Pull-Out Resistance of Geogrids in Sand

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To further knowledge of the pull-out resistance of grids, a series of pull-out tests was performed in the laboratory. The test regimen included the effects of overburden pressure, grid specimen length and width, and relative density of the sand on the pull-out resistance of the reinforcement. Tests were also performed to find the effect of soil particle size on the pull-out resistance of grids. It was found that the pull-out resistance of grids is a function of the relative density of the soil, the particle size, the length and width of the grid specimen, and the mechanical properties of the grid material. A mechanism of soil-geogrid interaction is described and used to explain the results of the pull-out tests. A significant finding is that the selection of geogrid specimen dimensions for laboratory pull-out tests must take into account the strain to failure of the soil and the stiffness of the geogrid in order to properly represent the maximum pull-out stress that will be available in field applications.

Reinforced soil is a composite construction material that consists of alternating layers of compacted backfill and tensile reinforcing material. The theory behind reinforced soil is that the vertical normal stresses that the backfill exerts on the embedded reinforcement are a source of frictional resistance that results in tensile stresses being carried by the reinforcement.

Long galvanized steel strips were almost exclusively used as reinforcement in early applications in reinforced soil structures. It has been found that ribbing the metal strips greatly improves the frictional resistance developed between the reinforcement and the soil. Newer materials such as geotextiles and geogrids are now being used in some reinforced soil structures. Geotextiles appear to be useful when large deformations are allowable and when stresses are relatively low. Geogrids, made of strong plastics, are not as extensible as textiles and develop higher resistance to pulling out of soil.

Two requirements common to the design of all reinforced soil structures are that (a) the reinforcement must not fail in tension, and (b) the reinforcement must not pull out of the soil. Designing against a tension failure requires that the stresses in the reinforcement be less than the ultimate strength of the reinforcing material. This is done by adjusting the cross-sectional area of each reinforcing member or varying the number of reinforcing elements per unit area of the structure.

In designing against pull-out failure of metal strip reinforcement, a coefficient of friction between the soil and the reinforcement is used. It is assumed that the pull-out resistance is supplied by friction along both surfaces of the reinforcement and is given by the relation

$$T = 2LW \sigma_n \tan \delta \qquad (1)$$

where

T = maximum pull-out force developed,
L = length of reinforcement,
W = width of reinforcement,
σ_n = overburden pressure, and
δ = friction angle between the soil and reinforcement.

An assumption associated with the use of this equation is that the frictional resistance is uniform along the length of the reinforcement. It is known, however, that the friction developed along the reinforcement is not uniform but varies along the length. In a reinforced soil retaining wall, for example (*1–4*), it has been found through careful instrumentation that the tensile stress reaches a maximum near the point of crossing the theoretical Rankine failure wedge boundary. The stress decreases to zero at the free end of the reinforcement. It does appear, however, that the use of this equation for the design of metal strip reinforcement is adequate if care is taken. The required length of embedment of the reinforcing strips must be selected to provide an adequate factor of safety against pulling out of the soil.

For design of geotextile-reinforced retaining walls the same approach is sometimes used. Barrett (*5*) recommends using $\delta = \frac{2}{3} \phi_{soil}$ in the design. Murray (*6*) attempts to make allowances in the design for the large strains that develop in the fabric.

Material published by a geogrid manufacturer (Tensar Corporation, 1210 Citizens Parkway, Box 986, Morrow, Georgia 30260) also recommends using a two-dimensional approach in designing against pull-out for their grids.

Three test methods are commonly used to determine the pull-out characteristics of a reinforcing material. The first is a modified direct shear test in which the reinforcing material is firmly attached to a solid block and placed in the upper ring of a direct shear device. Soil is prepared in the lower ring. The test is then performed exactly like a conventional direct shear test to find the friction angle between the soil and the reinforcement.

The second test is called a "free shear" test. It is similar to the first test except that the reinforcement is placed at midheight of a soil sample. The reinforcement is attached to the top ring of the device on the side toward the direction of movement. As the soil and reinforcement are sheared,

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the reinforcement is allowed to strain freely between the soil layers.

The third method is a reduced-scale pull-out test. A reinforcing member is placed horizontally at midheight of a prepared soil sample, an appropriate overburden pressure is applied to the soil, and the reinforcing member is pulled out. Data from a pull-out test may be interpreted to give a soil/reinforcement friction coefficient (δ). The test is a systems test that most closely approximates the condition of the reinforcement in an actual structure.

