COMPARISONS OF ONE AND TWO-SPECIMEN CFS TESTS

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SYNOPSIS

The CFS test is designed to permit the determination of the strain variation of the mobilization of c and \( \phi \) components from a test using only a single specimen. This paper includes a review of the theory and performance of this test. The validity of using only a single specimen is investigated by comparing the stress-strain and cohesion-friction-strain results from one-specimen CFS tests with results from identical tests using two specimens. Each such test permits a check of the curve-hopping technique used in the one-specimen test but not required in the two-specimen test.

The paper includes 14 such comparisons, involving nine different normally consolidated soils. Seven are remolded and saturated, with plasticity indexes between 0 and 21% and at 105%. The other soils are undisturbed—one a dry, cemented sand and the other a sensitive Leda clay. Only these two were tested to strains exceeding conventional failure. The remainder investigate the cohesion failure, but the strains do not reach conventional failure. Two of the remolded clays were also tested for the validity of curve-hopping after allowing different times for secondary compression.

All one and two-specimen test comparisons show good qualitative agreement. The quantitative agreement is usually good, particularly for the maximum value of cohesion. However, there is a tendency for cohesion to decrease more rapidly with strain in the two-specimen tests. The comparisons for the undisturbed soils are also encouraging. Increasing secondary time with remolded clay appears to result in improved comparisons. The available evi-

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dence indicates that undisturbed soils can be tested successfully with the one-specimen CFS test. Overconsolidated clays were not investigated.

The paper includes a brief examination of the soil type, speed of compression, drainage, and equipment precision requirements for the successful performance of one-specimen CFS tests. Also considered are constant pore pressure and constant volume versions of the CFS test.

INTRODUCTION

Review of One-Specimen CFS Test.—The laboratory test under investigation is the Cohesion-Friction-Strain (CFS) test. In this test, the investigator attempts to determine the strain-mobilization of the cohesion and friction components of a soil's resistance to shear stress. The test is designed to permit computation of redefined cohesion and friction components of the total shear resistance at selected values of strain during a compression test. From these computed values, curves of the mobilization of cohesion and friction with strain can be determined.

The CFS test procedure (herein referred to as “standard”) involves the determination of two stress-strain curves, each at a different constant value of the major, principal effective stress, \( \bar{\sigma}_1 \). The specimen is placed in a triaxial cell, consolidated in any desired manner, and then is subjected to a constant rate of compressive strain. The imposed strain forces the development of a principal stress difference \( \bar{\sigma}_2 - \bar{\sigma}_3 \), herein called the deviator stress. During this strain, the pore fluid pressure is controlled to maintain a constant presclected value of \( \bar{p}_f \). Any increase in pore pressure then reduces effective stresses and weakens the soil with the result (because of the strain control) that a new equilibrium stress-strain curve is established at a lower magnitude of \( \bar{p}_f \). Decreasing pore pressure similarly increases \( \bar{\sigma}_2 \). The one-specimen CFS test procedure consists of alternating between two values of \( \bar{p}_f \) in such a way that two stress-strain curves are obtained—one for each \( \bar{p}_f \). Any strains where these two curves are both sufficiently well defined, the investigator can mathematically determine the desired shear resistance components.

The CFS test procedure is neither drained nor undrained. Small changes in volume necessarily occur in conjunction with changes in \( \bar{p}_f \) at the same strain, but require a void ratio change of less than 1%. A somewhat greater change may occur during strain at constant \( \bar{p}_f \). The test is not free-draining because of the imposed pore pressure control.

For the reader who is not familiar with the previous publication describing the CFS test theory and procedures, a brief review is presented in Appendix I. However, this paper is part of a sequence, and familiarization with these references should be helpful. They also describe the Norwegian Geotechnical Institute equipment used in this research, as does the paper by Andreasen and Simons.

Notation.—The letter symbols adopted for use in this paper are defined where they first appear and are listed alphabetically in Appendix II.

Question of Validity of Use of Single Specimen.—The preceding description indicates that because the performance of the CFS test requires only one specimen, the test may permit the practical determination of the mobilized cohesion and friction components of undisturbed and otherwise nonhomogeneous soils. However, the discussers of the paper by Schmertmann and Osterberg indicated that the one-specimen CFS test procedure must be proved valid before the profession can use any advantages it may offer. Quotes from the discussions are reproduced:

"The determination of the shear characteristics of cohesive soils in an undisturbed state requires a considerable number of samples of practically identical materials which, in most cases, cannot be obtained. If the procedure proposed by Schmertmann and Osterberg should prove sufficiently reliable, this difficulty would disappear, because the procedure would make it possible to obtain the essential data from triaxial tests on a single specimen."

By such a procedure, it appears possible to determine the cohesion intercept c and the angle of shearing resistance \( \phi \) of a soil from a test upon a single sample. Such a procedure, if valid, would have great value in testing undisturbed soils, for it would avoid the difficulties which stem from the fact that it is almost impossible to obtain two or more genuinely identical samples.

The potential advantages of the "curve hopping" (used in CFS test) or "stage" (used by D. W. Taylor) techniques are so great as to warrant careful investigation into their validity."

Scope of Paper.—Several aspects of the validity of the one-specimen CFS test appear important. Foremost is whether or not a one-specimen test, which defines two stress-strain curves, yields the same computed results as would be obtained from two initially identical specimens each tested at constant \( \bar{p}_f \), and each defining only one of the stress-strain curves of the one-specimen test. This paper deals with this question alone.

