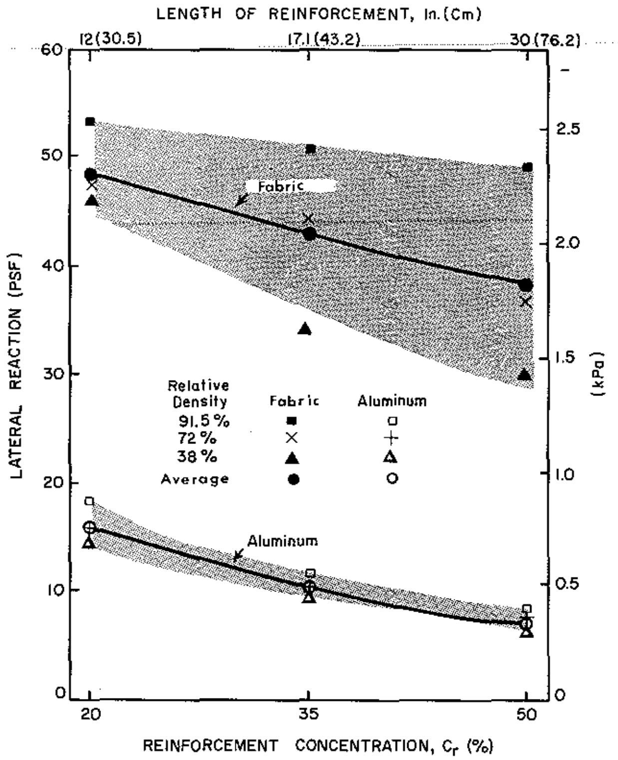

Fig. 12. Relationship Between Lateral Reaction on the Middle Plate, Concentration and Type of Reinforcement

The wall generally failed by tilting around its lower edge; first the top plate moved and then the whole wall tilted outward a great distance.

Fig. 13 depicts a comparison of data for a relationship between height of backfill at failure, length of reinforcement, relative density of sand and type of reinforcement used. As mentioned earlier, the lower limit in the length of reinforcements is a result of the self-supporting characteristics of this model. The dotted lines going to point A try to clarify this lower limit for the aluminum reinforcement to avoid any confusion due to the ending of the solid failures lines.

The longest length of the fiber fabric reinforcement was 12 in. (30.5 cm) because of model equipment limitations in building walls with more than 25 in. (63.5 cm) of backfill. The dotted lines going to point B for the aluminum reinforcement are extrapolated possible lines of failure due to the fact that for 23.5 in. (59.7 cm) of backfill the wall did not fail for a reinforcement length of 14.5 in. (36.83 cm) with the dense and medium sand specimens and 16.5 in. (41.91 cm) with the loose sand specimen.

It can be seen that no significant difference in safe wall height was observed when aluminum reinforcements were used with specimens of medium and dense sand. A significant difference was obtained only when a loose sand specimen was used; this

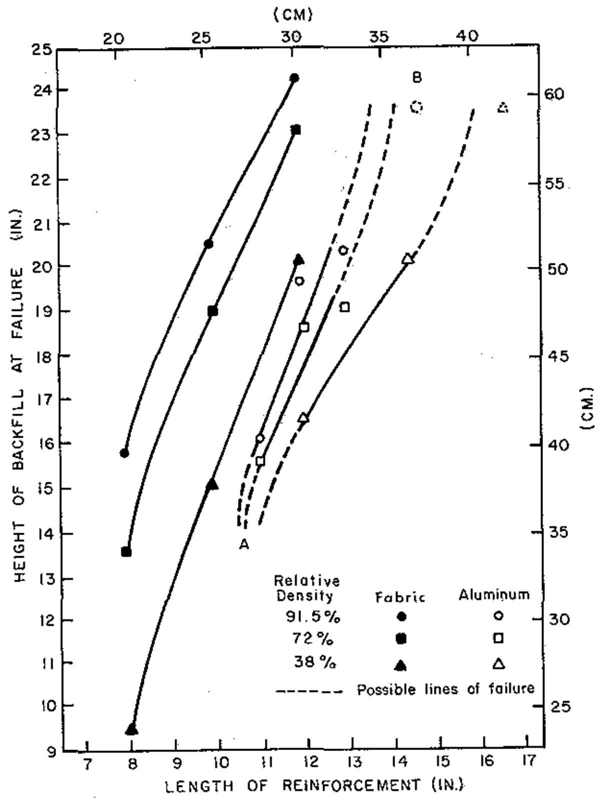

Fig. 13. Comparison of Data for Reinforcement Overstress tests

agrees with the theory that predicts a decrease of the safe wall height as the density of the sand decreases. Therefore, the increase in safe wall height when aluminum is used will depend more on the length of reinforcement than on the density of the sand.

When using the fiber fabric reinforcements, the height of a safe wall will increase by either increasing the length of the reinforcement or the density of the sand. It should be noted that there is improvement in the height of the wall for the same length of reinforcement as the density of the sand increases.

CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this research, the following conclusions are made:

1. The efficiency in mobilizing the interaction between sand and reinforcement due to the grabbing effect of the fiber fabric is about three times greater than the frictional effect of the metal.
2. For a given reinforcement concentration, an increase in the density of the sand will increase the grabbing strength of the fiber fabric, while the friction developed in the metal does not show any significant improvement. The reinforcement pull-out tests show that the efficiency of the aluminum is about the same for any relative density.
3. A decrease in reinforcement concentration (an increase in length of reinforcement) increases the efficiency in mobilizing sand-tie interaction for both types of reinforcement. For fiber fabric a greater improvement is obtained with low densities of sand.
4. The overstressing tests of the reinforcement made with similar retaining artifacts showed that a safe wall height would need shorter lengths of fiber fabric than metal reinforcement.

The results obtained from this research provide considerable knowledge regarding the advantage of using reinforcement made of fiber fabric instead of metal reinforcement in reinforced earth structures. However, the following studies are recommended:

1. Development of techniques for identifying the strain distribution along the length of the fiber fabric reinforcement for a better understanding of the nature of grabbing between sand and reinforcement.
2. Models in saturated conditions under shock loading to investigate the superiority of fiber fabric over metal due to its permeability.
3. Determination of minimum lengths of fiber fabric in earth reinforcement design.
4. Use of more rigid skin elements to check for deformations and settlements due to the elongation of fiber fabric.

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