Schlosser and Elias (*4*) presented results of pull-out tests performed on smooth bronze strips in sand. They drew several conclusions from their tests:

- The pull-out resistance offered by dense sand is much greater than that offered by soils of lower densities.
- At low densities (of soil) the friction is uniformly distributed across the length of the reinforcement.
- At higher densities deformation of the reinforcement predominates, and, as a result, the mobilized friction is maximum at the end that is pulled out and decreases to zero at the free end.
- At low densities the δ angle observed during pull-out testing is less than δ obtained from direct shear methods, probably because of collapse of the sand structure under strain during the pull-out test.
- At higher densities the δ angle from the pull-out testing is more than δ obtained from direct shear testing, probably because of dilatancy effects of dense sand.
- More pull-out resistance is developed from ribbed reinforcement than from smooth reinforcement.
- The peak pull-out resistance occurs at larger displacements for the ribbed strips than for the smooth. Also, smooth strips have a much more pronounced peak in the force-displacement curve than do ribbed strips. (The authors suggested that the more pronounced peak with the smooth strips is probably due to an effective collapse of the structure of the sand surrounding the strips during pull-out. The zone of affected sand is larger for the ribbed strips; therefore the displacement to peak is larger and the strength is less affected by the displacement.)
- δ increases as the length of the strip increases.
- δ increases as the overburden stress increases.

Bacot et al. (*7*) found that in compacted samples of sandy gravel the pull-out resistance was less than in uncompacted samples. (They said that this might be because the compaction process used smoothed out the surface of the sand. The undulations in the uncompacted sand probably caused the increased pull-out resistance.) They also found that, as the length of reinforcement increases, the friction angle (δ) between the soil and the reinforcement increases.

Ingold (*8*) reported on a comparison of the modified direct shear, free shear, and the pull-out tests for evaluating the pull-out resistance of grids. The pull-out resistance of textiles (woven and nonwoven) was also compared with that of grids. Ingold concluded that, for reinforcements that are extensible (such as textiles) or have a three-dimensional structure (such as geogrids), the pull-out test is the only reasonable method for determining pull-out characteristics. From the pull-out tests, it was determined that, for very low normal stresses, the friction angle between the reinforcement and the soil can be a very large value (from 55 to 85 degrees for the materials tested). For the textile materials, the δ angle decreased to a value that was less than the friction angle for the soil alone at normal stresses of about 15 psi and appeared to reach a constant value at some fraction of the soil friction angle at normal stresses of about 20 to 25 psi. The grid material, at normal stresses of about 15 psi, reached a constant value of δ at a value of about 10 degrees above the friction angle of the soil alone.

In a later study, Ingold (*9*) concluded that the pull-out resistance of grids is a function of the cumulative embedded area of grid members normal to the direction of pull-out and not the embedded plan area of the reinforcement. An analytical model was presented that shows that pull-out resistance is dependent on the normal stress level and some exponential function of the friction angle of the sand and the geometry of the grid member.

Jones (*10*) stated that the pull-out resistance of grid reinforcement in sand is a combination of the frictional resistance presented by the grid plus the anchor resistance of the grid. The frictional resistance was the same as that of methods using the δ angle. The anchor resistance was evaluated through the use of a modified bearing capacity equation.

In the present study, the pull-out resistance of grids in sand was studied. The effects of the following parameters on pull-out resistance were evaluated in the testing:

1. Relative density of the sand,
2. Grid sample length,
3. Grid sample width,
4. Particle size of the soil, and
5. Grid type.

EQUIPMENT

The pull-out test box is 11.5 in. wide by 30 in. long by 4 in. deep (inside dimensions). It is made of aluminum plates ⅜ in. thick. At one end of the box there is a slot, parallel to the bottom, that allows a geogrid to be pulled through. There is a pistonlike lid, made of aluminum plates, that fits into the box. The lid has a reinforced honeycomb structure attached to it to make it very stiff. Attached to the honeycomb structure at the top is a heavy steel plate with a small depression in the center in which a steel ball is placed. The normal load is applied to the steel ball. This ensures that there are no eccentricities of the normal load. The stiffness of the lid plus the great care with which the sand surface is smoothed ensure that the load is applied uniformly over the entire area of the box.

The pull-out box is mounted on a large frame from an old consolidometer modified for this purpose. A weight hangar is used to apply the normal load to the lid of the testing box. There is room for about 900 lb of weights in the weight hangar.

