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Laboratory testing and model studies of friction in reinforced earth

Etude du frottement dans la terre armée par essais de laboratoire et modèles

La détermination correcte du frottement sol-armature est l'une des composantes les plus importantes de l'analyse et du dimensionnement des structures en terre armée. En effet, la valeur du frottement developpé le long de l'interface sol-armature, sur une large étendue, détermine la quantité d'armature (c'est-à-dire la largeur, la longueur et l'écartement des bandes) requise dans le sol. Pour cette raison, le frottement sol-armature influence de manière significative, et la stabilité et l'économie du projet définitif.

Cet article présente les résultats d'une étude paramètrique concernant le frottement des systèmes sol-armature. Aussi bien des essais en laboratoire (y compris essais de cisaillement et de traction) que des essais sur modèles (utilisant des éléments à face rigide et flexible) ont été effectués. Ainsi il a été trouvé que l'essai de traction était le moyen de représentation le plus précis du comportement à la friction pour un modèle sol-armature en laboratoire.

Introduction

The concept of reinforced earth, as explained by Vidal (9), is essentially the addition of a cohesion property to the soil. This cohesiveness arises from the development of friction between the soil grains and the reinforcement. A correct determination of the soil-strip frictional behavior is, therefore, among the most important considerations in the design and analysis of a reinforced earth structure. The amount of friction developed along the soil-strip interfaces will, to a significant extent, control the amount of reinforcement (i.e., the strip width, length, and spacing) required in the soil mass. For this reason, the soil-strip frictional behavior significantly influences both the stability and the economy of the final design.

At the ASCE 1978 Spring Convention in Pittsburg, the subject of soil-strip frictional behavior was widely discussed. However, to the surprise of many, little or no agreement was reached. It was learned that the coefficient of friction at the soil strip interface, or angle of skin friction, ϕ_μ, measured in the field often differs from that obtained in the laboratory; and the values obtained in the laboratory differ depending upon the method. Furthermore, both of these data often differ quite drastically from the values of the coefficient of wall friction which are normally assumed in soil-structure interaction problems. The study reported herein summarizes the results of recent research on the frictional behavior of soil-strip systems. Both laboratory tests (including direct shear and pull-out tests) and model tests (using rigid and flexible wall facing elements) were employed. The conclusions drawn from this study are limited to the scope of this investigation. However, discussions which pertain to the overall frictional behavior of soil-strip interactions are also presented.

Laboratory Testing

Two types of laboratory tests were employed in this investigation. These were the conventional direct shear test and the pull-out test. The soil used in the laboratory tests was a uniform, fine, river sand, consisting mainly of sub-rounded particles with a medium grain size of 0.49 mm. This sand had a uniformity coefficient of 1.40 and was, in all cases, placed in a "dense" state, such that it had a dry unit weight of 1.60 gm/cm^3 and a relative density of 90%. The reinforcing elements used in these tests were made of 0.1 mm thick steel shim stock with a yield strength of approximately 4.14×10^5 kN/m^2 and an ultimate stength of 5.52×10^5 kN/m^2. The surface of the steel was polished to a smooth mirror finish.

A). Direct Shear Tests

The angle of internal friction of the sand was determined by means of direct shear tests. Be performing these tests under normal pressures of 21 to 110 kN/m^2, the angle of internal friction was found to be approximately 31°.

To determine the coefficient of friction at the soil-strip interface, the steel was mounted on a 6.35 cm diameter, 1.30 cm thick circular phenolic laminate block which was cut to fit inside the direct shear apparatus. Once this "steel block" was placed in the bottom half of the shear box, the sand was poured into the top half of the box and then compacted to the desired dry density. The results of these tests are shown in Figure 1. As may be seen, the angle of skin friction at the soil-strip interface was found to be approximately 21°.

