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**Strength and deformation of partly saturated soils**

**Résistance et déformation des sols partiellement saturés**

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**SYNOPSIS:** Controlled suction tests (up to 15 MPa) on three compacted soils have been performed with the special devices developed for running oedometer, direct shear and penetration tests. Some factors affecting the time of equilibrium have been considered. The penetration tests show an increase with suction of the modulus of deformation and resistance up to a maximum. The direct shear tests show the same behaviour and indicate an apparent gentle decrease after the maximum. Ellipses of degree 2.5 reproduce very accurately the variation of shear strength with suction for the tests available.

**INTRODUCTION**

During the last decades, several researchers from different countries in the world have carried out very important works on the strength and deformation properties of partly saturated soils, which have led to the construction of a basic framework (for instance, Bishop, Alpan, Blight & Donald, 1960). In this paper a synthesis of the developments carried out in the Laboratorio de Geotecnia (CEDEX) on the subject, based on the so called axis translation technique, will be given.

The well known principle of the pressure membrane apparatus, used for the determination of the suction-water content relation, was applied to the design and construction of a suction controlled oedometer (Escario, 1969, Escario and Saez, 1973) on which the volumetric changes of soils, including collapse, can be studied up to suction values of 15 MPa. The samples used are 70 mm diameter and 20 mm high.

The same principle was applied to a new device for performing direct shear tests under controlled suction (Escario, 1980). The sample dimensions are 50 x 50 mm and 22 mm high. The use of penetration test was also proposed in the same publication and some tests presented, using the suction controlled oedometer and a piston 10 mm diameter.

This type of testing comes always across the problem of the time to be allowed to the samples for equilibrium to be reached and the rates of shear to apply for the suction at failure to be known. Some research on this aspect has, for this reason, been carried out, together with the tests performed with the equipment mentioned.

Three soil types, which cover a wide range of materials, have been used. The samples have been prepared to predetermined moisture and density conditions by static compaction. In Table 1 the main soil characteristics and initial conditions have been summarized.

**Table 1. Soil characteristics and initial conditions**

<table>
<thead>
<tr>
<th></th>
<th>W_L</th>
<th>P_I</th>
<th># pass x 16/40/200</th>
<th>St. Proctor</th>
<th>w_s</th>
<th>w_o</th>
<th>w'_o</th>
<th>Suction (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Madrid</td>
<td>71</td>
<td>35</td>
<td>100/99 1,33</td>
<td>33,7 1,33</td>
<td>29,0</td>
<td>0,85</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Guadalix</td>
<td>33</td>
<td>13,6</td>
<td>100/86 1,80</td>
<td>17,0 1,80</td>
<td>12,6</td>
<td>0,28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Madrid</td>
<td>32</td>
<td>15</td>
<td>94/48/17 1,91</td>
<td>11,5 1,91</td>
<td>9,2</td>
<td>0,07</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Actually w'_o = 24%*

**FACTORS INFLUENCING MOISTURE EQUILIBRIUM CONDITIONS**

The suction-moisture content curves determined with the standard pressure membrane apparatus for the three types of soils and initial conditions shown in Table 1, have been plotted in Fig. 1 as continuous lines. The meaning of the other points shown will be commented later.

**Figure 1. Suction-moisture content relationships and final moisture content in the shear tests**

The samples were prepared by static compaction in a steel ring 42 mm diameter, and 20 mm height. They were placed on the membrane and operated within the steel ring.

Some authors (Coleman, 1959) have called the attention on the need of having as good a contact as possible between the sample and the membrane. In order to investigate this point, a series of tests have been carried out by placing a calibrated spring against the top of the sample, reacting on the chamber cell. Different spring pressures have been tested and 0.02 MPa was adopted for the tests here presented, even though it seems that 0.01 MPa might be adequate. In Figs. 2 and 3, the curves showing the process of equilibrium for the clayey sand and the Guada-
lix clay for different suctions with and without spring are plotted. As may be seen, equilibrium is reached much faster when applying a slight pressure on the sample. In Table 2 the number of days necessary for various percentages of moisture equilibrium, $U_w$, with and without spring, is shown. As may be observed, the differences in time are very important.

Some more comments on the subject will be given in the following paragraphs.

**Table 2.- Moisture equilibrium time (days)**

<table>
<thead>
<tr>
<th>$U_w$ (%)</th>
<th>With/Without spring Suction (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0,5</td>
</tr>
<tr>
<td>Clayey sand</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>95</td>
</tr>
<tr>
<td></td>
<td>100</td>
</tr>
<tr>
<td>Guadalix clay</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>95</td>
</tr>
<tr>
<td></td>
<td>100</td>
</tr>
</tbody>
</table>

* $U_w = (w_0 - w)/(w_0 - w_f) \times 100$

![Figure 2. Equilibrium process under different suctions](image1)

![Figure 3. Equilibrium process under different suctions](image2)

![Figure 4. Variation of the modulus of deformation and penetration resistance with suction](image3)

**PENETRATION TESTS**

An extensive testing program is now under way and some of the results will be shown here. The soil types and initial conditions are again as given in Table 1. No vertical surcharge has been used.

From the stress–deformation curves obtained for each suction, the modulus of deformation, $E$, of the straight part, expressed as a ratio of the zero suction modulus $E_0$, has been determined and plotted in Fig. 4 as a function of suction. As may be seen, it increases with suction and, for the clayey sand, arrives to a maximum, that has also been closely approached with the two other soils. After the maximum, no decrease has been detected, for the range of suctions tested, but the differences observed fall within the expected dispersion of the testing results.