The pull-out force is applied manually by a gearbox from an unconfined compression test device that is attached to the testing box by a bracket. A 1-kip load cell is attached in line with the pull-out force. A grid-holding device connects into the other side of the load cell. This device was designed to fit the type of grid tested and consists of a small piece of angle, approximately 10 in. long, with notches cut in one leg. A grid specimen hooks into the notches and is held in place by two 4-in.-long pieces of iron that are held to the angle by bolts. Attached to the end of the pull-out mechanism is a linear varying differential transformer (LVDT) that is used to measure the displacement of the moving parts of the pull-out mechanism and the geogrid as the pull-out test is performed. With this equipment it was found that pull-out forces of approximately 1,000 lb could be achieved. The equipment is shown in Figure 1.

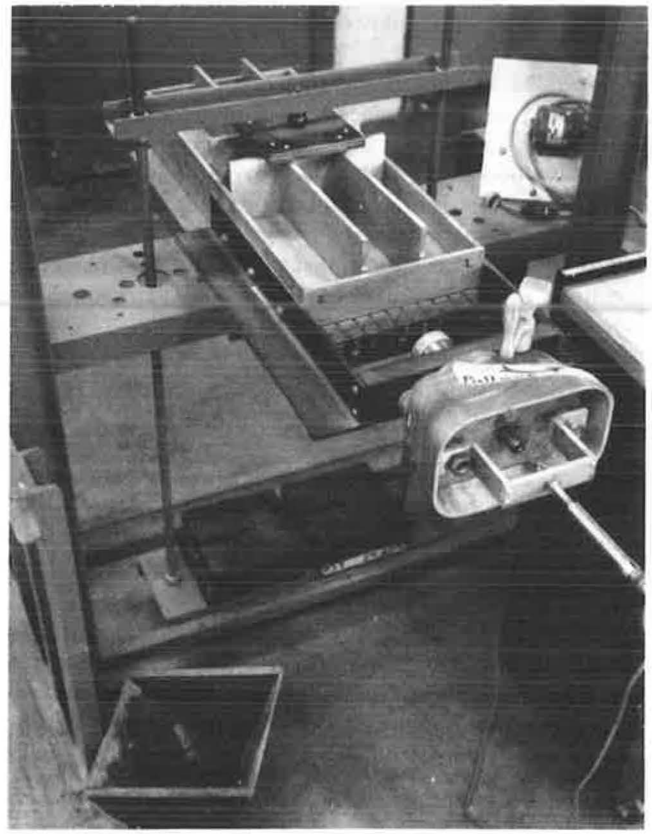

FIGURE 1 Pull-out test apparatus.

SAND

A fine sand and a coarse sand were used in the testing program. The fine sand consisted predominantly of subrounded quartz particles. The coarse sand had subangular particle shapes. A sieve analysis was performed to determine the gradation of each sand.

From these analyses, index properties of effective particle size (D_{10}), average grain size (D_{50}), coefficient of uniformity (C_u), coefficient of skew (C_z), and Unified Soil Classification were determined (Table 1). The minimum and maximum densities of each sand were determined by the methods described in ASTM standards 04254-83 and 04253-83 and are also given in Table 1.

The frictional characteristics of the sand were determined by consolidated-drained triaxial tests. Specimens of sand were prepared by placing a weighed amount of sand in a membrane-lined split mold and vibrating the mold until the height of the specimen indicated that the target relative density had been obtained. The angles of internal friction for the fine sand were 34 and 39 degrees for relative densities of 41 ± 3 percent and 84 ± 3 percent, respectively. The angle of internal friction for the coarse sand at a relative density of 40 ± 4 percent was 41 degrees. The Mohr envelopes from the triaxial tests are shown in Figures 2–4.

GEOGRIDS

Geogrids are made of parallel-oriented long-chain polymers such as polypropylene or high-density polyethylene. The grid structure is attained by heat-stretching a perforated sheet of the polymer. The geogrids used in this study were Tensar SS1 and SS2 made of polypropylene.

Tensar geogrid type SS2 was used in nearly all of the tests performed. The hole size in these grids is slightly smaller than 1.5 by 1.1 in. The grid members are 110 mils wide and 50 mils thick. At the juncture of grid members, the thickness is 160 mils. The tensile strength of grid type SS2 is 2,190 lb/ft width in the primary direction and 1,230 lb/ft width in the secondary direction.

Grid type SS1 is a slightly lighter-weight version of grid type SS2. The hole size is the same, but the grid thickness is only 30 mils and the juncture thickness is 100 mils. The tensile strength of grid type SS1 is 1,430 lb/ft width in the primary direction and 860 lb/ft width in the secondary direction. (The preceding information is from the manufacturer's literature.) All pull-out tests on both types of grid were performed with the grids pulled in the primary direction.