Comparative one and two-specimen CFS tests were performed for a variety of soils. In all cases, an effort was made to obtain the comparative specimens in as initially identical a condition as possible. A "Vac-Aire" extrusion

2 Definitions are restated in Appendix I.
machine was used to prepare duplicate specimens of six cohesive soils, five with plastic index measurements (PI) between 4% and 21%, and the sixth with a PI of 109%. Specimens of Ottawa sand were prepared individually by dry compaction in a triaxial specimen mold. Two natural, undisturbed soils are included. The specimens were trimmed from blocks. One is a lightly cemented angular sand from Tupelo, Mississippi, and the other a sensitive Leda clay from Ottawa, Canada. The comparative specimens of natural soil are possibly not as nearly identical as those from the extruded cohesive soils. Except for the curve-hopping, all the other test conditions such as length of time in primary consolidation and secondary compression, rate of compression, temperature, and stress measurement and pore pressure control accuracy were also duplicated within a comparative test series.

In addition to the variety of soils used, the scope of the comparative tests was restricted to a study of strength component mobilization at low values of compressive strain. Previous one-specimen CFS test research indicated that the cohesion was fully mobilized at much lower strains than was required to develop friction. The writer thought it especially interesting to study the cohesion development in the two-specimen test. Restricting the comparative tests to the low strain range permitted a more careful check of the difference in the strain behavior of the two components over the range where they are the most different, and also permitted a more accurate comparison of the computed values of maximum cohesion. However, for the extruded specimens, this meant that the strain did not reach sufficiently high values to attain conventional failure (cohesion plus friction failure).

The scope also includes comparative tests on two of the extruded soils after allowing different times for secondary compression—with all other variables held constant. This was done to obtain a preliminary evaluation of the comparative-test behavior of undisturbed cohesive soils. One of the most outstanding differences between undisturbed and remolded clays is the highly developed structure in undisturbed clay that is associated with long times in secondary compression. After the performances of these tests, an undisturbed cube of Leda clay became available and the comparative CFS test results are included.

**PRESENTATION OF DATA**

**Tables.**—Listed in Tables 1 and 2, in order of increasing plasticity index of the soil, are the mineralogy and other classification characteristics of the soils used. The subsequent tables, and the presentation of figures, are also in order of increasing plasticity index.

Table 3 is a summary of the soil parameters that provide the best available information regarding the uniformity of the specimens in each comparative group, or groups, of specimens. Table 3 includes computed values of water content, void ratio, and degree of saturation at the time of placement in the triaxial cell (subscript i for initial) and at the time of removal from the cell (subscript f for final). The void ratio after one-increment, hydrostatic consolidation, but before the CFS test, is also included (subscript o). This value is the average of two computations, one computing forward from the initial condition and the other computing backward from the final condition.

Table 4 contains a summary of the pressures, drainage conditions, and consolidation times permitted during the one-increment consolidation.
full cell pressure was applied suddenly without the use of back pressure in the pore water. The drainage aids used include 1/8 in. to 1/4 in. wide filter paper strips the same length as the 8.00 cm long specimen and placed vertically, with approximately equal spacing, around the circumference of the 3.58 cm diameter specimen. The internal drains are the same as those previously described. 10 The Casagrande semi-log method was used to determine the time to 100% primary consolidation. Secondary times listed are the differences between the total time allowed for consolidation and the primary time indicated. Primary and secondary could not be distinguished during the consolidation time allowed the Leda clay, and the total time allowed is listed under primary.

Table 4 also includes a summary of the effective stresses and compression rates used for the comparative CFS tests. The q values listed are the

<table>
<thead>
<tr>
<th>Soil</th>
<th>Gs Used</th>
<th>Per cent finer than 200 sieve (washed)</th>
<th>Atterberg Limits</th>
<th>Activity PI</th>
<th>Liquidity Index-start of CFS-test</th>
</tr>
</thead>
<tbody>
<tr>
<td>OS</td>
<td>2,600</td>
<td>0 0</td>
<td>nonplastic</td>
<td></td>
<td></td>
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<tr>
<td>TCS</td>
<td>2,661</td>
<td>5 2</td>
<td>not determined</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q-EPK</td>
<td>2,609</td>
<td>100 60</td>
<td>29 4</td>
<td>0.07</td>
<td>23%</td>
</tr>
<tr>
<td>ENID</td>
<td>2,790</td>
<td>65 20</td>
<td>37 9</td>
<td>0.45</td>
<td></td>
</tr>
<tr>
<td>Leda</td>
<td>2,802</td>
<td>0 85</td>
<td>n.d.</td>
<td>1</td>
<td>220</td>
</tr>
<tr>
<td>JSC</td>
<td>2,718</td>
<td>62 13</td>
<td>30 14</td>
<td>1.05</td>
<td>19</td>
</tr>
<tr>
<td>BBC</td>
<td>2,810</td>
<td>98 53</td>
<td>38 19</td>
<td>0.36</td>
<td>20</td>
</tr>
<tr>
<td>DWEPK</td>
<td>2,609</td>
<td>100 60</td>
<td>52 21</td>
<td>0.35</td>
<td>15</td>
</tr>
<tr>
<td>LWC</td>
<td>2,810</td>
<td>100 85</td>
<td>150 105</td>
<td>1.24</td>
<td>14</td>
</tr>
</tbody>
</table>