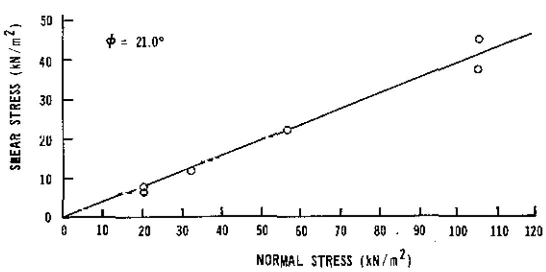

FIG 1 Soil-Strip Friction by Direct Shear Tests

B). Pull-out Tests:

A pull-out testing apparatus was specially constructed for this investigation. The system consisted of a constant strain pulling motor, a laboratory constructed load cell for measurement of the pulling force, and a strong box which held the sand backfill. A Tinius-Olsen testing machine was used to apply the normal pressures, and an air bag was placed between the loading ram and the top of the backfill in order to ensure that these pressures would be evenly distributed. By varying the magnitude of the applied normal pressure, an average value for the angle of skin friction could readily be obtained. A general view of the pull-out testing apparatus is shown in Figure 2. A detailed description of the apparatus and testing procedures is given by Mitchell (6).

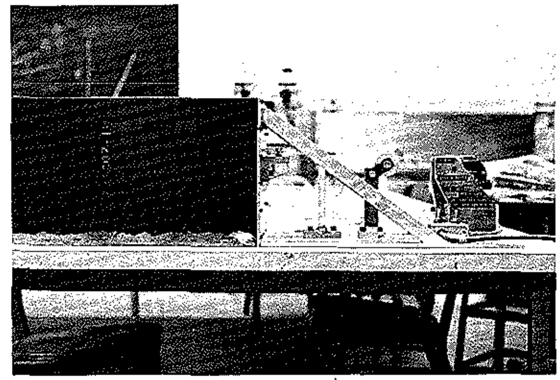

FIG. 2 General View of the Pull-Out Testing Apparatus

An extensive series of pull-out tests was performed on the smooth steel strips described earlier under normal pressures ranging from 6.9 to 103.5 kN/m^2. Tests were conducted using strips of various lengths (39.12 cm, 31.50 cm, 23.88 cm, and 16.26 cm) and various widths (1.27 cm, 2.54 cm, and 5.08 cm). The testing procedure consisted of first placing the strip in the box and loading it to the desired normal pressure. The strip was then pulled out at a constant rate of strain, while both the pulling force and lateral displacement were measured. The data from a typical test is shown in Figure 3. The angles of skin friction obtained from the various pull-out tests are summarized in Table I. By comparing these 12 values, one may investigate the dependence of skin friction angle on strip length and strip width. The variation with length appears to be random, and is probably within the bounds of experimental error. The variation with width appears to follow a slight trend towards increasing values with increasing width. However, the scatter in the data masks any definitive relationship for such a variation. It may be noted that the scatter between different strip sizes is relatively large, whereas the scatter for each individual strip is only slight. Because of this, it may be proposed that different beddings (each strip is placed in a new bedding of sand) or any other factors associated with the local environment of the strip can change the measured skin friction angle by up to 2°.

It was postulated that these differences could be due to the presence of waves or undulations in the backfill strip. In order to investigate this effect, tests were conducted on a long strip (39.12 cm) which was formed into a given wave shape before being placed in the backfill. Before the strip was placed in the pull-out apparatus the sand bedding was formed into the same shape (the amplitude and frequency of the waving were 0.64 cm and 0.91 cycles per cm respectively). The results of such a pull-out test under different normal pressures are shown in Figure 4. It is apparent that undulations in a strip while it is in a soil backfill can have a dramatic influence on the measured angle of skin friction. For the test which is documented in Figure 4 there was an initial increase in ϕ_u of 18° and an average increase of 8°. The reduction in the angle of friction with increasing normal pressure can be related to a possible straightening out of the strip as the test proceeds through higher normal pressures. Ideally, the bedding should be reset to the initial amplitude and frequency for each normal pressure to obtain proper quantitative results.