It was necessary to determine the volume per unit area for each type of grid so that the calculated density of sand in the pull-out device could be adjusted for the volume

TABLE 1 INDEX PROPERTIES OF SAND

	D_{10} (mm)	D_{50} (mm)	C_u	C_z	Class	γ_{dmax} (pcf)	γ_{dmin} (pcf)
Fine sand	0.22	0.35	1.86	1.00	SP	108.7	92.6
Coarse sand	3.00	4.50	1.67	1.01	SP	95.2	83.4

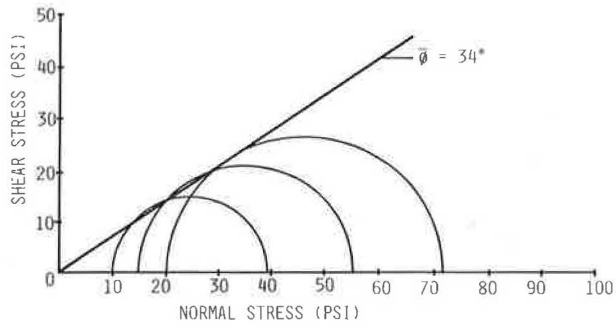

FIGURE 2 Mohr envelope for loose fine sand.

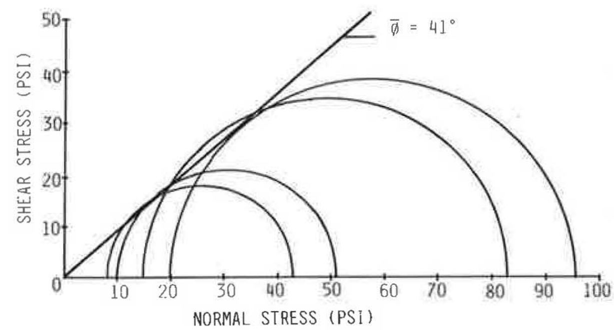

FIGURE 4 Mohr envelope for coarse sand.

occupied by the geogrid. This was done by immersing a known area of the grid in a graduated cylinder of water and determining the volume of water displaced.

TESTING PROCEDURE

The sand was placed in lifts that were roughly ½ in. thick with a sand-spreading device. The sand spreader was a V-shaped hopper that was moved along the sides of the pull-out box to place each lift in multiple passes. The sand particles were dropped from a 1-in. height at the start of the lift. The drop height decreased to ½ in. at the end of the lift. When the sand had been placed, it was screeded smooth. Then the height of sand was measured with a dial gauge device and the density was calculated. The same procedure was used on the second lift of sand.

In the tests with the dense samples, after the second lift had been placed, the sand was densified by using a vibrating motor mounted on a 10.5- by 10.5-in. aluminum plate. After it was vibrated, the sand was screeded smooth, the new height of sand was measured, and the density was calculated.

After the second lift was prepared, the grid was placed on the sand surface and inserted through the slot in the end of the box. The grid was placed with a grid member within the plane of the end of the box. This allows about ¾ in. of grid travel during a pull-out test without appreciable interaction of the grid and sand with the slot of the box. The free end of the grid was attached to a grid-gripping device that was, in turn, attached to a 1-kip load cell. The other end of the load cell was attached to the pull-out mechanism.

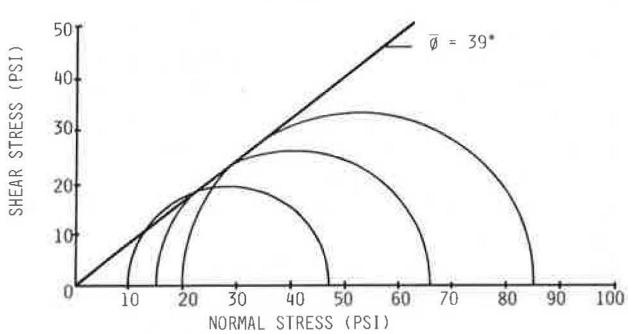

FIGURE 3 Mohr envelope for dense fine sand.

After the grid had been positioned, the second two lifts of sand were placed. The procedure was identical to that used for the first two lifts.

It was found that, by using the procedure discussed previously with the fine sand, an average loose relative density of 41 ± 4 percent and an average dense relative density of 85 ± 3 percent could be consistently achieved. With the coarse sand, an average loose relative density of 38 ± 13 percent was achieved. The relative density for each test is given in Table 2. Note that there is more variation in relative density for the coarse sand because of the small range between maximum and minimum density, which makes the result sensitive to small variations in placement density. Also, the large particle size made it more difficult to screed the surface smooth without disturbing the density.