In the same figure, the penetration resistance versus suction has also been plotted for each soil. The value of the resistance adopted corresponds to local failure, as defined by the point where the stress–deformation curve departs from a straight line. As may be seen, a maximum is again reached for the clayey sand. For the two other soils the curves show a clear tendency to approach to a maximum. But no decrease is apparent after the maximum for the sand. This behaviour is very similar and the suctions corresponding to the maximum values of the same order of magnitude, to those observed for the direct shear tests, as will be shown latter.

The modulus of deformation seems to be more sensitive to time allowed for equilibrium than the failure load. Nevertheless a more detailed study on the subject is being carried out, since the number of tests available is not considered sufficient.
DIRECT SHEAR TESTS

A set of tests results for suction values up to 1 MPa was presented by Escario and Saez (1986). The testing program has recently been enlarged for suction values up to 15 MPa and the operating procedures have been subjected to some improvements. Part of the results have been progressively published (Escario and Saez, 1987 a and b). Of the three soils prepared under the conditions shown in Table 1, the tests corresponding to the clayey sand and the Guadalix clay have been completed; the tests with the gray clay have only partly been performed, but will also be shown here.

The time allowed for equilibrium to each sample was in general 6 days, extended to 5 days for some of the tests at high suctions. The time to failure can also be added to these figures (as an idea, from 10 to 20 hours). The shear velocity was in all cases of 2.4 mm/day.

The final moisture content of the samples tested has been represented as points with different signs in Fig. 1, together with the suction-moisture content curves. As may be seen, the agreement is very satisfactory in general, despite the differences in vertical stress; the total time includes the post-peak period, but it may be inferred that at failure, equilibrium has likely been reached.

In Fig. 5 the results obtained for the clayey sand have been plotted. As it is seen, the shear strength increases up to a maximum, for suction from 0.8 to 1.0 MPa. From there on, it seems there is a slight decrease, but the differences are of the same order of magnitude of the possible experimental accuracy.

In Fig. 6 the results for the Guadalix clay have been plotted and the general trends are similar. The maximum values is reached in this case for $\Delta u = 8$ MPa.

In Fig. 7 the tests results available for the gray clay are shown. Only the curve for 0.3 MPa is presented, with the results corresponding to the first test series, which are less accurate. But again, the trend is similar to that described for the two first soils. The maximum value is attained for $\Delta u = 10$ MPa as a preliminary approximation. A new test program with this soil is under way.

In all three cases it may be assumed that the tangent at the origin is equal to $\tan 0'$, since the soil should be there fully saturated.

In Fig. 8, the same results of the clayey sand and the Guadalix clay have been plotted in a different way. As it is seen, in the first case the corresponding straight lines are approximately parallel, but they are clearly divergent for the Guadalix clay. The plots for the values of $\delta_{ap}$ and $\delta_{c}$, represented in Fig. 9, clearly show these results in terms of apparent friction and cohesion.

An empirical formulation for representing the variation of the shear strength with suction has been tried (Escario, 1988). Elliptical curves of degree 2,5 of the general type:

$$(x/a)^{2.5} + (y/b)^{2.5} = 1$$

have shown a very good degree of approximation from a zero suction to the maximum, for the clayey sand and red clay and different values of $\Delta u = \Delta u'$. The basic parameters of each curve are obtained by obliging it to have at the origin a tangent equal to $\tan 0'$ and the corresponding shear strength for zero suction; and maximum for the suction and shear strength corresponding to the
experimental values. The general formulation with the parameters adopted is shown in Fig. 10. The equations relative to each curve are given and plotted as full lines, besides the experimental points, in Figs. 5 and 6. Tentative results for the gray clay are shown in Fig. 7.

CONCLUSIONS

- Equilibrium conditions in the pressure membrane apparatus are reached in a much shorter period of time, if a good contact with the membrane is assured by applying a vertical pressure to the soil sample. A very simple procedure is proposed for samples prepared in a short section of steel tube, by means of a calibrated spring acting against the top cover of the device.
- With the soils and compaction conditions used, a total period of equilibrium of the order of five or six days seems to be long enough for shear strength determinations. There are nevertheless indications that such a period of time may not be sufficient for evaluations of the modulus of deformation. This is a tentative conclusion to be confirmed with current research.
- In the penetration tests carried out, the modulus of deformation increases with suction. A maximum has been reached in the clayey sand, but no decrease has been detected for higher suctions, within the range experimented and accuracy of the testing procedure. The local failure load, as defined in the paper, also increases and arrives to a maximum in the clayey sand; but for higher suctions no decrease may be observed, though the dispersion of results somewhat shades the picture. With the two other soils, the maximum has not been reached but has been closely approached.
- In the direct shear tests, the shear strength versus suction curves, at constant vertical stress, start increasing with a slope equal to tan θ' and gradually flatten until a maximum is reached. A slow decrease seems to follow, but the differences are of the same order of magnitude of the testing accuracy; therefore, more testing points are necessary. For the clayey sand the maximum is reached for suction values of 0.8 to 1.0 MPa; for the Guadalix clay, 8 MPa; preliminary results are shown for the gray clay. All this values are of the same order of magnitude of those observed in the penetration tests.
- By plotting the direct shear test results as shear strength versus vertical stress, the straight lines corresponding to each suction are clearly divergent for the Guadalix clay and practically parallel for the clayey sand. The increase of C<sub>ap</sub> and θ<sub>ap</sub> with suction is more pronounced at low suction values and the corresponding curves tend towards a maximum.
- For the soils and compaction conditions described, the variation of shear strength with suction can accurately be represented by ellipses of degree 2.5 up to the maximum value; nevertheless, for the gray clay the data are still preliminary and, therefore, this conclusion should be taken as tentative. The corresponding parameters have been obtained by obliaging the curve to have at the origin an ordinate equal to the zero suction shear strength and a slope of tan θ'; at the maximum it has to fulfill the experimental values determined.

REFERENCES


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