Measurement of Soil/Reinforcement Interaction

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SUMMARY Parameters of soil/reinforcement friction and adhesion are generally determined in direct shear tests or pull-out tests, or are deduced from the interaction of the behaviour of models or full-scale structures. The results obtained show a large variation and are significantly affected by the placement condition of the soil, the geometry of the reinforcement and the method of testing. Direct shear tests performed allowed measurements of the thickness of the shearing zone, the relative slip and the rate of dilatancy. Preliminary results presented indicate that this type of experiment can contribute to the understanding of the mechanism of soil/reinforcement interaction.

1 INTRODUCTION

The evaluation of the friction or adhesion between soil and structural elements has always been a significant problem in civil engineering. It is of particular importance in the design of pile foundations, caissons, conventional retaining walls, tie-back anchors and, most recently, reinforced earth and similar construction techniques.

The analysis of the internal stability of reinforced earth structures considers two basic causes of failure: slippage between the soil and the reinforcement and rupture of the reinforcement. Both cases require an estimate of horizontal earth pressures. Field measurements have shown that these generally correspond to at-rest pressures near the top of a wall and active pressures further down, reflecting the wall deformations which occur during construction. Since the strength properties of the reinforcements are known, the rupture mode of failure can be analysed with reasonably reliable data for the predominantly cohesionless soils used.

Considerably greater uncertainties are involved in the evaluation of failure by soil/reinforcement slippage, also interpreted as failure by pull-out. Many designers and researchers are of the opinion that values of the soil/material friction angle δ as obtained in a modified standard shear box give a conservative assessment of the potential shear resistance between granular material and reinforcement. However, some experimental data appears conflicting and it is the aim of this paper to present and discuss recent findings from laboratory and field studies and indicate avenues of further research, with special consideration given to the direct shear test.

2 DETERMINATION OF SOIL/MATERIAL FRICTION ANGLE

2.1 Direct Shear Tests

Most commonly soil/material or "skin"-friction characteristics are evaluated in a direct shear box. Although the state of stress in the soil is not completely known in this form of testing, its results have generally been adopted as reference values for comparing data obtained from other laboratory or field investigations and for specifying design criteria. For preliminary design purposes, the friction angle between soil and construction materials is often assumed to be between 1/2 and 2/3 of the internal friction angle.

Figure 1a shows the typical arrangement of materials for measuring skin friction such as used in the original comprehensive work by Potyondy (1961) and more recently by Schlosser and Long (1975) in an effort to establish basic design criteria for reinforced earth. Particularly for testing the friction between soil and flexible fabric-type reinforcement, the choice of support material in the lower half of the box is important, as demonstrated by Delmas, Gourc and Giroud (1979).

In an attempt to simulate the development of shear resistance along cylindrical anchors, Wernick (1978) developed a direct shear box where the two halves

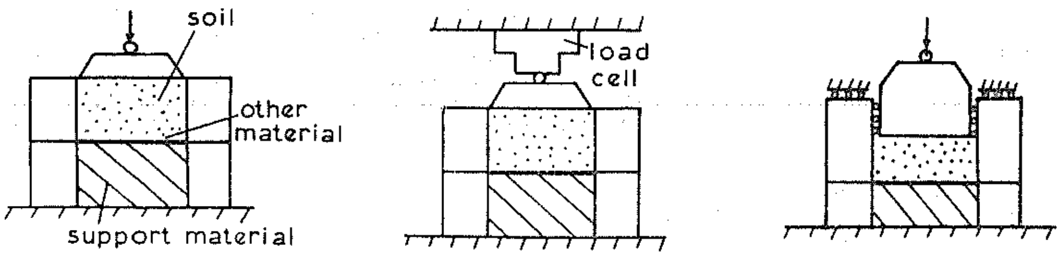

Fig. 1a Standard direct shear box Fig. 1b Constant volume type shear box Fig. 1c "True shear" apparatus after Wernick (1978)

Figure 1 Typical direct shear test arrangements are forced to move exactly parallel to each other and where the vertical force is induced by a non-tilting loading cap block (Figure 1c). The kinematic conditions in Wernick's "true shear apparatus" are similar to that in a conventional ring shear apparatus but unequal rates of shear strain in the failure plane are avoided. This apparatus proved particularly useful to measure dilatancy characteristics of sand.

