Multiple-Stage Triaxial Test for Determining c' and Φ' of Saturated Soils

Détermination des paramètres c' et Φ' des sols saturés au moyen d'essais triaxiaux échelonnés

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Summary

The multiple-stage compression test provides a possible method of determining the shear strength parameters of a soil, c' and Φ', by means of a single test on a single sample. In the past, the multiple-stage principle has been used successfully for testing unsaturated soils, and this paper reports its application to compression testing of saturated natural and remoulded soils. For consolidated undrained tests with pore pressure measurements, it was found that the values of c' and Φ' determined from multiple-stage tests compare favourably with the results of conventional tests. For fully drained tests, it was found that the multiple-stage compression test could only be applied for soils having low sensitivities.

Sommaire

L'essai triaxial échelonné, ou triaxial à étapes permet la détermination des paramètres de cisaillement c' et Φ' en un seul essai d'une seule éprouvette. Autrefois, le principe de l'essai échelonné fut effectué avec succès pour essayer des sols non-saturés et cette communication décrit l'application du même principe aux sols saturés naturels ou remaniés. Les résultats des essais triaxiaux consolidés non drainés échelonnés, avec mesure des pressions interstitielles conduisent à des valeurs de c' et Φ' qui peuvent se comparer favorablement aux résultats obtenus par des essais conventionnels. D'autre part, les résultats d'essais complètement drainés montrent que l'essai triaxial échelonné ne devrait être appliqué qu'aux sols à faible sensibilité.

Introduction

Perhaps the first application of the multiple-stage principle to compression testing of soils was in the development of the "Cell Test" used to measure the shear strength characteristics of saturated soils (see for instance De Beer, 1950). However, there are several serious objections to this test in its original form, one of which is that the behaviour of the soil sample is largely dependent upon the flexibility of the testing cell. Taylor (1950), and Fleming (1952), have successfully utilized the multiple-stage principle for determining the effective stress shear strength parameters c' and Φ' of unsaturated soils by loading samples to failure at several different cell pressures and measuring pore pressures throughout the tests.

This paper reports the results of an investigation of the possibility of applying the multiple-stage principle to compression testing of saturated soils in much the same way as it was applied for testing unsaturated soils.

Testing Equipment and Procedures

This investigation was carried out in the laboratories of H.G. Acres & Company Limited. The triaxial compression machine and cells were manufactured by Wykeham Farrance Engineering Limited. The constant cell pressure apparatus and the pore pressure measuring apparatus were built in likeness to those used at the Imperial College, London, and the Norwegian Geotechnical Institute, Oslo, respectively. The samples used were 1·5 inches in diameter and approximately 3·5 inches high. For all tests full end and radial drainage was provided by the use of porous stones and filter paper drains. The top loading cap was fitted with a collar which prevented the op of the sample from rotating more than 6 degrees from the horizontal.

After each consolidation period, the height, volume, and average cross-sectional area of the samples were computed and to avoid possible errors in measuring pore pressures in undrained tests due to entrapped free air, the pore pressure and the cell pressure were both raised 10 psi in order to dissolve the free air. Since all the samples tested were fully saturated, this procedure is quite acceptable. For all undrained tests, the rate of axial strain used was approximately 4 per cent per hour, while for drained tests the rate of axial strain was usually in the order of 0.3 per cent per hour. This axial strain was applied at a constant rate. After any undrained test had been completed, the load was removed from the sample and a condition of constant pore pressure was allowed to be reached before the test was continued or the sample removed.

Failure Conditions

In Fig. 1 is shown the results of some conventional compression tests. These data are presented in the form of stress paths defined by the measured values of σ_a' and σ_r' (axial and radial effective stresses acting within the sample, respectively) which are plotted for various values of strain throughout the test. Drained tests are represented by vertical paths because σ_r' remains constant, and undrained tests are represented by curved stress paths along which both σ_a' and σ_r' vary. Any point on a stress path, whose position in stress space is defined by particular values of σ_a' and σ_r' can be represented by a Mohr stress circle, and a line joining