The data for Table 2 was obtained from "The Influence of Rate of Loading on the Shear Strength of Saturated Clays" by Carl D. Crawford, Special Technical Publication No. 546, ASTM, 1959.

intended constant values for each curve (approximately 95% and 75% of the hydrostatic preconsolidation value, Gs). Reference to Table 4 will show that most of the tests were performed with Gs = 3.50 kg per sq cm. This value was chosen for convenience because the piston load cells are then used almost to capacity, and the two stress-strain curves are separated with maximum precision. The final computed values of Gs may vary slightly from the intended value, but usually by no more than 0.02 kg per sq cm. The compression rates listed are the averages for the entire strain range of each test. Because of compression and extension of the load cell during curve-hopping, the compression rate between successive data points in the 1-specimen tests may

vare as much as 26% from the average of the entire test. When interpreting the experimental results, this compression rate variation was assumed negligible and was disregarded. The section "Consideration of Data" includes additional examination of errors in the computations of the shear resistance components.

Figures.—The upper half of Figs. 1 through 15 present the comparative one and two-specimen stress-strain curves. The solid line at greater deviator stress presents the behavior of a specimen held at a high, constant value of \( \sigma_1 \). The solid line at lower deviator stress presents the behavior of another specimen held at a lower, constant value of \( \sigma_1 \). These two-specimen test curves are well defined by many data points with negligible scatter from the curves presented. These individual points are therefore omitted in the figures to enhance clarity. The dashed lines present the behavior of a single specimen, using the CFS test curve-hopping technique. The open circles are all the data points obtained at the high value of \( \sigma_1 \), and the solid circles are all the data obtained at the low value of \( \sigma_1 \). As shown in Table 4, the intended high and low \( \sigma_1 \) values were the same in each comparative one and two-specimen test series. These intended values are also shown in each figure.

The lower half of Figs. 1 through 15 show the results of cohesion and friction computations (circles and crosses, respectively) at various values of axial strain, as calculated from the stress-strain curves directly above. Again, the solid lines represent the results of the two-specimen test and the dashed lines the results of the one-specimen test. The curves shown are the writer's estimate of the best fit through the computed points. It should be noted again that cohesion and friction are components of mobilized shear resistance. At zero strain, the stress is still hydrostatic, and there is no shear stress of zero on any plane. If the concepts of negative cohesion and negative friction are rejected, both components must be zero at zero strain (as shown in Fig. 5). This fact was sometimes useful in estimating the best fit curve. However, the \( c_\phi \) and \( \phi_c \) curves were omitted for the strain interval between zero and the first computed point (except in Fig. 5) to restrict the test comparisons to the strain interval studied in detail.

Fig. 1 presents the comparison for tests with Ottawa sand. In each test, the specimen was compacted to approximately 90% relative density and completely saturated. A high relative density was chosen because it was more reproducible.

Data for the Tupelo cemented sand, presented in Fig. 2, resulted from the use of a variation in the "standard" CFS technique described in the references cited and used in all the other tests reported herein. First, the soil was air-dry, and its structure was easily destroyed by water. Air, rather than water, was therefore used as the pressure-controlled pore fluid. Second, two constant \( \sigma_1 \) curves could not be used with this soil because its cohesive strength was primarily caused by a dried kaolinite cement between the sand grains, and the compressive strength of the soil exceeded the cell confining pressure. To maintain a constant \( \sigma_1 \), the pore pressure would have to be able to exceed the confining pressure—which cannot be done in the triaxial test. Testing this soil required another procedure. Two curves were obtained with each representing a constant, though different, value of pore air pressure. This proce-

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Fig. 1.—One and Two-Specimen CFS Test Comparison, Ottawa Sand

Fig. 2.—One and Two-Specimen CFS Test Comparison, Tupelo Cemented Sand
dure also results in two stress-strain points at any strain, each of which is at a different value of $\Theta_1$. Calculations for cohesion and friction at this strain can then be made in the same manner as with the “standard” constant $\Theta_1$, CFS test procedure.

The original reason for keeping $\Theta_1$ constant during the generation of a stress-strain curve was to keep void ratio, and therefore presumably structure, approximately constant in compressible cohesive soil. Soils with significant cement-cohesion are not significantly compressible, and the investigator need not keep $\Theta_1$ constant in order to minimize structural changes. Therefore, for the purposes of the comparisons made in this research a constant $\Theta_1$ version of the CFS test was considered acceptable for the Tupelo cemented sand.

Fig. 3 presents the comparative test results for the Q-EPK. This clay has the same mineralogy as the "Edgar Plastic Kaolin" mixed with distilled water (DWEPK), for which similar comparative tests are presented in Figs. 11, 12, and 13. The difference is that the "as received" powdered kaolin was mixed with a 1/25 M solution of "Quadrofos" (NaP4O13). This change resulted in a more dispersed structure after machine extrusion than that of the extruded untreated kaolinite.

Groups of specimens of two clays were permitted to consolidate for different lengths of time prior to compression in the one and two-specimen test comparisons. Figs. 4, 5, and 6 present the data for Enid clay, and Figs. 12 and 13 for the untreated kaolinite clay.

Figs. 9 and 11 present the results of a preliminary series of comparative one and two-specimen tests. Subsequent tests on the same soils, shown by Figs. 10 and 12, respectively, permit a check of reproducibility.

Fig. 15 presents the comparative results of two one-specimen tests in which a different sequence of effective stress "curve-hops" was used for each test. The analysis of Fig. 15 will be continued subsequently.

