The Shear Strength of Silt

La Résistance au cisaillement du limon

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SUMMARY

After the direct shear apparatus had proved itself unsuitable for the investigation of the shear strength of silt, the shear deformation behaviour and the shear parameters were investigated in three disturbed, saturated silts, and in a clay sample, by means of systematic triaxial tests with pore-water-pressure measurements. For drained and undrained triaxial tests the governing stress criterion for the definition of the effective shear parameters was defined. It was possible during the utilization of the natural dilatation of the silt, to develop a method, by means of the evaluation of the course of the stress and also the pore water pressure during the test, which permitted all the shear parameters of silt for both the true and the effective strength to be determined by means of one single test. The true cohesion is a logarithmic function of the water content. The dependence of the shear strength on the water content and the effective normal stress is illustrated in a three-dimensional co-ordinate system. The various angles of friction depend on the plasticity index.

SOMMAIRE

La boîte de cisaillement simple s'étant montrée inutilisable pour examiner la résistance au cisaillement du limon l'on scruta le comportement de la déformation au cisaillement et les paramètres de cisaillement de trois sols limoneux, remaniés et saturés d'eau, ainsi que d'un échantillon d'argile, à l'aide d'essais triaxiaux systématiques comportant des mesures sur la pression de l'eau interstitielle. Pour les essais triaxiaux drainés et non drainés l'on détermina le critérium de contraintes décisif pour la définition des paramètres de cisaillements effectifs. En tenant compte de la dilatation propre du limon, il fut possible de développer un procédé permettant de déterminer, avec un *seul* essai *tous* les paramètres de cisaillement du limon aussi bien pour la résistance effective que réelle, en mettant en valeur la variation de contraintes et la pression de l'eau interstitielle au cours de l'essai. La cohésion réelle est une fonction logarithmique de la teneur en eau. L'interdépendance de la résistance au cisaillement, de la teneur en eau et de la contrainte effective normale est représentée dans un système d'axes de coordonnées dans l'espace. Les différents angles de frottement dépendent de l'indice de plasticité.

IN THE LAST FEW YEARS the shear strength of silt has been investigated as a part of a comprehensive investigation of the properties of silt. The following aspects have already been treated: the statistics of undisturbed samples, especially these of the compressibility (Schultze and Kotzias, 1961; Kotzias, 1963); the general rheological behaviour (Akai, 1960) and the rheological behaviour in connection with the degradation with time of the pore water pressure in compression tests (Schultze and Krause, 1964; Krause, 1964); the sounding resistance (Menzenbach, 1959); the thermal solidification (Horn, 1964); and the stabilization by chalk in highway construction (Brand, 1962; Frank, 1965).

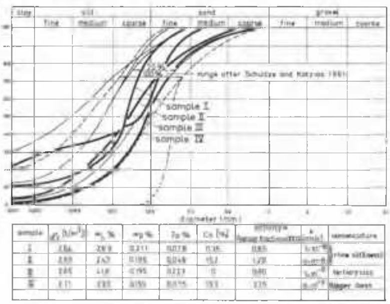

FIG. 1. Grain size distribution and soil characteristics of the soils investigated.

SHEAR TESTS

Types of Soil

Two silts from the Aachen district were investigated (I–II), one from Israel (IV), and as a comparison, a silty clay from Duisburg (III). The main tests were carried out on soil I (Fig. 1).

State of the Samples

The samples were disturbed and mechanically homogenized in a water-saturated state somewhat above the liquid limit. In sample I the built-in water content amounted to 30 to 32 per cent.

Direct Shear Tests

The effective angle of friction of the drained direct shear tests is appreciably smaller than in the drained triaxial tests, a value of 32.5 deg. was measured as opposed to 36.2 deg. The cause of this deviation lies for the most part in the appearance of a progressive failure which was clearly recognized on the shear surfaces. Also, disturbances arise as a result of friction at the wall, tilting, sticking, and the larger average principal stress during the direct shear tests.

Triaxial Tests

Apparatus. Most of the triaxial tests were carried out with a cell suitable for 3.8-cm diameter samples and a small number of 10-cm samples. The pore water pressure was measured by the apparatus of Bishop and Penman, and by a newly developed part of the apparatus.

Types of test. The important investigations carried out were drained and consolidated-undrained tests with the pore water pressure measurement being made each time under constant lateral pressure. In addition, some special tests were performed.