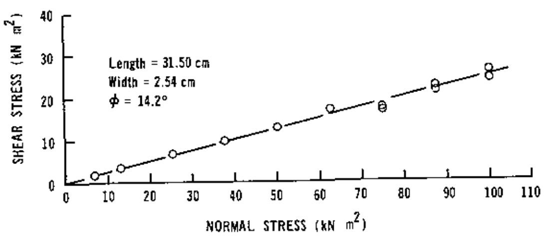

FIG 3 Soil-Strip Friction by Pull-Out Tests

Length (cm) \ Width (cm)	1.27	2.54	5.08
39.12	11.9	16.5	15.7
31.50	12.4	14.2	16.2
23.88	12.6	14.1	15.5
16.26	13.0	14.1	14.1

TABLE I

Angles of Skin Friction from Pull-out Tests

The strips used in the model tests to be described later were identical to the 2.54 cm wide strips except that they were instrumented, with strain gages, wires, and lacquer along their surfaces. In order to determine if this coating changed the skin friction angle, pull-out tests were also performed on these instrumented strips. From the strain gage readings, the force distribution over the length of the strip was calculated and plotted for different normal pressures. A typical plot is shown in Figure 5. In addition, the angle of skin friction for each normal pressure was also calculated. These values are given in Table II. While there is a distinct trend towards lower friction values at higher normal pressures, it appears as though the coated strips with their rougher surfaces have angles of friction which are approximately 5° higher than those of the uninstrumented strips.

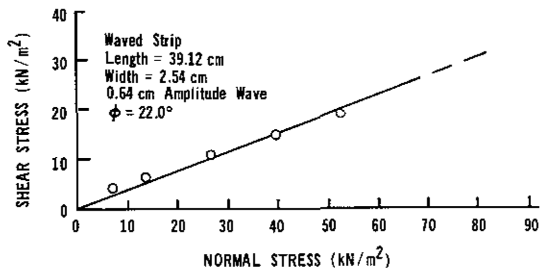

FIG 4 Soil-Strip Friction by Pull-Out Tests on an Undulated Strip

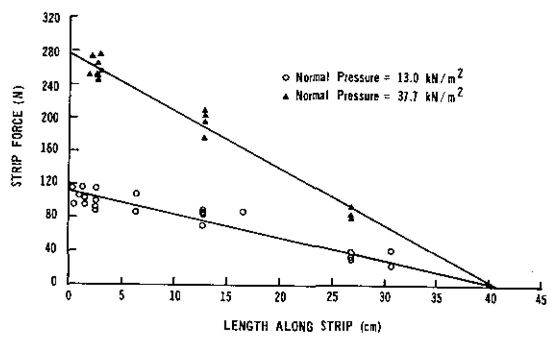

FIG 5 Strip Force Distribution Along the Length in a Pull-Out Test

Normal Pressure (kN/m^2)	6.8	13.0	25.3	37.7
Skin Friction Angle (Degree)	26	22.2	19.6	19.2

TABLE II

Angles of Skin Friction for Coated Strips

Model Testing

The model tests performed in this study were housed in a 76.20 cm square, 45.72 cm high box. The actual model was 60.96 cm deep, 76.20 cm wide, and 40.64 cm high. Two types of facing elements were used to retain the reinforced earth backfill. The first was a "rigid" 2014 T4 aluminum plate, 0.32 cm thick, 40.64 cm high, and 72.39 cm wide. The second was a "flexible", 0.25 mm thick mylar sheet. Two pins were placed between the rigid facing plate and the bottom of the box and cotton was placed at its sides in order to minimize any frictional effects at the boundaries. The Mylar sheet was turned in at the sides and the bottom to prevent the sand backfill from pouring out, and its high flexibility made the boundary effects negligible on the interior instrumented strips. The box itself was lined with Marlite to further reduce any boundary friction.

The strips used in model tests were 48.26 cm long, with 2.54 cm outside the model and 45.72 cm in the backfill. The strip was secured to the facing plate by bolting the outside portion to an angle which was riveted to the facing. A total of 20 steel strips were placed in the backfill at a vertical spacing of 10.16 cm, starting 5.08 cm up from the base of the box, and a horizontal spacing of 15.24 cm, center to center. The strips in the center column were all instrumented so that the stress distributions along the length of those strips could be measured. Strain gages were located at four locations along each strip, as shown in Figure 6. Both the construction and the testing of the models are described in detail by Mitchell (6).