Using an apparatus similar to that shown in Figure 1b, Guilloux, Schlosser and Long (1979) were able to monitor the variation of σ during direct shear at constant volume. A medium to fine dense sand which yielded an internal friction angle $\phi = 43^0$ in the standard test with σ = constant indicated a friction angle $\phi_c = 34^0$ at constant volume shear, while the normal stress increased more than twentyfold. However if the shear resistance was related to the original normal stress $\sigma_0 = 50$ kPa, an apparent friction angle of $\phi^* = 85^0$ was obtained. The difference between ϕ and ϕ_c was attributed to dilatancy.

For sand sliding on reinforced earth type smooth steel, the skin friction angle determined with σ = const. was $\delta = 26.5^0$. At constant volume, in contrast to the sand only tests, the skin friction angle increased slightly to $\phi_c = 31^0$. Guilloux et al concluded that in this case dilatancy was insignificant.

Apparent friction angles ϕ^* as computed by Gilloux et al lend themselves to be compared to friction angles backfigured from pull-out tests, where the normal stress is assumed to be equivalent to the overburden pressure. As indicated by Fig. 2 the ϕ^*-values decrease with increasing normal stress and appear to give an upper bound to friction angles computed from full-scale pull-out tests.

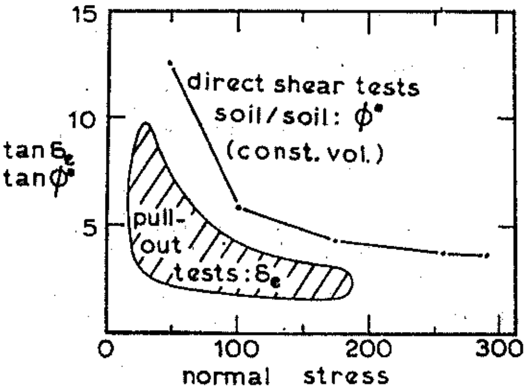

Figure 2 Apparent friction for constant volume conditions (Guilloux et al, 1979)

2.2 Pull-Out Tests

Vidal (1969) conceived reinforced earth as a new composite material in which a perfect bond between soil and reinforcement exists prior to failure. Reflecting this view, early design methods for reinforced earth walls assumed that frictional resistance developed along the entire length of the reinforcing strips contributes to the internal stability of the wall. In contrast, Lee et al (1973) thought that the earth pressure acting on the face elements is balanced by the pull-out resistance of the strips (or "ties") over that part of their total length which is beyond the potential failure wedge in the soil mass. Lee's concept of reinforced earth action led to a comprehensive program of pull-out tests in laboratory conditions and full-scale structures in the field.

A large range of results are now available, from small scale tests with less than 0.6m overburden to pull-out tests of dummy strips embedded in the backfill during the construction of full-size walls. Tie materials tested include standard reinforced earth galvanized steel strips, conventional reinforcing bars, bar mesh, mylar tape, geotextiles and other experimental materials. Tie dimensions, overburden pressure and soil characteristics are the principal variables in this research work. Pull-out resistance was also found to be affected by soil vibration. In some types of tests, the peak pull-out force required was significantly higher than the ultimate (or residual) resistance. In some large scale tests, the distribution of tie forces was recorded during pull-out.

Pull-out test results can be interpreted in terms of an "equivalent" (or "apparent") surface friction angle δ_e if it is assumed that the shear resistance is uniformly distributed along the strips and that the normal stress corresponds to the weight of the overburden plus any surcharge applied. This interpretation neglects the possible significance of relative strains between the soil and the reinforcing material and the possibility of arching.

Typical test arrangements are shown in Fig. 3. Most laboratory tests have been carried out by pulling strips out of a simple box as shown in Fig. 3a. Strips can be pulled through a rigid or flexible wall, or even without any restraint in front of the box (Chang et al, 1977), out of a soil mass of carefully controlled density, with or without surcharge on top. A sleeve may be provided to reduce any wall influence. Pull-out forces have also been measured on strips attached to a wall rotating outwards during the test (Hausmann and Lee, 1978) as shown in Fig. 3b. Delmas et al (1979) pulled fabrics through a modified direct shear box (Fig. 3c) in order to evaluate soil/fabric interaction.

An informative test series was conducted by Alimi et al (1977) who pulled out standard size Reinforced Earth strips from an experimental embankment with up to 2.5m overburden, using a pipe sleeve to avoid edge effects (Fig. 3d).