CONSIDERATION OF DATA

When making an evaluation of the agreement, or lack of agreement, between the results of one and two-specimen tests we are faced with the lack of objective standards on which to base such comparisons. Since the point of interest is an evaluation of the curve-hopping technique, the writer herein makes the assumption that the two-specimen test is the standard for comparison. However, the cohesion-friction-strain behavior computed from two-specimen test data is not necessarily a better representation of the strength component behavior of a soil in the field.

Even with a standard, an evaluation of the comparisons depends on whether the cohesion or friction component is of principal interest and on the strain of principal interest. What constitutes a good or poor comparison? Considering that the CFS test may represent the first experimental attempt to separate shear resistance components as a function of strain, and that identical specimens for many natural soils may not be obtainable for use in a two-specimen test, perhaps a deviation as great as 100% is a “good comparison.” In view of these uncertainties, this investigation is somewhat general.
FIG. 4.—ONE AND TWO-SPECIMEN CFS TEST COMPARISON, EXTRUDED
ENID CLAY, 70 MIN SECONDARY

FIG. 5.—ONE AND TWO-SPECIMEN CFS TEST COMPARISON, EXTRUDED ENID
CLAY, 1,340 MIN SECONDARY
FIG. 6.—ONE AND TWO-SPECIMEN CFS TEST COMPARISON, EXTRUDED ENID CLAY, 9,700 MIN SECONDARY

FIG. 7.—ONE AND TWO-SPECIMEN CFS TEST COMPARISON, UNDISTURBED LEDA CLAY
FIG. 8.—ONE AND TWO-SPECIMEN CFS TEST COMPARISON, JACKSONVILLE SANDY CLAY

FIG. 9.—ONE AND TWO-SPECIMEN CFS TEST COMPARISON, EXTRUDED BOSTON BLUE CLAY
FIG. 10.—ONE AND TWO-SPECIMEN CFS TEST COMPARISON, EXTRUDED
BOSTON BLUE CLAY

FIG. 11.—ONE AND TWO-SPECIMEN CFS TEST COMPARISON, EX-
TRUDED KAOLINITE, 1,400 MIN SECONDARY
FIG. 12.—ONE AND TWO-SPECIMEN CFS TEST COMPARISON, EXTRUDED KAOLINITE, 1,300 MIN SECONDARY

FIG. 13.—ONE AND TWO-SPECIMEN CFS TEST COMPARISON, EXTRUDED KAOLINITE, 9,500 MIN SECONDARY
FIG. 14.—ONE AND TWO-SPECIMEN CFS TEST COMPARISON, EXTRUDED LAKE WAUBURG CLAY

FIG. 15.—COMPARISON OF ONE-SPECIMEN CFS TESTS USING DIFFERENT CURVE-HOPPING SEQUENCES, EXTRUDED KAOLINITE
specimen tests. Of course, the quantitative agreement is good in some comparisons and perhaps only fair, or even poor, in others.

Cohesion.—The agreement in the values of peak (maximum) cohesion is excellent. With the exception of two tests (the cemented sand in Fig 2 and the Lake Wauburg clay (LWC) in Fig. 14) the deviation in peak cohesion is 6% or less. This deviation is within the ordinary range (Table 6). As explained previously, the cemented sand tests involved the use of adjacent undisturbed specimens. It is probable that the specimens were not sufficiently identical and that this accounts for the deviation in the peak cohesion of approximately

<table>
<thead>
<tr>
<th>TABLE 5.—PRECISION OF MEASUREMENTS AND PLOTTING</th>
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<tr>
<td>Experimental Measurement</td>
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<tr>
<td></td>
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<tr>
<td>( \sigma_3 )</td>
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<tr>
<td></td>
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<tr>
<td>( u )</td>
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<td></td>
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<tr>
<td>( \sigma_d )</td>
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<tr>
<th>TABLE 6.—RANGE IN COHESION AND FRICTION DUE TO ERRORS SHOWN IN TABLE 5</th>
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<tr>
<td>Computed Minimum</td>
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<tr>
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<tr>
<td></td>
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<tr>
<td>(a) Cohesion, ( c_\sigma ), in kilograms per square centimeter</td>
</tr>
<tr>
<td>Low strain</td>
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<tr>
<td>High strain</td>
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<tr>
<th>(b) Friction Coefficient, ( \tan \phi_c )</th>
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<tr>
<td>Low strain</td>
</tr>
<tr>
<td>High strain</td>
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</table>

25%. The LWC is an exceedingly plastic and impermeable soil, and it is likely that even the slow strain rate (1.665 mm per 1% strain) used during the compression of the one-specimen test did not allow sufficient time for pore pressure or \( \phi_1 \), equilibrium. This reduces the effect of pore pressure changes and the computed results then indicate a cohesion in error on the high side. Such behavior may account for at least part of the 9% deviation in peak cohesion found in the LWC test (Fig. 14).

The agreement on the strain at which the peak cohesion develops is also good. In only a few cases (Figs. 6, 10, and 13) does there appear to be any important difference in this comparison, and this can probably be accounted
for by the flat nature of the cohesion-strain curve. Small errors in cohesion magnitude can result in large errors in the strain position of the peak cohesion.