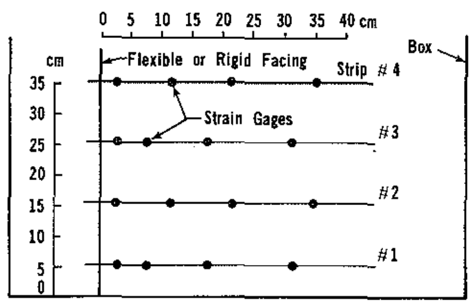

FIG 6 Locations of Strain Gages in Model Tests

Four complete model tests were carried out with both the rigid and flexible facings. In each of these tests the model was first constructed and then loaded, with the surcharge pressure ranging from 4.8 to 34.5 kN/m^2. In order to simplify the analysis of the strain gage data, each of the gages was zeroed at the end of construction. This places the same incremental normal stress at each location when analyzing the incremental change in stress. Typical plots of the strain gage readings over the length of the strip for different normal pressures are shown in Figures 7 and 8 for flexible and rigid facings, respectively. The strain gage data was fit to a third order polynomial.

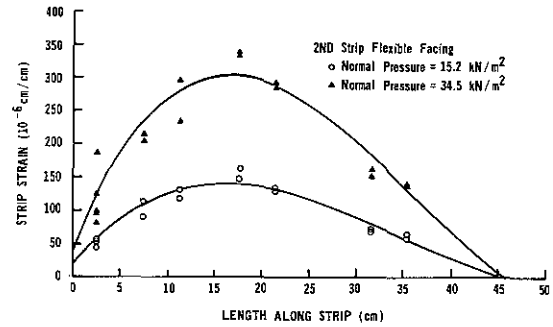

FIG 7 Tensile Strain Distribution Along the Strip Length for Flexible Facing Model

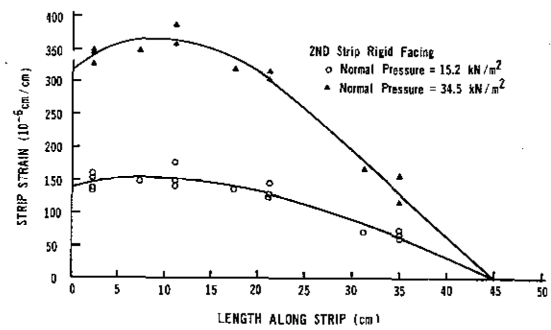

FIG 8 Tensile Strain Distribution Along the Strip Length for Rigid Facing Model

If the free end of the strip is assumed to be slipping with constant horizontal and vertical soil stresses along the length of the strip, then the force gradient from the free end of the strip will be linear with its maximum value defined by the maximum coefficient of skin friction. Nonlinearities in the force gradient along the length from the free end may be caused by variable soil stresses, edge effects and incomplete mobilization of full friction. However, using the strips which exhibit the maximum gradients which are essentially linear in nature (assuming slipping is occurring) allows one to back-calculate the associated maximum angle of skin friction. This has been done for appropriately selected strips and the various values are given in Table III.

Facing	Strip Number	Normal Pressure (kN/m^2)	
		15.2	34.5
Flexible	1	17.3	16.2
	2	21.3	21.0
	3	23.2	22.5
	4	22.1	21.0
Rigid	1	15.6	16.2
	2	23.2	21.2
	3	19.9	20.6
	4	20.9	20.0

TABLE III

Angles of Skin Friction from Model Tests

Discussion

A given soil and reinforcing material should have a unique angle of skin friction and the fact that different investigators and different tests methods yield different values of skin friction implies that all reported values should be termed "apparent angle of skin friction." Since many researchers (2, 3, 4, 5, 7, 8) report different values, the "apparent angle of skin friction" is clearly highly dependent on the test method by which the value is measured. It has been suggested that arching, dilation, boundary conditions, soil compaction, and the length, width, and undulation in the strips may all affect either the magnitude and distribution of normal pressure or the resistance to shearing at the soil-strip interface. Normally, these factors are not explicitly accounted for when calculating the "apparent angle of skin friction." However, in discussing the results of the present study, the possible influence of the above mentioned factors will be considered.