Fig. 3e gives typical dimension of the test sections of the Californian wall on Highway 39 (Chang et al, 1977) where pull-out of dummy strips was achieved without breakage for lengths of up to 7m under 5.5m overburden.

Generally researchers confirm that pull-out resistance is significantly affected by the placement conditions of the soil, the geometry of the strips and the mechanical arrangement of the experiments. French engineers concluded that the direct shear box yields conservative values of skin friction angles. In contrast, many American laboratory test results show that average shear resistance in pull-out can be substantially less than would be estimated from direct shear tests.

2.3 Indirect Methods

Soil/reinforcement interaction parameters can be backfigured from the results of model tests, the performance of full-size structures or from strength measurements in more basic tests such as triaxial or plane strain shear tests. Frictional properties are usually expressed in terms of angle

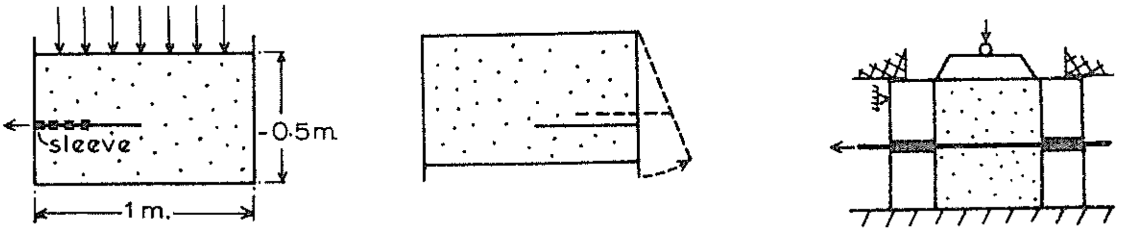

Fig. 3a Box pull-out test Fig. 3b Moving wall test Fig. 3c Modified direct shear test

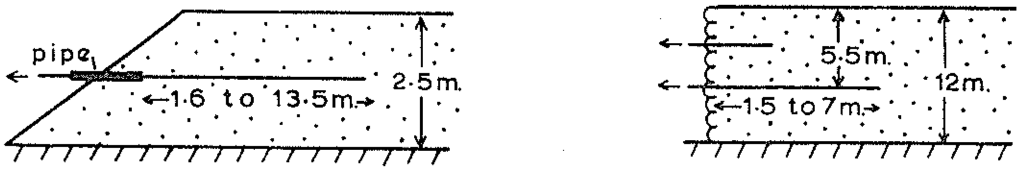

Fig. 3d Large prototype test Fig. 3e Field tests on dummy strips

Figure 3 Typical pull-out test arrangements

δ of skin friction (Alternatively called surface friction or bond stress) or a friction factor f = tan δ. For cohesive soils, adhesion s_a may be calculated and, as with δ, is often presented as fractions (or multiples) of the strength parameters of the soil alone (internal friction angle ϕ and cohesion c).

The computed values of δ or s_a are only as good as the basic assumption made in the method of analysis proposed. Actually most researchers start by assuming the validity of a particular value of δ, say as determined in a standard shear box test. In order to fit experimental data to theoretical results, it may then be hypothesised that a certain lateral stress coefficient K (usually within the range K_a to K_o) or a particular distribution of normal stress σ_v or shear stress τ (based on assumed relative displacements) applies to the soil/reinforcement interface. On the other hand, if K, σ_v and τ are seen or made to follow a specific pattern, δ (and/or s_a) can be back-figured from the test. An additional complication arises in the interpretation of laboratory size model tests, where soil may be sheared at very low confining stresses. In these conditions, the angle of internal friction ϕ of a sand may be significantly higher, say, by 10°, than the value obtained in standard triaxial tests using more "practical" higher cell pressures. A variation in ϕ has a significant effect on the values of K. Still unable to explain certain test results, researchers may then take recourse to concepts of dilatancy, arching, collapse of granular soil structure or progressive failure (emphasising the difference between peak and ultimate shear strength parameters).

Fig. 4 qualitatively compares typical shear stresses developed between mylar reinforcing material and sand in three different tests at the same overburden pressure: in strips attached to a rotating model wall, in a laboratory pull-out test and a direct shear test. Obviously the friction angles δ_e backfigured from these three tests will differ markedly, so does the general stress-strain behaviour. Fig. 4 is however only typical for the particular materials used. For rough or ribbed reinforcement, e.g., pull-out tests will likely show resistance in excess of that exhibited in direct shear.