Comparison of the cohesion values as strain increases shows a general trend for the cohesion to decrease more rapidly with strain in the two-specimen than in the one-specimen CFS test. This deviation varies from a rather small one in Figs. 3, 6, 12, and 14 to a rather pronounced one in Figs. 8, 9, and 11. The cohesion data in Fig. 2 is opposite to this trend, but this may be caused by the special nature of this test, as explained previously. Usually, the greater the strain, or perhaps just the greater the number of curve-hopping cycles, the greater the deviation in cohesion between the two tests, with the one-specimen tests yielding the greater values.

Friction.—With the exception of the Ottawa sand (Fig. 1) and the undisturbed soils (Figs. 2 and 7), the tests were not carried to high enough strains to permit a comparison of the maximum friction values. For the two sands, the agreement was essentially perfect. For the Leda clay it is very good. Such results should be expected for the sands because structure of these soils is not sensitive to effective stress history. The results from Leda clay are surprising.

Comparisons of the strain-rate development of friction indicate, in almost all cases, that the two-specimen test shows a more rapid rate of development than the one-specimen test. It is not known whether this is a cause or consequence of the comparative loss of cohesion with strain.

There is also a tendency (as exhibited in Figs. 3, 6, 8, and 10) for the one-specimen test to have higher friction values at low strain and then to cross-over the two-specimen test with lower values at higher strains. The writer believes that this behavior is caused by experimental errors or by the effect of overconsolidation on the low strain behavior of the low $\beta$ specimen in the two-specimen test. No special importance is attached to this cross-over behavior.

Undisturbed Soils.—Because the one-specimen CFS test offers the special advantage of permitting the testing of soils from which duplicate specimens cannot be obtained, as is the case with many undisturbed natural soils, the test comparisons from such natural soils are of special interest. Both the Tupelo cemented sand and the Leda sensitive clay are such soils and the good comparative test results from both are encouraging for the use of the one-specimen testing procedure. Note that the tests for both soils passed through conventional failure.

Because of the difficulty of obtaining duplicate specimens, the writer also approached the problem indirectly via the length of time allowed for secondary compression during the consolidation of two of the extruded cohesive soils. As cited previously, the structural changes resulting from long secondary times are thought to be a major factor accounting for the differences in strength behavior of remolded and undisturbed soils. Therefore, better comparative test agreement with increasing secondary time suggests that undisturbed soils could be successfully tested with the one-specimen test.

Figs. 4, 5 and 6 show the comparative test data for three groups of duplicate Enid clay specimens in which each group was allowed a different time for secondary compression under a constant hydrostatic pressure. These times were approximately 70, 1,340, and 9,700 min, respectively. Although the comparisons of the stress-strain curves and the computed cohesion and friction versus strain are reasonably good for all three groups, the agreement improves with longer secondary time.

Figs. 11, 12, and 13 permit a similar comparison for the kaolinite in which the secondary time was approximately 1,300 min for the groups in Figs. 11 and 12 and about 9,800 min in Fig. 13. A comparison of the results in Figs. 11 and 13 supports the previous conclusion of better one and two-specimen test agreement with longer secondary time. Agreement is approximately the same when comparing Figs. 12 and 13. However, in part, the good results shown in Fig. 12 reflect the fact that the stress-strain curves from the two-specimen test are not properly separated at low strain. Had the specimens been more nearly identical at the beginning of compression, the agreement would not have been as good as that shown in Fig. 12.

On the basis of the limited evidence presented, it appears that the use of the one-specimen CFS test, with its curve-hopping technique, will be successful with undisturbed soils. However, highly overconsolidated cohesive soils (either undisturbed or extruded) were not tested, and such soils may present unexpected problems. But, they could also prove to yield even better test comparisons.

**CONDITIONS FOR SUCCESSFUL ONE-SPECIMEN TESTS**

Type of Soil.—This paper is partly a survey of those soil types that appear suitable for use with the one-specimen CFS test procedure. From the results presented herein, as well as from experience with many other CFS tests, the writer believes that all soils investigated to date are suitable. Some are more easily tested than others. In general, the higher the plasticity index the more difficult the performance of the test because of the accompanying lower permeability and the fact that more time must be allowed for pore pressure uniformity within the specimen.

For the engineer interested in trying the one-specimen CFS test in his laboratory, the writer suggests that it is easiest to obtain good results on a soil having a low $P_I$; Ottawa sand is an ideal material for pilot tests.

Choice of Speed of Compression.—It is important that the investigator be aware of the maximum compression rate at which a CFS test can be successfully performed. This is dependent on the speed with which the pore pressure changes imposed during curve-hopping can be distributed throughout the specimen. This, in turn, is dependent on the permeability of the soil and its resistance to the volume changes associated with pore pressure changes. It appears convenient to use the length of time required to complete primary consolidation during the consolidation increment that precedes the performance of the CFS test, as a measure of permeability and resistance behavior. This time is designated $t_{100}$, and can usually be determined by a method such as the well-known Casagrande graphical method. Based on experience to date (May, 1962) in which $t_{100}$ was obtained during normal consolidation, the writer suggests that the CFS test be performed with a compression rate not greater than 1% axial compressive strain per $t_{100}$ time interval.

