Triaxial Shear Tests Holding Effective Lateral Stress Constant

Essai de Cisaillement Triaxial Tenant Constante la Tension Latérale Efficace

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Summary

Research by the Bureau of Reclamation in shearing strength of compacted cohesive soils has produced new procedures for specimen preparation and test operation of triaxial shear tests. Drainage is not permitted in these tests, but pore pressures are measured to obtain the Mohr strength envelope on an effective stress basis. In the new technique, effective lateral stresses are held constant during application of shearing stresses to the specimen. At constant effective lateral stress the phenomenon of false strength due to pre-stress is eliminated and the criterion of failure is not subject to interpretation.

In an attempt to simulate embankment stress conditions, soil specimens are prepared at the same water content but at different densities and are then compressed, without drainage, to a predetermined void ratio prior to being sheared. Preliminary results indicate that the new method of shear testing is practicable. The slope of the Mohr strength envelope obtained is somewhat smaller than was obtained by the previously used method.

Sommaire

Les recherches effectuées par le Bureau de Réclamation sur les forces de cisaillement d'un sol cohérent compacté ont donné lieu à de nouveaux procédés pour la préparation des échantillons et le mode d'opération pour l'essai de cisaillement triaxial. Dans ces tests le drainage n'est pas permis, mais la pression de l'eau interstitielle a été mesurée afin d'obtenir l'enveloppe résistante de Mohr pour la tension effective. Dans la nouvelle technique les tensions latérales effectives sont tenues constantes pendant l'application des forces de cisaillement sur l'échantillon. A tension latérale constante, le phénomène de fausse résistance dû à la précontrainte est éliminé et le critère de rupture n'est pas sujet à l'interprétation.

Afin de reproduire dans un test les conditions des forces dans les terrassements, des échantillons de sol sont préparés, ayant le même pourcentage d'eau mais des densités différentes, et sont alors compressés sans drainage, jusqu'à un indice de vides prédéterminé, avant d'appliquer la pression de cisaillement. Les premiers résultats indiquent que la nouvelle méthode d'essai de cisaillement est praticable. La pente de l'enveloppe résistante de Mohr obtenue est plus petite que celle obtenue par les méthodes précédentes.

The strength of compacted cohesive soils is being given renewed attention by the Bureau of Reclamation engineers in view of project requirements for embankments of unprecedented heights. Earth dams 500 ft. high are now under active consideration in the western portion of the United States of America. The proposed dams are located in mountainous areas where the presence of rock foundations provides adequate supporting capacity, but where the available impervious embankment soils may be of mediocre quality. These circumstances warrant the attempt at refinements in laboratory testing designed to approach more nearly prototype stress conditions. This interim report describes a new procedure of triaxial shear testing of cohesive embankment soils in which: (1) effective lateral stress is held constant throughout the test; and (2) application of shearing stresses to each specimen begins at the same void ratio.

The former laboratory procedure for triaxial shear testing of compacted embankment soils was to prepare three or more identical specimens, usually at Proctor optimum water content and maximum laboratory density. Each specimen was jacketed with a rubber membrane and placed in the testing machine where it was first compressed without drainage under an ambient stress; then sheared to failure by application of deviator stress ($\sigma_1 - \sigma_3$), holding the applied lateral principal stress (σ_3) constant. Each specimen was compressed under a different magnitude of ambient stress before being subjected to shear in order to obtain a strength-stress relation for the entire range of loadings in the fill. Pore pressures were measured at the end of the specimen and were used to determine effective stresses for the Mohr strength envelope. The criterion of failure used by the Bureau for this test was the maximum principal effective stress ratio (σ'_1/σ'_3).

The details of laboratory pore pressure measurements and the failure criterion have been given by HOLTZ (1947). Further research on pore pressure measurements is now in progress but will not be reported here. The use of the maximum principal stress ratio as the criterion of failure has been objected to by TAYLOR (1950) as being less satisfactory than the criterion of maximum deviator stress.