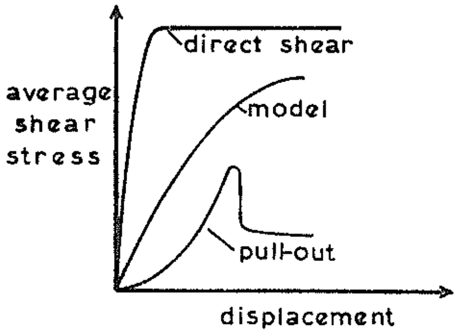

Figure 4 Shear stress between mylar and sand (typical results)

3 INTERNAL DEFORMATIONS IN DIRECT SHEAR TESTS

From the previous discussions, it can be seen that dilatancy and relative strains are significant factors affecting soil reinforcement friction. Dilatancy has already been subject of research by numerous investigators, notably Rowe (1969), Davis (1969), and Oda (1975), but experimental data is still limited.

In order to further study the dilatant properties of cohesionless soils, the authors devised a series of direct shear tests which allowed measuring the thickness of the shear zone and relative strains at the interface with another material.

3.1 Test Details

The sand used in following tests was a uniform fine sand with a sub-rounded grain. Cylindrical columns of dyed sand were formed in the shear box using drinking straws. After testing, a gelatine solution was poured into the shear box and allowed to set. The sand could then be removed and dissected to reveal the deformation pattern within the box. Most tests were carried out for two cases: (1) shear box full of sand and (2) sand sliding on a roughened plate. This plate was formed by glueing a layer of the same sand to a metal plate.

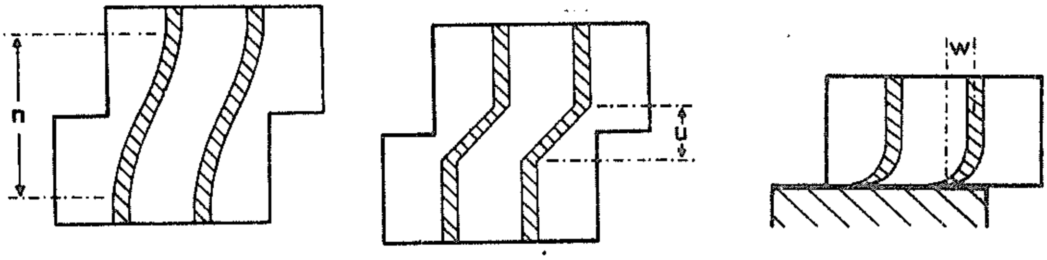

Fig. 5a Loose sand Fig. 5b Dense sand Fig. 5c Sand/plate

Figure 5 Deformation patterns in direct shear test

3.2 Test Results

The results clearly showed a marked difference between the deformation patterns obtained with a loose sand and a dense sand. Typical examples are shown in Figure 5a and 5b.

Similar patterns were found for sand sliding on a roughened plate. This is illustrated in Figure 6 where the thickness of the zone of shearing, u, is plotted against relative density. This figure shows that u for the full sand case is approximately double that for sliding on a roughened plate. The deformation pattern for this condition was found to be virtually symmetrical about the central horizontal plane of the box. Further, for the plate case, measurements of the horizontal shift as defined in Figure 5c can be used to give the relative strains at the soil/plate interface. The distance w was found to equal the shear movement applied during the test, as it would be expected for a rough plate. Rough interface behaviour was also confirmed by the friction angles computed from these tests, which are plotted in Figure 7.