The strain interval of interest for a cohesion-friction separation also influences the compression rate chosen. The more detail desired over any strain interval, the slower the required compression rate to permit a sufficient number of curve-hopping cycles to obtain this detail.
Artificial drainage aids can greatly reduce $t_{100}$ and decrease the time necessary for a CFS test. For instance, the writer performed duplicate, one-incancement consolidation tests on saturated kaolinite clay specimens 8.00 cm long and 3.59 cm in diameter, drained at the bottom only. Each external drain was one vertical strip of Whatman No. 54 filter paper approximately 1/8 in. wide (1/8 in. when No. 12 used). An internal drain was punched axially with an 0.19 cm diameter needle and filled with a double length of wool yarn. Table 7 presents the results obtained. It is apparent that drainage aids can be effective in reducing the time for a CFS test if they are desired. The problem is usually with the very impermeable clays in which the use of the maximum number of internal drains that will not seriously damage the soil structure still results in high $t_{100}$ values. Then, the CFS test simply must be run slowly, often spanning several days or even weeks.

Precision of Triaxial Equipment.—To perform one-specimen CFS tests with the accuracy shown in Table 6, the investigator must have equipment capable of the precision of measurements indicated in Table 5. Furthermore, this equipment must be used with the care necessary to maintain this precision. Less precise equipment will necessarily result in greater probable error in the individual cohesion and friction determinations.

### Table 7. Example of Use of Drainage Aids to Reduce $t_{100}$

<table>
<thead>
<tr>
<th>Number of Drains</th>
<th>External</th>
<th>Internal</th>
<th>$t_{100}$ in minutes</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>550</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>210</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
<td>70</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>0</td>
<td>55</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>0</td>
<td>25</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>0</td>
<td>22</td>
</tr>
</tbody>
</table>

Although all the published CFS test work has been done with the triaxial machine, it is not essential to use this machine. It is merely convenient because the average stress conditions are known with sufficient accuracy to construct Mohr circles of stress and to interpret small changes in these circles (see APPENDIX I). The CFS test theory is intended to be generally valid. It should be possible to use any of the discussed forms of the test in conjunction with any suitable stress-strain measuring device. It is not certain that curve-hopping will be successful in other strain controlled devices, but the writer knows of no reason to think otherwise.

**Variations in the Type of CFS Test.**—The test procedure reviewed in the Introduction and in APPENDIX I, examined in previous publications, and used for all the one-specimen tests reported herein (except Fig. 2), is called the standard CFS test. This is a constant $\sigma_1$ test. This test could not be used with the Tupelo cemented sand and a modification was made, as described previously, resulting in a constant $u$ version of the CFS test. Other versions are possible. One that may be of special interest to the reader, the constant volume CFS test, is considered.

In the constant volume version, the investigator performs the curve-hopping between two predetermines levels of constant volume. The saturated soil is compressed in a strain-controlled test with all drainage valves closed. Pore pressure measurements must be obtained during compression with a suitable no-flow device. The pore pressure line is then opened, and the increment of volume change is imposed by increasing the pore pressure in order to force water in, or by decreasing pore pressure in order to permit the intended volume reduction. After the volume change is accomplished, the line is closed. After allowing time for equilibrium under the new conditions, data are taken on the new volume level. The test consists of hopping between the two volume levels and finally obtaining two stress-strain curves—one for each constant volume. A $\sigma_1$ versus strain curve must also be drawn for each constant volume condition. Then, at any strain, the two deviator stress and $\sigma_1$ values are interpolated and the cohesion and friction calculations can be performed in the same manner as in the standard CFS test. An example of such a test is available.

This version of the CFS test requires not only a no-flow pore pressure measuring device, but also equipment to measure accurately volume changes of less than 0.5 cu cm forced on the specimen. Thus, this version of the test requires additional equipment. Because pore pressure is measured rather than controlled, and $\sigma_1$ interpolation is more difficult, the test is also somewhat less accurate. However, the no-volume-change condition may be of practical interest. The writer has performed a few tests of this type, and the results are similar to those obtained from constant $\sigma_1$ tests at the same effective stress levels.

It is also possible to perform a stress controlled CFS test using either of the three versions. However, curve-hopping is not possible, and the investigator must use a two-specimen test with the attendant uncertainty of whether or not specimens have been genuinely duplicated.

**Importance of $\sigma_1$ Control.**—One might ask about the importance of maintaining constant, accurate control of $\sigma_1$ during the CFS test, and particularly during curve-hopping. Can $\sigma_1$ control be lost, with considerable deviation from the intended level, and yet return to the correct stress-strain curve as if control was not lost?

In part to answer the above question the writer performed tests in which the sequence of curve-hopping was 3.30, 2.95, 2.60, 2.25, 1.90; 3.30, 2.95 kg per sq cm, and so forth. Note that these five stress levels included the 3.30 and 2.60 commonly used herein for one-specimen tests. Using only these two of the five stress levels, the stress-strain curves and the cohesion and friction curves computed from them are presented in Figs. 10 and 15 (short dashes). There they can be directly compared with one-specimen tests performed with only two stress levels (long dashes). The comparisons are good and indicate that temporary loss of $\sigma_1$ control would have only a minor, and perhaps negligible, effect on the subsequent position of the stress-strain curves at the intended $\sigma_1$ levels.

However, if $\sigma_1$ control is poor and each point deviates considerably and randomly from the intended value, then $\sigma_1$ interpolation at any strain is less accurate and the component separation is less accurate. In other versions of the CFS test it is desirable that $\sigma_1$ versus strain plot as a smooth curve so that interpolation can be accurate. The more closely this curve approximates constant $\sigma_1$, the more accurate this interpolation.
CONCLUSIONS

From the results of this research involving comparisons of one and two-specimen CFS tests using Ottawa sand, undisturbed cemented sand, and sensitive clay and six machine extruded soils with plasticity indexes between 4 and 21 and at 10%, the writer reaches the following conclusions:

1. The one-specimen test, using a curve-hopping technique, when compared with a two-specimen test not using this technique gives excellent qualitative agreement in the curves of cohesion and friction against strain. Quantitative agreement on the maximum cohesion values is also excellent. These comparisons promote confidence in the validity of the use of the one-specimen test with the variety of soil types tested.