In the 1953 conference, CASAGRANDE (1953) pointed out that, in consolidated-quick triaxial shear tests on saturated clays, the effective principal stress ratio at failure was larger than in slow (drained) tests on the same soils. This was attributed to pre-stress caused by steadily falling effective lateral stresses during tests in which pore pressures are present. The loci of computed points representing effective normal and shearing stresses on the failure plane, which are called vector curves, were used to illustrate the phenomenon of pre-stress. Similarly, it should be recognized that quick triaxial tests on unsaturated embankment soils may induce pre-stress in the specimen as its volume decreases under application of the deviator stress. The magnitude of pre-stress in tests on unsaturated soils will depend on the amount of pore pressure developed during the tests.

Controversy over which criterion of failure to use (maximum principal stress ratio or maximum deviator stress) and the possibility of pre-stress during the triaxial shear tests can both be avoided by the revised technique developed by the Bureau of Reclamation engineers. The procedure requires adjustment of the applied lateral stress during the triaxial shear test so that the initial lateral *effective* stress remains constant. This, of course, can be done only when pore pressures are measured. Under these circumstances, the vector curve becomes a straight line of positive slope and the maximum principal stress ratio point is always identical with the maximum deviator stress. The practicability of this procedure has been determined by actual tests which are reported herein.

The procedure of compressing identical test specimens at different ambient loads prior to application of shearing stress has been critically reviewed. In order to determine the Mohr strength envelope it is necessary to obtain failure of several specimens over a range of stress values. However, this procedure amounts to shearing each specimen at a different initial void ratio, a situation which does not correspond to conditions in the embankment. During construction of a rolled fill, the objective is for each layer of soil to be identical and to be compacted at the same water content and to the same density. Immediately after compaction, it can be assumed that the soil is virtually unstressed externally. As construction proceeds, the load of superimposed layers of fill simultaneously applies normal and shearing stresses to the impervious soil, causes it to change in volume, and induces pore pressures. Hence, the laboratory process of triaxial compression without shear does not occur in the fill.

It is possible to simulate prototype conditions in the laboratory by compacting a specimen to expected placement conditions and varying the chamber and deviator stresses in such a manner as to preclude pre-stress and gradually to approach failure. Different specimens all starting at identical densities and water contents could be made to fail at different effective stress conditions to provide an effective Mohr strength envelope. However, this procedure is not as practicable as the following method which, it is believed, accomplishes the objective that shearing stresses should be applied to all specimens at identical void ratios and water contents. This can be done by compacting specimens 1, 2 and 3 of the sample to be tested to about 99, 98 and 97 per cent, respectively (actual percentages to be

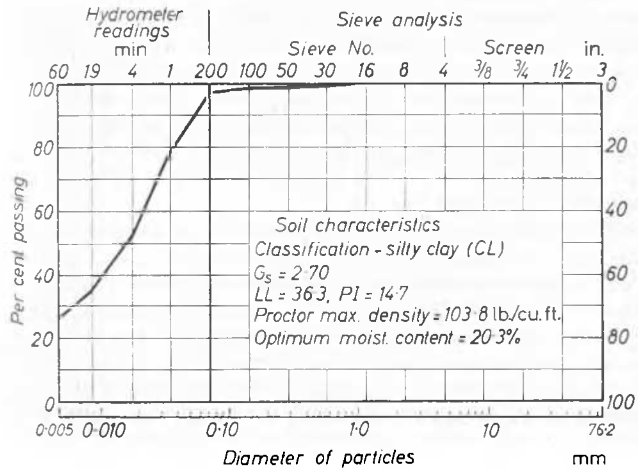

Fig. 1 Soil characteristics
Caractéristiques du sol

determined by experience) of the desired placement density and at the desired water content. Each specimen is then placed in the triaxial machine and compressed without drainage to the desired placement density. Since volume change of the specimen is measured, accurate control of density can be accomplished without particular care in specimen preparation. The applied stress will, of course, vary for each specimen as will the induced pore pressures, but the effective pressures (applied stress minus pore pressure) should vary sufficiently so as to obtain a strength envelope of the desired stress range.

The triaxial shear apparatus used for these tests is that described by Holtz (1947). This equipment permits the testing of cylindrical specimens of various sizes and has provisions for measuring volume change, pore fluid pressure, and applied stresses during the test. The specimen size used in these tests was 3¼ in. in diameter by 9 in. high. The pore pressure was measured through perforated end plates using a measuring device which did not permit drainage. This device consists of an electrical automatic recorder fitted with pressure transducers that permitted simultaneous readings of the applied lateral pressure and the pore pressure at the end plates. Since the effective lateral stress is equal to the applied lateral pressure minus the pore pressure, the automatic recorder provided a simple method of holding the effective lateral pressure constant. This was done by measuring with calipers the distance on the recorder sheet between the pore pressure markings and the applied lateral pressure markings immediately prior to the application of deviator stress. The applied pressure was then regularly adjusted by the operator during the test as pore pressure varied so that the distance between these markings remained equal to the set calipers.