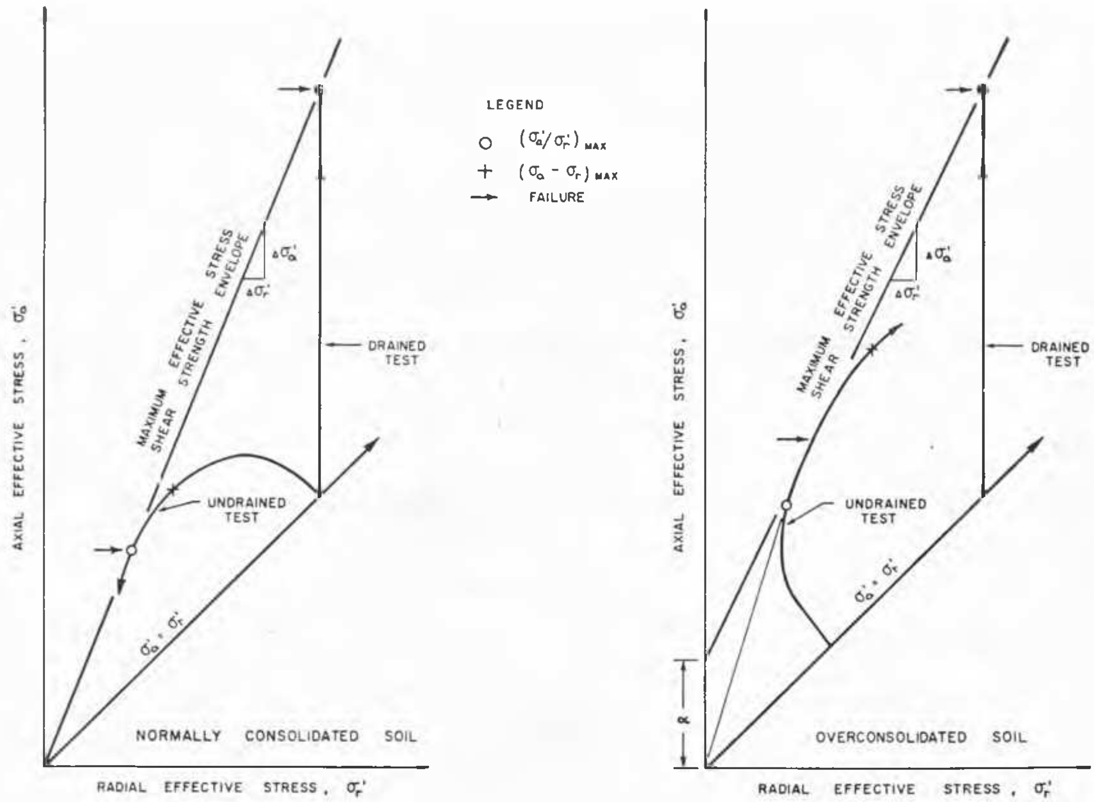

Fig. 1 Method of presenting test results and definition of failure conditions.
Méthode de représentation des résultats d'essais et définition d'états de rupture.

two points on different stress paths can be related to the line tangent to the corresponding stress circles in the following manner :

$$\sin \Phi_a' = \frac{\dfrac{\Delta \sigma_a'}{\Delta \sigma_r'} - 1}{\dfrac{\Delta \sigma_a'}{\Delta \sigma_r'} + 1} \qquad (1)$$

$$c_a' = \frac{\alpha}{2}\left(\frac{1 - \sin \Phi_a'}{\cos \Phi_a'}\right) \qquad (2)$$

where Φ'_a denotes the apparent mobilized angle of shearing resistance, c'_a denotes the apparent mobilized cohesion, α denotes the σ_a' intercept of the line joining the two stress points produced back to the condition of $\sigma_r' = 0$.