PULL-OUT

After the sample had been prepared with the grid at mid-height, the following pull-out test procedure was used: First, the lid of the testing box was carefully placed on the sand surface. Then the loading ball and weight hangar were placed on the lid. Next, weights were carefully placed on the shelf of the weight hangar, below the testing box. It was determined through monitoring with four dial gauges that placing the lid, weight hangar, and weights on the sand has a negligible effect on the density and that the lid moves downward uniformly.

The pull-out force was applied by turning the crank on the pull-out mechanism. A constant, slow rate of approximately 0.1 in./min was maintained throughout each test. The test was continued until the displacement of the grid was about 0.6 in. A peak in the pull-out force was reached in all tests at or before this displacement.

Pull-out force, measured by the load cell, and displacement, measured by the LVDT, were recorded directly in the form of a load-deformation curve using an X-Y recorder.

TABLE 2 PULL-OUT TEST RESULTS

Test No.	Soil	q	L	W	D_r	P	δ
1	FS	1.265	29.50	10.38	39	576	36.6
2	FS	1.265	29.50	10.38	39	547	35.2
3	FS	1.841	29.50	10.38	40	777	34.6
4	FS	0.690	29.50	10.38	37	268	32.4
5	FS	2.416	29.50	10.38	40	965	33.1
6	FS	1.265	29.50	10.38	86	750	44.1
7	FS	0.690	29.50	10.38	81	375	41.6
8	FS	1.841	29.50	10.38	84	965	40.6
9	FS	1.265	24.25	10.38	42	394	31.8
10	FS	1.265	18.50	10.38	40	295	31.3
11	FS	1.265	18.50	10.38	84	493	45.4
12	FS	1.265	12.25	10.38	41	236	36.3
13	FS	1.265	29.50	8.13	41	493	39.1
14	FS	1.265	29.50	5.88	43	450	45.7
15	FS	1.265	29.50	5.88	84	563	52.1
16	FS	1.265	29.50	3.63	45	375	54.2
17[a]	FS	1.265	29.38	10.50	45	515	33.4
18[a]	FS	1.265	29.38	10.50	44	523	33.8
19	FS	1.265	29.50	3.63	86	450	59.0
20	FS	1.265	29.50	10.38	41	545	35.1
21	FS	1.265	29.50	10.38	87	680	41.3
22	FS	0.690	29.50	10.38	40	285	34.0
23	FS	1.265	24.25	10.38	41	462	36.0
24	FS	1.265	24.25	10.38	87	540	40.3
25	FS	1.265	18.25	10.38	42	320	33.7
26	FS	1.265	12.25	10.38	43	280	41.1
27	FS	1.265	12.25	10.38	87	415	52.2
28	FS	1.265	29.50	8.13	86	635	46.3
29	CS	1.265	29.50	10.38	51	760	44.5
30	CS	0.259	29.50	10.38	25	240	56.6
31	CS	1.265	29.50	10.38	37	740	43.7
32	CS	1.265	22.75	10.38	36	700	49.5
33	CS	1.265	16.63	10.38	38	660	56.5
34	CS	1.265	10.63	10.38	35	620	65.8
35	CS	0.690	29.50	10.38	43	500	49.8

NOTE: Tests 17 and 18 were performed with Tensar grid type SS1.

TEST RESULTS

The results of the 35 pull-out tests are given in Table 2. All tests but Tests 17 and 18 were performed with Tensar grid type SS2. Tests 17 and 18 were performed using Tensar grid type SS1. In the table, the following terminology is used:

Soil = soil type tested,
CS = coarse sand,
FS = fine sand,
q = normal stress (psi),
L = length of embedment (in.),
W = width of reinforcement (in.),
D_r = relative density of sand before loading (percent),
P = maximum pull-out force (lb), and
δ = average friction angle between soil and grid.

DISCUSSION OF RESULTS

All tests were performed at stresses in the working range of the grids tested. In only 1 of the 35 tests did the grid break, causing a very sudden loss of pull-out force. Test 19, during which the grid broke at a tensile force of 68 percent of the material's ultimate strength (according to the manufacturer), was the test with the highest stressed grid sample. To avoid damage to the equipment, no deliberate attempts to reach the ultimate strength of the grids were made.

Effect of Normal Stress

From the study of the effect of normal stress on pull-out resistance, it was found that, for each soil type tested, pull-out stress is directly proportional to normal stress. Figure 5 is a graph of pull-out stress versus normal stress; the figure shows the results for the loose fine sand, the dense fine sand, and the coarse sand. These results compare well with the results presented by Ingold (*9*), except that the plot presented by Ingold had a concave down curvature at the low-stress end.