2. There is a general tendency for cohesion to decrease, and friction to increase, more rapidly with strain in the two-specimen tests.

3. The tests on the two undisturbed soils showed excellent comparative one and two-specimen test agreement. Increasing the length of time allowed for secondary compression in two of the extruded clays resulted in improved comparative agreement. The writer interprets the improvement as additional evidence that undisturbed soils can be tested successfully with the one-specimen test.

ACKNOWLEDGMENTS

The writer is pleased to thank the Engineering Sciences Division of the National Science Foundation for Grant No. G 14671, which made this work financially possible. The writer also greatly appreciates the encouragement and suggestion by Kari Terzaghi, Hon. M. ASCE, that a study of this type be pursued.

Carl B. Crawford of the Soil Mechanics Section, Division of Building Research, National Research Council, Ottawa, Canada, kindly sent the sample of undisturbed Leda clay.

APPENDIX I.—CFS TEST DEFINITIONS, PROCEDURE, AND EXAMPLE ANALYSIS

Component Definitions.—The CFS test research began with an attempt by the writer to find a method of separating the Hvorslev effective cohesion and friction components over the entire strain range of a compression test, rather than only at failure. This proved impossible. New component definitions had to be developed that permitted a variation in void ratio for equal cohesion. However, the variation permitted is slight (less than 1%), and the new definitions are thought to be at least approximations of the Hvorslev components. Hence, the use of the terms cohesion and friction was continued in the writer’s previous works and, for continuity, in this paper.

The writer now prefers to call CFS test friction and cohesion “D*” and “I*,” respectively. This frees the mind from the many possible prior associations with the terms “friction” and “cohesion” and one can more serenely contemplate the CFS test as a means of distinguishing two arbitrary shear resistance components, D and I, which may or may not have engineering significance.

The following is a rewording of the original definitions of D* and I*. The meaning remains essentially the same, but the definitions are now stated in mathematical terms and include component separation on any plane.

“D*” = Dependent component.—Component of shear resistance mobilized on any plane and at any strain = ε, which is dependent on effective stress on that plane according to the equation

\[ D_\varepsilon = \left(\frac{\sigma(\Delta\varepsilon)}{\Delta\varepsilon}\right)_\varepsilon = \left[\frac{\tau(\Delta\theta)}{\Delta\theta}\right]_\varepsilon \]  

(1)

when, at ε, the shear resistance on that plane changes by Δτ due to Δθ. Because there must be no change in soil structure, Δθ must approach zero.

“I*” = Independent component.—Remaining component defined by

\[ I_\varepsilon = \tau_\varepsilon - D_\varepsilon \]  

(2)

when \( \varepsilon \) is the total shear resistance mobilized at ε on the plane considered.

Fig. 16 graphically illustrates, in the incremental form necessary in experiments, the definitions of these components for the plane of Mohr envelope tangency. This is the only plane considered in this paper.

Of course, it is hoped to eventually prove that these components are directly related to fundamental cohesion and friction. Some data to support this has been published. However, such proof is not essential to appreciate the possible contributions of this paper, which deals with establishing the validity of laboratory technique.

One-Specimen Test Procedure.—The test to be performed is the constant \( \varepsilon_1 \) CFS test in which two stress-strain curves are obtained, one for each magnitude of \( \varepsilon_1 \). In the triaxial machine, \( \varepsilon_1 \) is always on the horizontal plane and is equal to the cell pressure plus the deviator stress minus the pore pressure; or (\( \varepsilon_1 = c_3 + c_4 - u \)). Then, to maintain \( \varepsilon_1 \) as a constant when the cell pressure is kept constant it is only necessary to keep

---

12 *Physical Components of the Shear Strength of Saturated Clays,* by M. Judd Hvorslev, ASCE Research Conference on the Shear Strength of Cohesive Soils, June, 1960, p. 211.

Investigator decided to hop to the lower curve. As explained in the
Introduction, the pore pressure increase resulted in the reduction of the magnitude of \( \sigma_d \) that the specimen could sustain at that strain. After some additional
strain, during which the investigator periodically adjusts the pore pressure
by the changing deviator stress to more closely approach the intended lower
magnitude of \( \bar{\sigma}_1 \), a first data point is obtained at the new magnitude. This is
point 7. After continuing the pore pressure control, now much stabilized,
point 8 is obtained. The process may be continued and still another point, No. 9,
is obtained. The positions of these points on a load-deflection curve that is
kept concurrent with the progress of the test indicates that it is likely that
they adequately define a portion of the lower \( \bar{\sigma}_1 \) stress-strain curve. From
the complete curves, it may be seen that point 7 alone was adequate to position
the lower curve, but point 8 provides additional assurance, and 9 still more,
that a practical \( \bar{\sigma}_1 \) equilibrium was established.

The pore pressure is then decreased and periodically adjusted to main-
tain the upper \( \bar{\sigma}_1 \) magnitude. After a similar waiting and adjustment period,
during which the controlled strain continues, the investigator ventured taking
the data for point 10. The check points 11 and 12 were also obtained. The
remaining cycles of curve-hopping are repetitions of the one described. Normally
at least one check point is obtained, and often the first is discarded as pre-
mature and the check point becomes the new first and is in turn checked.