At the beginning of the investigation it was first necessary to decide upon a definition of failure in order to determine c' and Φ'. For the purposes of this study, a sample was considered to have reached failure at the point where the stress path was tangent to the maximum effective stress shear strength envelope. Therefore, as it is shown in Fig. 1, failure during a drained compression test is determined by means of either the $\left(\dfrac{\sigma_a'}{\sigma_r'}\right)_{max}$ or the $(\sigma_a - \sigma_r)_{max}$ failure criterion, failure during an undrained compression test on normally consolidated soil (where $c' = 0$) is determined by means of the $\left(\dfrac{\sigma_a'}{\sigma_r'}\right)_{max}$ failure criterion, and failure during an undrained compression test on overconsolidated soil (where $c' > 0$) cannot be determined by either of these failure criteria (Bishop & Henkel, 1957; Kenney, 1959). However, since it is seldom known when samples are going to exhibit the properties of normally consolidated or overconsolidated soils, it follows from the above discussion that a rigorous failure cristerion is only available for the drained test but is unavailable for the undrained test.

For the multiple-stage compression test, and in particular for its application to the undrained type of test, the exact point of failure during any particular test stage does not have to be known; it is more important to know that the test has been carried out far enough to fully mobilize the shear strength parameters c' and Φ'. For this reason, it was decided to investigate the magnitudes of axial strain required to mobilize c' and Φ' to their maximum combined effect. In Fig. 2 are given the results of several drained and undrained compression tests on natural and remoulded normally consolidated soils the properties of which are listed in Table 1. If Φ'_a is the apparent mobilized angle of shearing resistance (Equation 1) and Φ'_{max} is the fully mobilized value, then M, the degree of mobilization of Φ' at any point during a test, is expressed by the equation :

$$M = \frac{\tan \Phi'_a}{\tan \Phi'_{max}} \qquad (3)$$

From the test results given in Fig. 2, the following conclusions can be drawn concerning the shear strength mobilization of normally consolidated soils :

(1) In most of the undrained tests, Φ' becomes fully mobilized at axial strains less than 15 per cent and generally less than 10 per cent, whereas, in the drained tests, Φ' becomes fully mobilized at axial strains between 15 and 30 per cent.

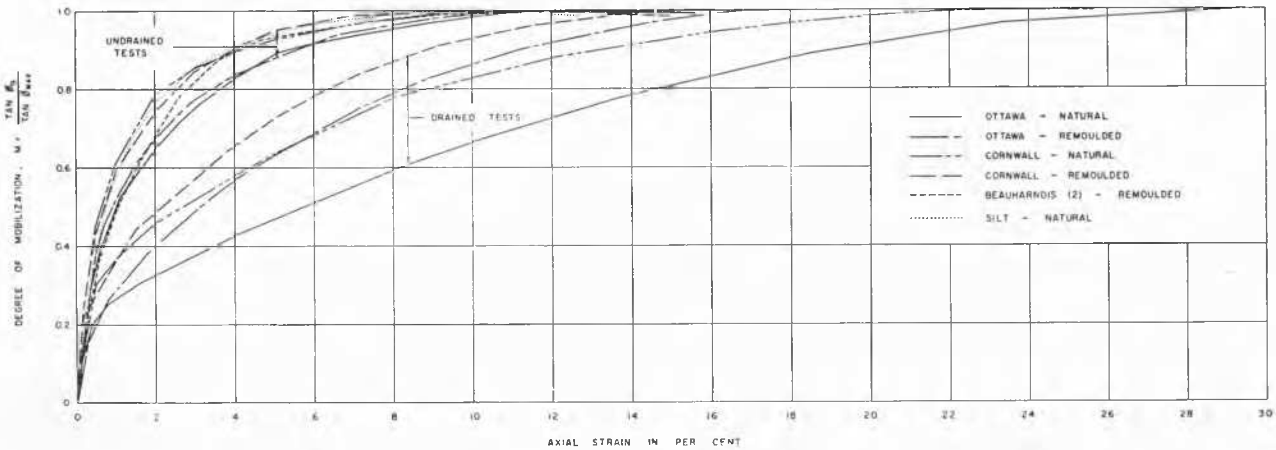

Fig. 2 Mobilization of Φ' with axial strain for several normally consolidated soils.
Mobilisation de Φ' en fonction de la contrainte axiale pour quelques sols normalement consolidés.