The same results presented as friction angle (δ) between the soil and the grid versus normal stress are shown in Figure 6. The coarse sand, because of its large pull-out resistance, was only tested at normal stresses below 1.5

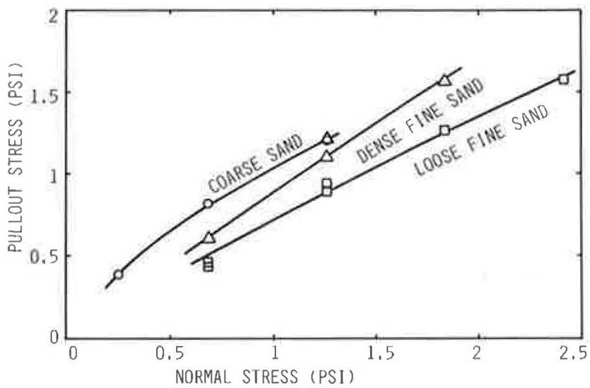

FIGURE 5 Pull-out stress versus normal stress.

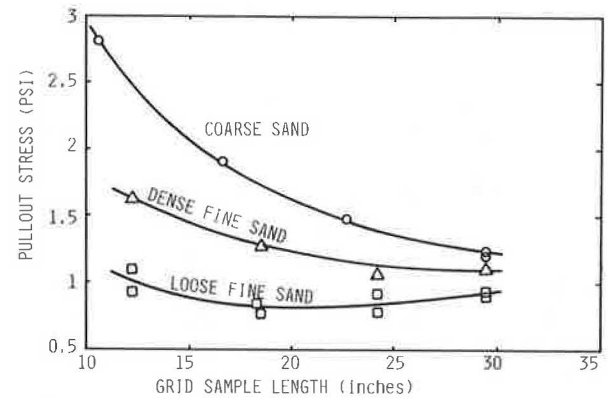

FIGURE 7 Pull-out stress versus grid sample length.

psi. Higher normal stresses would have resulted in pull-out forces approaching the ultimate strength of the geogrid. The results indicate that the friction angle tends to decrease toward the friction angle of the soil as the normal stress increases. This result is also in agreement with the results presented by Ingold. Inspection of Figure 6 shows that for the dense and loose fine sand the normal stress has less effect on the friction angle than for the coarse sand.

An assumption common to all design procedures studied is that pull-out stress is directly proportional to normal stress.

Effect of Grid Specimen Embedment Length

To study the effect of embedded length, several grid specimens, all the same width but of various lengths, were tested. All tests were at the same normal stress. The results are shown in Figures 7 and 8. Tests in loose fine sand showed a nearly constant pull-out stress for all embedded lengths. The friction angle (δ) from the length study on the loose sand showed a slightly decreasing trend, very near the friction angle of the soil alone. The same plots for the dense fine sand and the loose coarse sand show relatively high pull-out stresses (or friction angle) for short lengths that decrease to a constant value as the length increases. The friction angle decreases to a value slightly above that of the friction angle of the soil alone.

The curved, decreasing nature of the curves for the length study on the dense fine sand and the coarse sand is probably due to the extensibility of the grid reinforcement. A curve presented by McGown et al. (*11*) may be used to approximate the deformation of the grid material due to the stress levels present. For example, if a force of 600 lb is transferred by a grid 29 in. long and 10.4 in. wide held only at the ends, the specimen will elongate about ½ in. Given this, it is supposed that as the average pull-out stress in the grid reinforcement reaches higher values, the extensibility of the grid starts to play a more important role. For example, in the length study tests with the loose sand, the stress levels remained in a range slightly less than 1 psi, which indicates that the extensibility of the reinforcement plays only a minor role, if any. For the length study tests with the dense fine sand and the coarse sand, the frictional resistance is high enough at smaller lengths to produce large pull-out stresses. Over the short embedded length, there is not enough accumulated strain to cause the amount of mobilized soil strength to be appreciably different from one end of the grid specimen to the other. Therefore the soil at each grid member reaches its peak resistance at the same time. But, as the length of the grid specimen increases, the extensibility of the material plays a more important role. As the length of the specimen

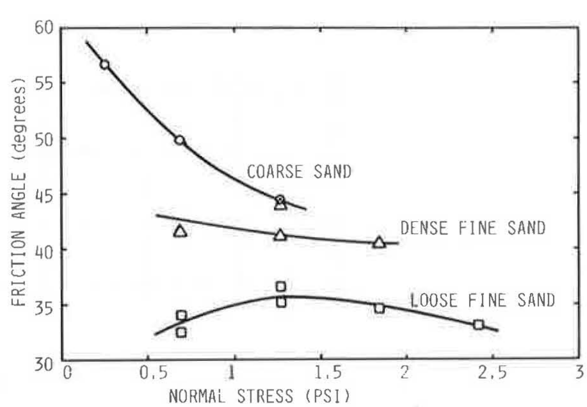

FIGURE 6 Friction angle versus normal stress.