The volume change was measured at regular intervals by measuring the volume of lateral fluid going into or leaving the chamber. The rate of testing was controlled at constant axial deformation. The best rate for reliable pore pressure measurements was found to be 0·025 in. of axial deformation per minute.

The initial investigation of the constant *effective* lateral stress method of triaxial shear testing included comparisons with the previous standard method. A representative series of six specimens was tested from a sample of typical embankment

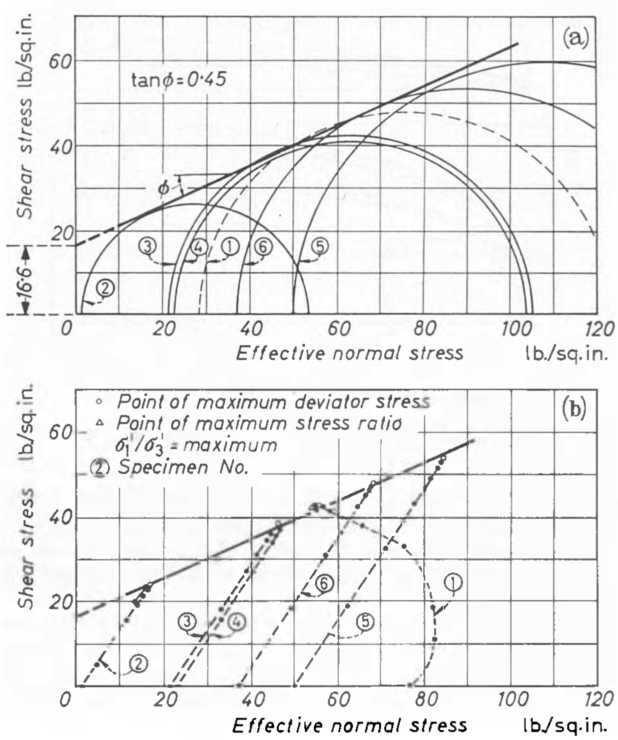

Fig. 2 Results of triaxial shear tests: (a) stress circles and shear strength envelope; (b) vector curves

Resultats des essais de cisaillement triaxial: (a) cercle de contraintes et enveloppe de resistance au cisaillement; (b) courbes de vecteur

material. The soil was a moderately plastic, silty clay embankment material from Webster Dam, Kansas, with soil characteristics shown in Fig. 1.

Specimen 1 was tested by using a constant *applied* lateral pressure of 100 lb per sq. in. It was placed at a density less than Proctor maximum and about average of the other five specimens. The purpose of the test on specimen 1 was to establish the approximate stress-strain and pore pressure relationships of the soil for use in preparing subsequent specimens as well as to provide a comparison with the other five specimens tested by the new method.

Specimens 2, 3, 4, 5 and 6 were tested by the method of constant *effective* lateral stress. The constant pressure for each specimen was varied to give a spread of failure stress circles and shearing resistance envelope. Each specimen was compacted at a density somewhat below Proctor maximum density so that the effective lateral stress used would cause a compression of the specimen to Proctor maximum density for all specimens prior to the application of shearing stresses.