Table 1
Properties of soils tested and summary of test results
Propriétés des sols essayés et résumé des résultats

Soil and Origin	L_L P_I	*A* *St*	W_n W_r	*Test*	*Natural* (1) c' Φ'	*Natural* (2) c' Φ'	*Remoulded* (1) c' Φ'	*Remoulded* (2) c' Φ'
Ottawa Estuarine	52·8 26·2	< 0·70 20 +	57·1 41·7	*U*	0 * 34·1 *	0 * 36·1 *	0 35·3	0 35·6
Cornwall Estuarine	27·7 14·1	0·58 10 +	31·4 21·7	*U*	0·26 34·1	0·26 34·1	0 37·4	0 37·4
				D	— —	— —	0 35·9	1·04 34·7
Beauharnois 1 Estuarine	69·9 41·8	0·70 —	— 40·4	*U*	— —	— —	0·36 31·6	0·53 32·2
				D	— —	— —	0·90 28·3	0·90 28·3
Beauharnois 2 Glacial Till	43·5 19·3	< 0·70 —	— 32·7	*U*	— —	— —	0 30·5	0 30·5
St. Catharines Glacial Till	46·0 25·9	0·43 2	27·2 26·6	*U*	2·34 26·1	2·34 26·1	2·20 25·8	2·48 26·4
Wallaceburg Glacial Till	40·5 17·2	0·57 4	40·4 35·4	*U*	0 30·0	— —	0·88 29·1	0 29·1
Allanburg Glacial Till	28·5 15·0	< 0·50 3	23·2 23·0	*U*	0 33·0	— —	0 34·8	0 33·4

L_L Liquid limit
P_I Plasticity index
U Undrained test
D Drained test
A Activity
St Sensitivity
c' Psi
Φ' Degrees
W_n Natural water content
W_r Remoulded water content
(1) Conventional tests
(2) Multiple-stage tests

*Values measured in the normally consolidated stress range of the soil.

(2) In undrained tests the Φ' mobilization characteristics are comparatively independent of the mineral composition and sensitivity of the soils.

(3) In drained tests the Φ' mobilization characteristics are strongly dependent on soil sensitivity and to a lesser extent on mineral composition.

In Fig. 3 are given the volume changes $\left(\frac{\Delta V_f}{V}\right)$ and axial strains at failure in drained tests of several normally consolidated and overconsolidated soil samples. The results of these tests indicate that the stiff, insensitive soils fail at low volume changes and low axial strains and that the softer, more sensitive soils fail at higher volume changes and higher axial strains. These test data also infer that for undrained tests, where zero volume change takes place $\left(\frac{\Delta V_f}{V} = 0\right)$, the range of axial strains required to fully mobilize c' and Φ' of normally consolidated and overconsolidated soils is from 0 to 15 per cent; present laboratory experience has been that the strains at failure range from 1 to 12 per cent.