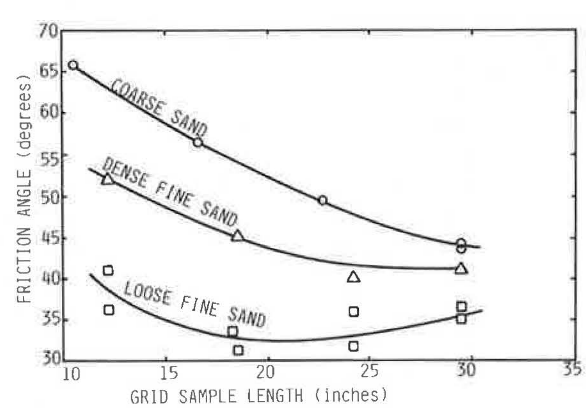

FIGURE 8 Friction angle versus grid sample length.

increases, the average pull-out stress (and also the δ angle) was observed to decrease.

It is hypothesized that, for the longer specimens, the geogrid deforms such that, as the pull-out test is performed, the embedded end does not contribute much to pull-out resistance because it has not been strained enough to mobilize the full strength of the soil surrounding it. The end of the specimen near the clamping device moves far enough to mobilize the full strength of the soil and possibly pass over a peak strength to a lower residual strength value. This will occur if the soil reaches its peak strength at a relatively low strain as does dense sand or angular material that exhibits dilatant behavior on straining. The grid material in the middle of the specimen is in some intermediate condition—the material is being stretched and is mobilizing at least part of the full soil strength. The maximum pull-out stress for the longer grid specimen will be lower than for the shorter specimens because the soil at some members will be past the peak strength.

As the embedded length of geogrid specimen in a dilatant soil increases, the variation in strain over the length of the specimen increases, which means that the soil surrounding a larger percentage of the grid members will have passed its peak strength. Thus the longer the specimen, the lower the average maximum pull-out stress. However, each successive increment of length increase results in a smaller decrease in pull-out stress until an almost constant value is approached.

Assuming that this soil-geogrid interaction mechanism is correct leads to the conclusion that, for a given soil condition, the stiffer the geogrid material, the longer the specimen must be to reach constant pull-out stress.

Effect of Grid Specimen Width

Specimens of geogrid of various widths but the same length were used to study the effect of width of reinforcement on pull-out resistance. The tests were performed on the fine sand in both the loose and dense condition. It was found that as the width increases, the pull-out stress decreases toward a constant value for the given normal stress level. If represented as friction angle versus width of reinforcement, the shape of the curve is the same with the friction angle decreasing, as specimen width increases, to a constant value that is very near the friction angle of the soil alone (Figure 9).

The shape of the curves from the width study can be qualitatively explained if the pull-out resistance of grids is broken down into two components. The first component is the passive resistance offered by the grid members perpendicular to the direction of pull-out. The second type of resistance is the frictional resistance that is offered by the grid members parallel to the direction of pull-out (Figure 10). In the tests performed, all grid specimens were cut such that no partial grid members were at the edges (i.e., sides) of the specimen. Grid members parallel to the direction of pull-out were at the extreme edges of the specimen, and, at the embedded end, grid members perpendicular to the direction of pull-out were at the extreme edge.

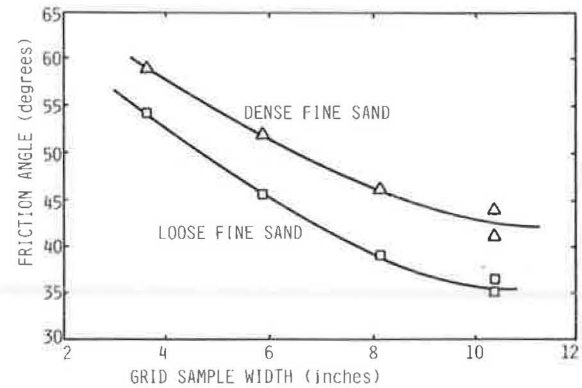

FIGURE 9 Friction angle versus grid sample width.

Suppose that pull-out tests are performed on a grid specimen one grid wide (one row of grid members perpendicular to the direction of grid travel and two rows of grid members parallel to the direction of travel). If the grid specimen width were doubled, the area of the grid members perpendicular to the direction of grid travel would also be doubled. This would cause the passive portion of the pull-out resistance to double. But doubling the specimen width only increases the total area of the grid members parallel to the direction of pull-out by 50 percent (from two rows to three rows). Similarly, if the width of the original one-grid-wide specimen were tripled, the area of the grid members perpendicular to the direction of pull-out would triple (from one to three rows), but the area of the parallel members would only double (from two to four rows). The passive resistance would triple and the frictional resistance would only double.