All specimens were prepared and tested at optimum moisture

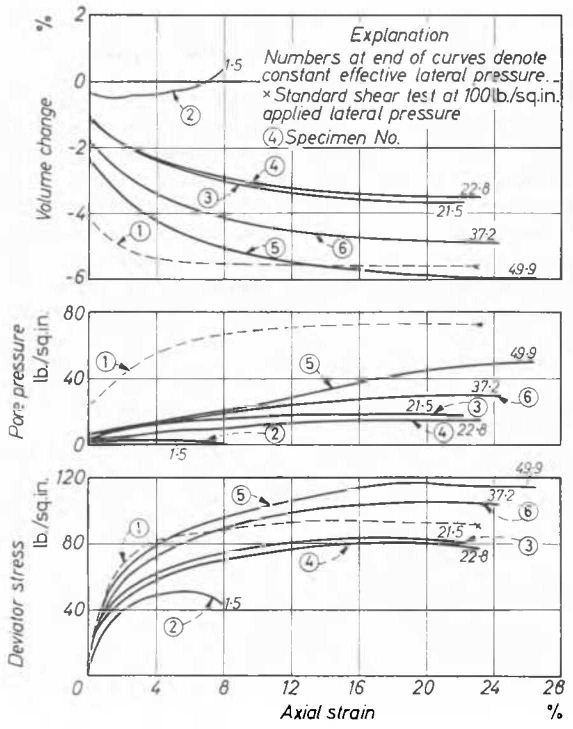

Fig. 3 Stress and strain relationships for shear specimens

Contraintes et deformations de l'echantillon au cisaillement

content (14·7 per cent) and were sealed during the entire test. Specimen 1, the first trial test, was sheared at a rate of 0·050 in. axial deformation per minute. The rate of testing was relatively slow, 0·025 in. axial deformation per minute, for specimens 2, 3, 4, 5 and 6 in order to obtain reliable pore pressure observations.

Fig. 2 shows the results of the triaxial shear tests for these specimens: (a) shows the failure stress circles and the shear envelopes—the stress circle for specimen 1 is shown by dashed line and is not included in developing the shear envelope; (b) shows the vector curves for each specimen. These were developed for each specimen by connecting points of tangency of a line of slope ϕ to stress circles representing each progressive observation of the test to failure.

The vector curves for specimens 2, 3, 4, 5 and 6 demonstrate the building up of effective normal and shearing stresses on the failure plane according to a straight line relationship as compared to the curved shape of the vector curve and dropping off of effective normal stress for specimen 1. It follows, therefore, that the effective normal stress in specimen 1 goes through a process of pre-stressing before failure is reached, whereas the normal stresses of specimens 2, 3, 4, 5 and 6 do not, but instead gradually increase to failure.

Fig. 3 shows the stress and strain relationships of specimens 1, 2, 3, 4, 5 and 6. In the volume change and deviator-stress plots, noticeable differences can be seen between the shapes of the curves for specimen 1 and for specimens 3, 4, 5 and 6. The curves for specimens 3, 4, 5 and 6 (tested by constant *effective* lateral pressure) show gradual increases in volume change and deviator stress whereas the dash curves for specimen 1 (tested by constant *applied* lateral pressure) show rapid increases at first, and a levelling off at later strains which further demonstrates the effects of pre-stressing and reducing of *effective* lateral load at greater strains. Curves for specimen 2 reflect slight expansion under light load.

Fig. 4 contains curves giving the records of placement void ratio, volume change, and stress conditions for each specimen. These curves show the history of stress and volume strain (in terms of void ratio) during the test. The initial placement conditions are shown as solid points and the circled numbers refer to the respective specimens. Specimens 2, 3, 4, 5 and 6 were placed at varying void ratios and initially compressed with different effective lateral loads to the void ratio corresponding