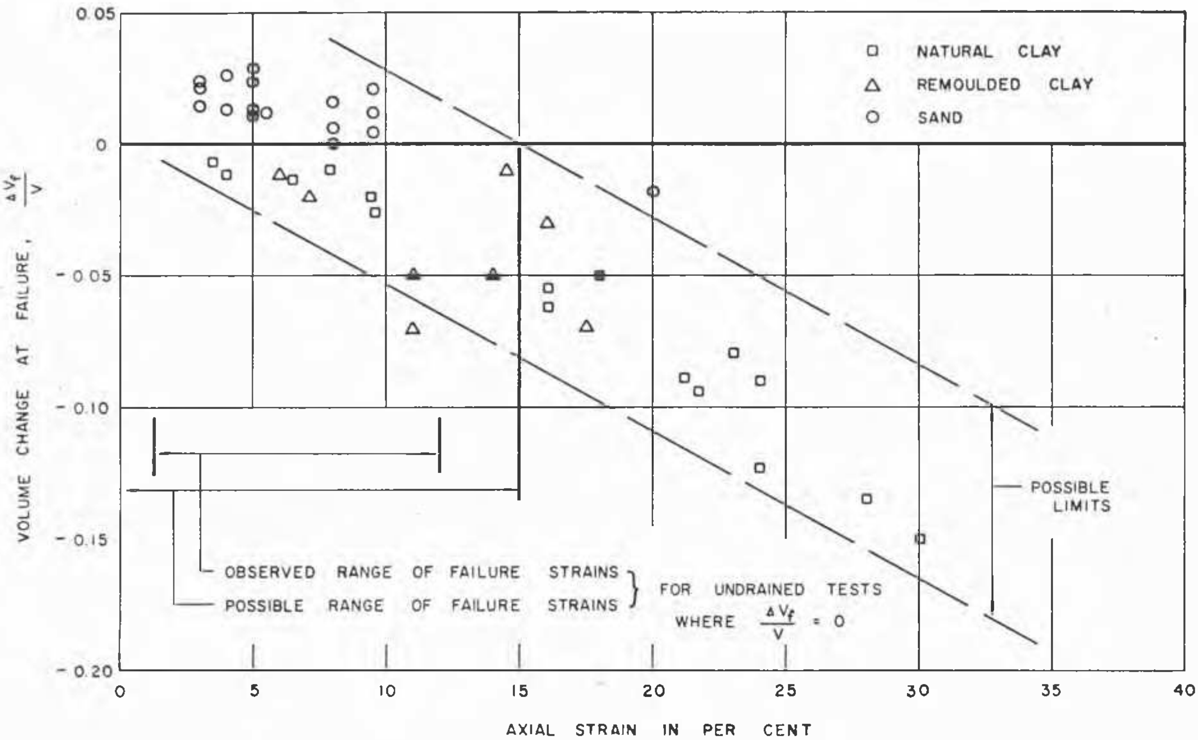

Fig. 3 Volume change and axial strain at failure. Results of drained compression tests on normally consolidated and overconsolidated soils.

Changement de volume et contrainte axiale à la rupture. Résultats des essais drainés de compression sur des sols normalement consolidés et sur des sols surconsolidés.

From the above conclusions it follows that it is possible to fully or nearly fully mobilize c' and Φ' in undrained tests at least two and possibly three times with one sample at different consolidation pressures if axial strains of the order of 25 per cent or more are attainable with the available testing apparatus. For drained tests, c' and Φ' can be fully mobilized in one sample two or more times only if the soils have stable structures and, therefore, low sensitivities.

Undrained Tests

The test procedure for the multiple-stage undrained compression test which was used, consisted of consolidating a sample under different cell pressures, computing the height and volume of the sample after each consolidation phase, raising both the cell pressure and the pore pressure by equal amounts (approximately 10 psi) to dissolve any free air, and loading the sample until an axial strain of 5 to 10 per cent was reached or, in the case of brittle materials, until a failure surface developed in the sample and the load taken by the sample began to decrease rapidly.

To compare the results of the multiple-stage and conventional types of undrained tests, samples of different soils were tested in natural and/or remoulded states. The properties of these soils and a summary of the test results are given in Table 1.

In all the multiple-stage tests recorded herein, three compression stages were used. Typical test comparisons are given in Fig. 4. The following comments are made concerning the testing experience to date :

(1) Only soils having activities less than 0.75 have been tested. In all cases it was possible to bring about failure conditions three times in a multiple-stage undrained test.

(2) The values of c' and Φ' determined from multiple-stage and conventional undrained tests compare very closely for all the soils investigated. The shapes of the stress paths of the two types of test were not generally similar.

(3) The consolidation pressures which are now generally used for the multiple-stage tests are 10, 30, and 60 psi.

(4) For soft soils of low sensitivity, axial strain increments of 10, 8, and 6 per cent for the first, second, and third stages of the test, respectively, have been found sufficient to fully or nearly fully mobilize c' and Φ.

(5) For brittle soils, such as overconsolidated or very sensitive soils, full mobilization of c' and Φ' generally occurred at low strains and in this case the test stage should be stopped when the load on the sample begins to decrease rapidly. The subsequent stages are generally extended to at least 10 and 8 per cent respectively unless a brittle type of failure again takes place.

Drained Tests

The test procedure for the multiple-stage drained compression test which was used consisted of consolidating a sample under different cell pressures, computing the height and volume of the sample after consolidation, and loading the sample under drained conditions until failure occurred. Very few of these tests have been performed and only the results of two comparisons are listed in Table 1, both of which were made on remoulded soils. The test results compare fairly closely but the data is insufficient to enable conclusions to be drawn.