As may be seen in both Figure 5 and Table II, the coated strips tend to exhibit lower friction values at higher normal pressures. It is possible that this trend is the result of dilation. It may be postulated that the smooth strips actually slide out of the sand while hardly disturbing the sand grains, while the rougher, coated strips, with all their protrusions, cause shearing to occur in the soil itself as well as at the soil-strip interface. This dragging of the sand grains by the strip causes dilation. If dilation occurs in the shear zone, both the normal pressure and friction angle will increase during shear. The fact that dilation is more pronounced at lower normal pressures thus possibly explains why the coated strips exhibit higher friction angles at lower normal pressures.

Material	Direct Shear	Pull-Out	Model
Uncoated Steel Against Sand	21°	12.5° (1.27 cm wide) 14.7° (2.54 cm wide) 15.4° (5.08 cm wide)	
Coated Steel Against Sand		20.3° (2.54 cm wide) Variation with Normal Pressure from 19° to 26°	21.1° (Rigid Facing) 21.9° (Flexible Facing)

TABLE IV

Summary of Angle of Skin Friction Values

Upon examining Figures 7 and 8 it becomes obvious that the rigidity of the wall has a very significant effect on the strip stresses and wall pressure. The flexible facing allows the soil to strain locally near the facing closer to the active state, thus reducing the strip force at the facing and causing a force gradient as the strip extends back into the soil. The rigid facing, on the other hand, deflects much less than the flexible one, causing the soil to exert considerable pressure on the facing which is then transferred into the strips at the connection. The "apparent angle of skin friction", as calculated from the friction build-up near the free end in the strips, varies between 20° and 23° for the 2nd, 3rd, and top strips. In the bottom strips, however, this value varies between 15.6° and 17.3°. These lower values are probably a result of boundary effects which cause the stress and strain patterns to only partially mobilize the friction.

It is also significant to note from Figures 7 and 8 that the way in which friction is mobilized along the length of a strip bears a strong resemblance to the frictional forces which are developed in a pull-out test; that is, the stress (or force) is zero at the free end and builds up gradually to a maximum at a rate depending upon the overburden pressure and the frictional behavior at the soil-strip interface. It therefore appears as though the pull-out test is the more appropriate testing method for estimating frictional behavior in reinforced earth masses.

Conclusions

The angles of skin friction as determined by the three different types of tests described in this study are summarized in Table IV. It may be noted that the relatively low friction angles which were exhibited by the bottom strips in the model testing were not entered. Based on these tabulated values, the following general conclusions may be stated: 1). For the smooth, flat steel strips, the angle of skin friction as determined by the direct shear apparatus is greater than that obtained from the pull-out test data. 2). Except at very low normal pressures, the results of pull-out tests on the coated strips agree well with the model test results. This suggests that the pull-out test, and not the direct shear test, should be used to determine the frictional behavior of the soil-strip interaction. Additional support for this contention comes from a finite element analysis by Al-Yassin and Herrmann (1). By analyzing the rigid facing model they found very good agreement between the model test data and the analytical results when the angle of skin friction as determined by pull-out testing was used. 3). The in situ frictional behavior at the soil-strip interface is affected by many factors. Hence, it is difficult, if not impossible, to quantify all contributions to the field frictional behavior of reinforced earth. Judging from the present state of our knowledge on this subject, it appears as though the angle of skin friction as determined by the laboratory pull-out test under average field normal pressures may be used as the lower bound value for reinforced earth design and analysis. If appropriate, it is possible to compensate for this conservativeness by using a relatively small factor of safety against the pull-out failure mode in the stability analysis.

Acknowledgements

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