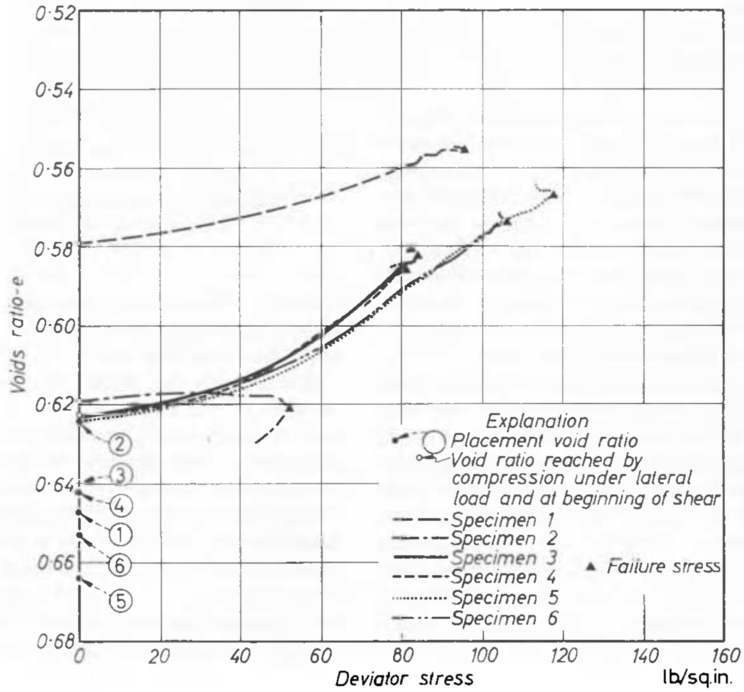

Fig. 4 Record of void ratio and stress during testing

Enregistrement de l'indice de vide et des contraintes pendant l'essai

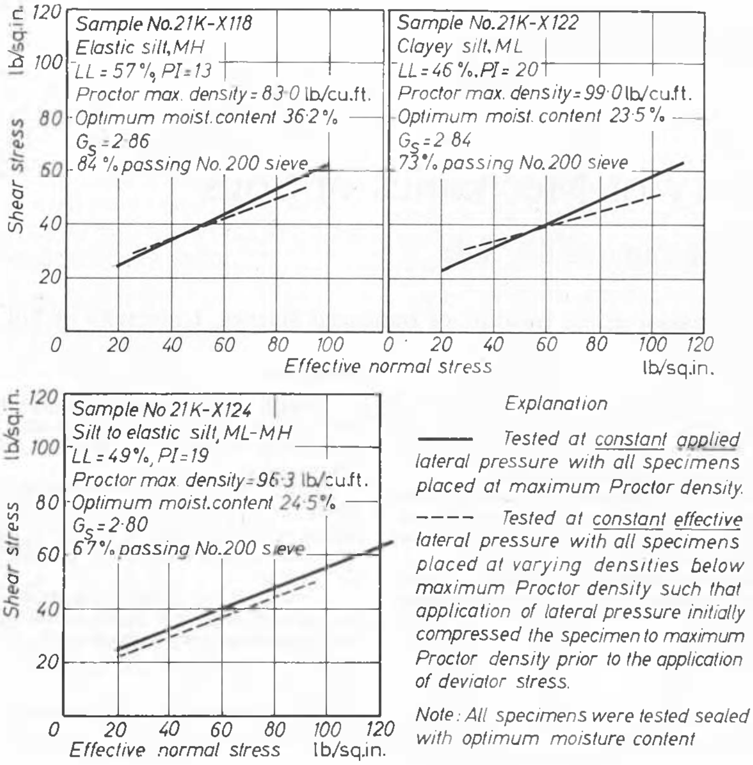

Fig. 5 Examples of tests on silts
Exemple des essais avec limon

to Proctor maximum density, approximately e = 0·62. The effective lateral load required to result in this void ratio for each specimen was maintained while shearing stresses (deviator stresses) were increased to failure. Specimen 1, similarly indicated on the graph, was placed at a void ratio which was about average of the other five but was compressed by a 100 lb. per sq. in. applied lateral pressure which was maintained constant while shearing stresses were applied. The curves demonstrate that the deviator stress and volume change relationships are quite similar for specimens 2, 3, 4, 5 and 6 but the compressive strengths at failure vary according to the effective lateral stress. The curve for specimen 1 was quite different in that the initial applied lateral load of 100 lb. per sq. in. resulted in higher initial effective lateral load than for the other five specimens, hence, caused a higher volume change. Nevertheless, deviator stress at failure was less than for specimens 5 and 6 because the initial effective lateral stress was reduced as pore pressures increased during the test.

Fig. 5 shows comparisons between the two methods of tests for three samples of another type of cohesive soil.

Conclusions

The method of shear testing using constant *effective* lateral pressure can be conducted in the laboratory with very little extra effort, using the automatic pressure recorder for observing pressure development and continuously adjusting the applied lateral pressure according to the development of pore pressure; also, it is possible to prepare recompacted specimens so that a certain density is reached prior to the application of deviator stress, although this involves trial and error methods in order to obtain a spread of lateral pressures for the various specimens.

The results of this study show distinct differences in stress and strain (both axial and volume change) relationships for the old standard and the above new methods of testing, and somewhat lesser values of tan ϕ. Greater differences in results between the two methods can be expected if higher moisture contents are used and for soils which develop pore pressure of greater magnitude.

Additional tests of this type are being made on a variety of cohesive embankment soils proposed for use in high earth dams.

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