Conclusions

It has been found possible to apply the multiple-stage principle to compression testing of saturated soils. For the inactive soils which have been tested, the values of c' and Φ' determined from undrained multiple-stage and conventional

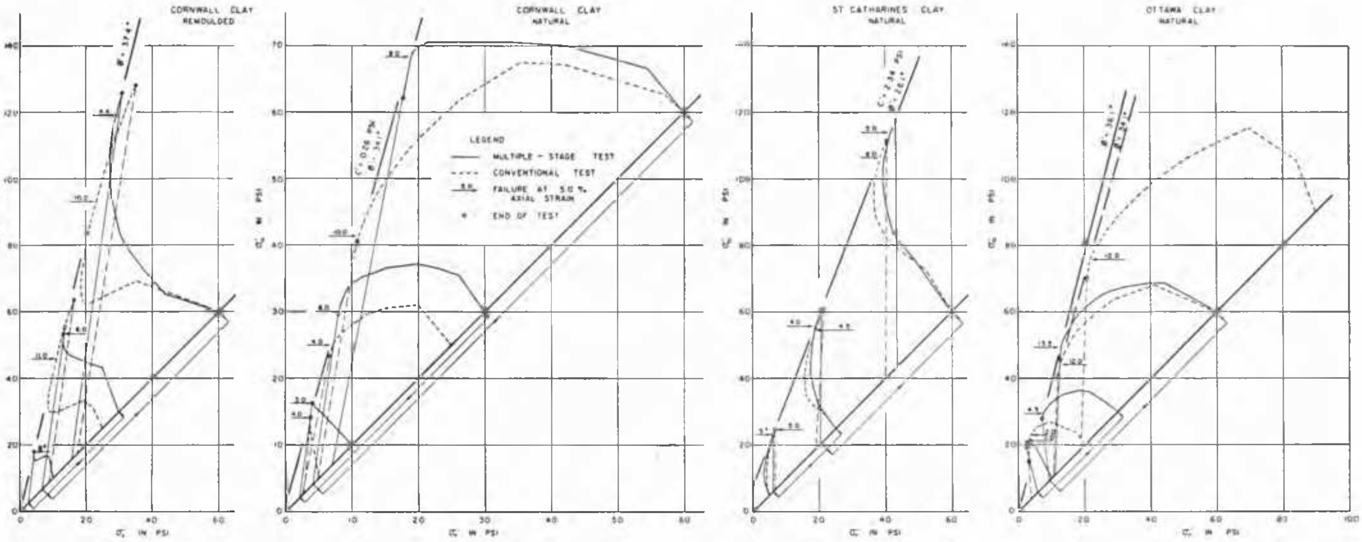

Fig. 4 Comparison of results of multiple-stage and conventional traixial compression tests.
Comparaison des résultats obtenus par les essais triaxiaux échelonnés et les essais conventionnels de compression triaxiale.

tests compared very closely; the shapes of the stress paths of the two types of test were found not to be similar and, therefore, the induced pore pressures were different.

Very few drained multiple-stage compression tests have been done. However, it was shown that this test is only applicable to soils which produce small volume changes at failure and, therefore have relatively stable structures.

An interesting observation which can be made from the test results in Table 1 is that the value of Φ' for normally consolidated sensitive soils is very nearly equal to Φ' for these soils in a normally consolidated remoulded state, even though the water contents of these materials are vastly different.

The testing experience reported here is limited and additional work is required concerning the application of the multiple-stage test to soils having activities greater than 0·75. The test does not seem to be applicable for drained compression tests on sensitive soils; however, the multiple-stage principle might be applicable to drained ring shear tests or extension tests.

Acknowledgment

The authors wish to thank the management of H.G. Acres & Company Limited, and especially Dr. D. H. MacDonald, for the use of the Company's laboratory facilities. They also wish to thank Mr. C. B. Crawford of the National Research Council of Canada and Mr. D. J. Bazett of The Hydro-Electric Power Commission of Ontario for supplying some of the natural soils which were tested.

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