The data in Figure 9, then, indicate that the effect of the varying proportional contributions of the two components of pull-out resistance on total pull-out resistance is to cause pull-out stress to decrease with increasing width of grid specimen.

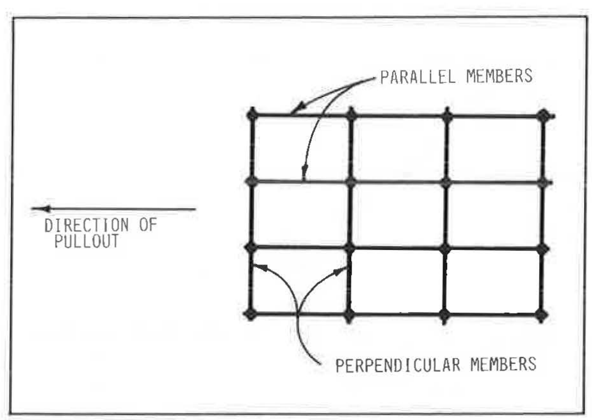

FIGURE 10 Grid sample configuration.

Effect of Soil Density

The effect of soil density on pull-out resistance is shown clearly in Figures 5–9. An increase in average relative density of the fine sand from 41 to 87 percent gave increases in the friction angle between the reinforcement and the soil of anywhere from 5 to 14 degrees. It appears that, for working sizes of reinforcement, the difference in friction angle (δ) is probably near the difference in the friction angle for the soil alone (i.e., 6 degrees). It was interesting to note that the pull-out force versus displacement curves from the pull-out tests on the dense fine sand had pronounced peaks, as did the stress-strain curves of dense fine sand in the triaxial shear tests. After the pull-out force reached a peak, it approached a smaller, residual value. The pull-out test curves from the tests on the loose fine sand exhibited no peaks.

Effect of Grid Type

Two pull-out tests were performed using a slightly lighter-weight Tensar grid. Grid type SS1 is the same size as type SS2, except that the thickness of the cross members is 40 percent less and the thickness of the junctures is 37.5 percent less. The decrease in cross-sectional area of the grid resulted in a decrease of pull-out resistance of about 7 percent. Although the results of the tests compared (Tests 1, 2, and 21 versus Tests 17 and 18) were consistent, a further study was not done because of the modest difference in pull-out resistance. The result does give some support to Ingold's hypothesis (*9*) that pull-out resistance is a function of the grid area normal to the direction of pull-out.

CONCLUSIONS

The results of laboratory pull-out tests using Tensar SS1 and SS2 geogrids in sand show that pull-out stress is a function of normal stress, relative density of the sand, angle of internal friction of the sand, the three-dimensional structure of the geogrid, and the dimensions of the geogrid specimen. A soil-geogrid interaction mechanism has been described and used to explain the results of the pull-out tests.

In the field the embedded area of geogrid is likely to be large enough that stretching will cause the pull-out stress to approach some minimum value, as demonstrated by the pull-out tests reported. Thus, if laboratory tests are performed on specimens too small to include this effect, the pull-out stress will be overpredicted, which will lead to unsafe design. This is most likely to happen with stiff geogrid material in a dilatant soil.

The significance of the results of this study is that when conducting laboratory pull-out tests to obtain friction angles for design of geogrid-reinforced structures the effect of the stress-strain behavior of the soil and the extensibility of the geogrid must be taken into account when choosing the size of geogrid specimen to test. The maximum dimensions of geogrid specimens used in the present study appear to be barely large enough to meet these criteria.

For the Tensar SS2 geogrid, the soil-geogrid friction angle (δ) approaches the angle of internal friction of the soil used in the pull-out tests. It could therefore be concluded that, for field conditions using the same geogrid and the same soil, the design δ could be taken equal to the angle of internal friction of the soil as determined by drained triaxial tests.

In comparison, Ingold (*9*) reported that, for pull-out tests using smaller specimens of a much stiffer geogrid and much higher normal stresses, δ was about 10 degrees greater than the angle of internal friction of the soil. This higher difference between δ and ϕ may be due partly to the different geometry of the geogrids used in the two studies. The difference could also have been caused because the short length of geogrid specimen used by Ingold did not meet the criteria proposed in the present study.

The lower values of normal stress used in this study, compared with those used by Ingold, are appropriate because the geogrid used in this study had much lower strength than did that used by Ingold.

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