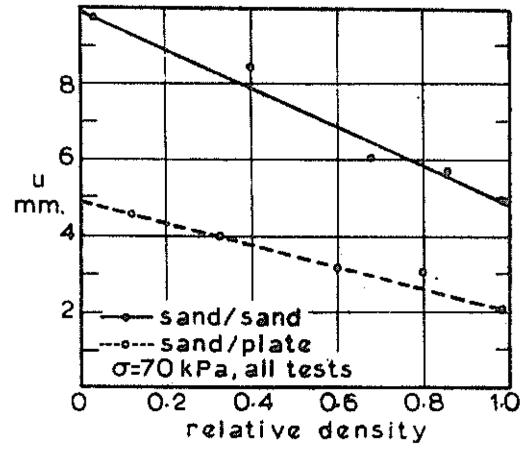

Figure 6 Variation of thickness of shear zone with density

The measure of the rate of dilatancy was taken as the maximum value of dv/dh where dv is the increment in vertical movement of the loading cap and dh the corresponding increment in shear displacement. The rate of dilatancy is plotted against relative density in Figure 8. It is interesting to note that the rate of dilatancy was approximately equal for both series of tests. The same conclusion is reached if the absolute magnitude of dilatancy is considered rather than the rate. Finally, in Figure 9, the rate of dilatancy is plotted against normal stress. The results shown include the skin friction angle δ. Its value corresponding to 1 kPa normal stress is likely to be unreliable because of the small value of shear stress obtained in this test. Also indicated is the relative amount of slip which occurred at the sand plate interface; it varies from all slip at low stresses to no slip at higher stresses.

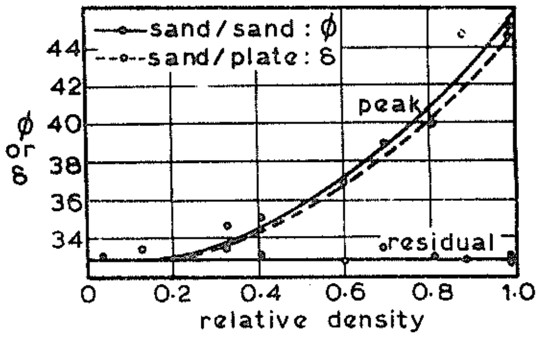

Figure 7 Friction angles as a function of density

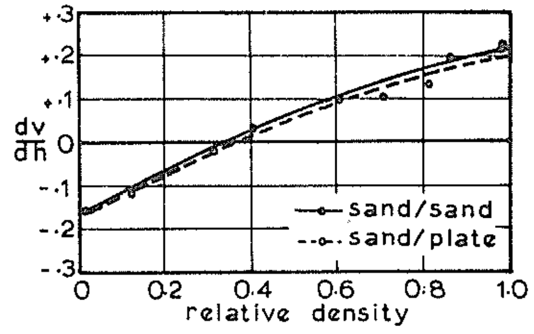

Figure 8 Variation of vertical rate of movement with density

3.3 Discussion of Results

The test results suggest that the amount or rate of dilatancy is not a function of the width of the shear zone but must be a property of the material itself and its state of density (Figures 6 and 8). Such a conclusion was theoretically reached by Oda, 1975.

If no slip occurs at the soil material interface, the skin friction angle is equal to the friction angle of the soil itself (Figure 7).

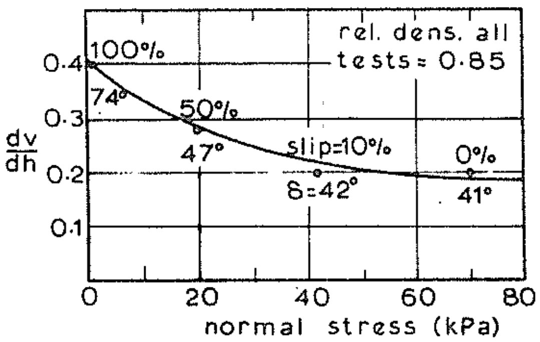

Figure 9 Variation of dilatancy, slip and friction with density

As a normal stress at the soil material interface is decreased, the amount of slip and the rate of dilatancy both increase (Figure 9). Rather surprisingly, the skin friction angle computed for low normal stresses is higher than the angle of internal friction, despite the fact more slip appears to occur. The question which must be asked is why failure does not occur within the soil itself at a lower shear stress. Kinematic restrictions of the shear box do not appear to be the answer because at higher normal stresses failure does occur within the soil. Further investigations are needed of this important low stress situation as many laboratory model tests are carried out at low stress levels.

There is a basic difference in the failure mechanism which occurs in a loose and a dense cohesionless material.

4 CONCLUSIONS

Parameters describing soil/reinforcement interaction have been obtained from direct shear tests, pull-out tests and from the interpretation of the behaviour of laboratory models and full-scale structures. The variation of the results obtained suggests that this interaction cannot be described by unique values of skin friction and/or adhesion.

Direct shear tests performed did not indicate any relationship between the thickness of the shearing zone and the rate of dilatancy. However it is felt that observing these characteristics will lead to better understanding of soil/material interface problems. The magnitude of relative strains in zones of interaction appears to be of prime importance for the interpretation of model tests and for the formulation of laws of interaction for the purpose of analysis by means of the finite element method.

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