**Example Analysis.** — For the reader who wishes a ready reference to the
manner in which the lower cohesion friction-strain curves in Figs. 1 through
15 were computed from the upper stress-strain curves, an example analysis
follows. The analysis is for the strain \( e = 0.31 \% \) in test 516.

Sufficient data is available to plot two Mohr circles for the strain of 0.31%.
The mathematical problem is to fit the common tangent to these two circles,
as shown in Fig. 16, and then to extract the slope angle and the tau axis
intercept. Analysis of the geometry of the problem gives the following equations
for the desired components:

\[
\tan \phi_e = \tan \left\{ \sin^{-1} \left[ \frac{\Delta \sigma_d}{2(\Delta \sigma_1 - \Delta \sigma_d)} \right] \right\} \quad \ldots (4)
\]

and

\[
c_e = \frac{\sigma_1 - \sigma_d}{2 \tan \phi_e} \quad \ldots (5)
\]

It should be noted that \( \sigma_d \) and \( \bar{\sigma}_1 \) must be taken from the same curve, but can
be either.

For the upper and lower curves, the \( \sigma_d \) values are obtained directly from
the stress-strain curves interpolated through the data points and spanning the
strain gaps during which the control is for the other \( \sigma_d \). In this case, the \( \sigma_d \)
values are 1.348 and 1.034, for a \( \Delta \sigma_d = 0.314 \)\%. Although the \( \bar{\sigma}_1 \) values were
intended to be 2.00 and 1.50, because of minor control inaccuracies they are
usually slightly different from this, and it is necessary to interpolate a value
for the strain investigated from the nearest points on each curve. In this

---

**FIG. 16.—ILLUSTRATION OF "F" AND "D" COMPONENTS MOBILIZED AT
STRAIN \( e \)**

Some assurance that the pore pressure control imposed at the bottom porous
stone is the pore pressure within the specimen. Special internal drains can
be used to speed pore pressure transmission (see Table 7). In addition, the
data is accumulated in such a way as to prove extra points on the stress-strain
curves, and these provide additional assurance that \( \bar{\sigma}_1 \), or pore pressure,
equilibrium is practically established.

The first ten points in the one-specimen test on Ottawa sand have been
numbered in Fig. 1, and they will be referred to in the following explanation.

After consolidation to \( \bar{\sigma}_1 = 2.00 \) (in test No. 516) the pore pressure may or
may not be increased slightly to establish the magnitude of \( \bar{\sigma}_1 \) for the upper
curve. In test 518, the upper \( \bar{\sigma}_1 \) curve was at \( \bar{\sigma}_1 = 2.00 \). Strain controlled
axial compression is then imposed and the deviator stress increases and one
obtains points 1, 2, 3, and so forth. With the increase in \( \sigma_d \), the pore pressure
must be adjusted, as explained, to maintain a constant \( \bar{\sigma}_1 \). After point 6, the

---

\[
u = \sigma_d + (\sigma_3 - \bar{\sigma}_1) \quad \ldots (3a)
\]

\[
u = \sigma_d + (\text{a constant}) \quad \ldots (3b)
\]
case, the interpolated values of $\bar{\sigma}_1$ are 2.005 and 1.521 and $\Delta \bar{\sigma}_1 = 0.484$. Using Eqs. 4 and 5 then gives $\tan \phi_c = 0.547$ and $c_c = 0.040$, which are the values plotted in the lower part of Fig. 1.

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**APPENDIX II. NOTATION**

The following symbols have been adopted for use in this paper:

- $c$: cohesion term in Coulomb's equation;
- $c_c$: cohesion at strain $\varepsilon$;
- $D_c$: suggested CFS test component of mobilized shear resistance, replaces $\bar{\sigma}$ tau $\phi_c$;
- $e_f$: void ratio of specimen at end of CFS test;
- $e_i$: void ratio of specimen before placing in triaxial cell;
- $e_o$: void ratio of specimen after consolidation, before CFS test;
- $G_s$: specific gravity of soil solids;
- $I_{c}$: suggested CFS test component of mobilized shear resistance, replaces $c_c$;
- LL: Atterberg liquid limit;
- PI: Atterberg plasticity index;
- $S_f$: degree of saturation at end of CFS test, after removal from triaxial cell;
- $S_{i}$: degree of saturation before placing in triaxial cell;
- $t_{100}$: time required for primary consolidation;
- $u$: pore fluid pressure, air or water saturated;
- $w_f$: water content at end of CFS test, after removal from cell;
- $w_i$: water content before placing in triaxial cell;
- $\varepsilon$: axial compressive strain (also used in general sense to denote strain);
- $\bar{\sigma}$: effective stress on any plane;
- $\sigma_1$: major principal stress;
- $\bar{\sigma}_1$: major principal effective stress;
- $\sigma_3$: minor principal stress, equals triaxial cell pressure;
- $\bar{\sigma}_c$: preconsolidation pressure by lab hydrostatic consolidation;
- $\sigma_d$: greatest principal stress difference, $\sigma_1 - \sigma_3$, deviator stress;
- $\tau$: shear stress;
- $\tau_{\varepsilon}$: shear stress at strain $\varepsilon$;
- $\phi$: angle of internal friction in Coulomb's equation; and
- $\phi_{\varepsilon}$: angle of internal friction at strain $\varepsilon$. 