TABLE I

No.	Test	v (per cent/min)	Test duration (hours)
1	drained	0.01	10 + 35 = 45
2	undrained		
2.1	with pore-water-pressure measurement	0.1	10 + 5 = 15
2.2	without pore-water-pressure measurement	1.0	10 + 0.5 = 10.5

Test speeds. In the standard tests with sample I the results given in Table I were obtained for shearing speeds and test duration. Here 10 hours were allowed for the consolidation of each sample and additional time for the actual shearing.

RESULTS OF TRIAXIAL TESTS

Test Diagrams

Drained test. The sample fails at a pore water pressure, $u = 0$. At the same time the quantities $\Delta V/V_1$, $(\sigma_1 - \sigma_3)$, and (σ'_1/σ'_3) attain their maximum. The failure point is therefore uniquely fixed. The shear line inclined at an angle φ' passes, also with overconsolidated silts, through the origin ($c' = 0$). This is due to the dilatation of the silt which reduces any pore water pressures. The test path ends at the maximum of $(\sigma_1 - \sigma_3)$ or (σ'_1/σ'_3) on the shear line. In this case both failure criteria are therefore identical.

Consolidated-undrained test. The sample shears at the maximum value of $(\sigma_1 - \sigma_3)$ which is only reached after large displacement (Fig. 2b). At this failure point the pore water pressure is not zero. The maximum of (σ'_1/σ'_3) appears significantly earlier because of decreasing pore water pressures during the shearing process (Fig. 2a). With the failure criterion for $(\sigma_1 - \sigma_3)$ in drained and undrained tests the same effective angle of friction is obtained. This failure criterion is therefore generally applicable for silt. φ' is therefore obtained by joining the origin of the co-ordinate system to the point of the maximum of $(\sigma_1 - \sigma_3)$ on the shear line. The test path for the effective stresses runs between the maximum of (σ'_1/σ'_3) and of $(\sigma_1 - \sigma_3)$ in the true shear line which is characterized by the parameters c_w and φ_w. Here $c_w \neq 0$, and $\varphi_w < \varphi'$ (Figs. 2d, 2e).

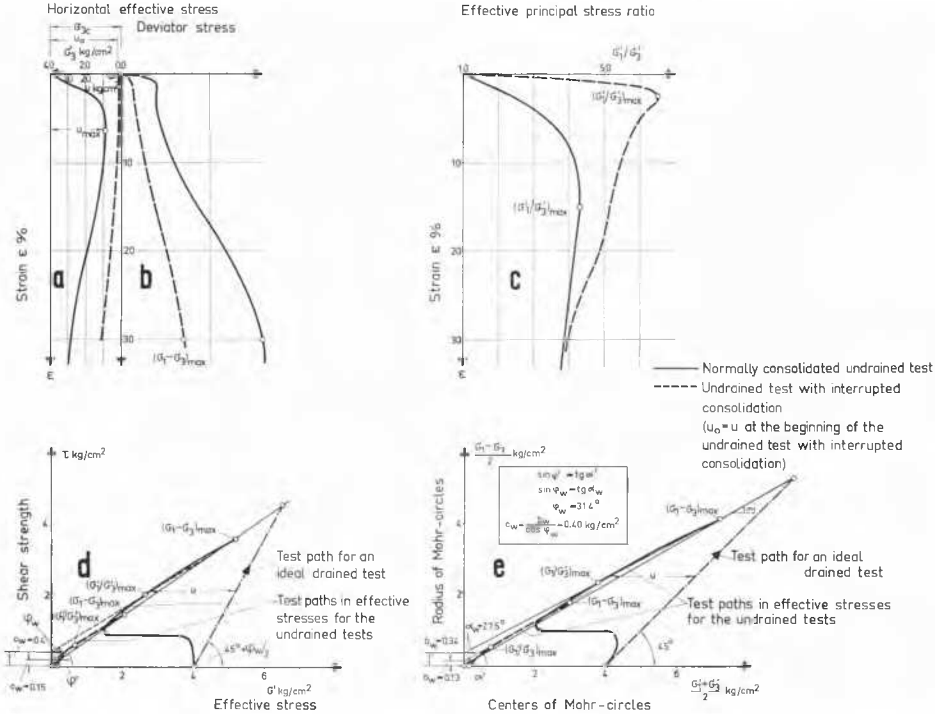

FIG. 2. Result of an undrained test (standard test) and undrained test with interrupted consolidation: (a) pore water pressure u; (b) deviator stress $(\sigma_1 - \sigma_3)$; (c) effective principal stress ratio σ'_1/σ'_3; (d) shear diagram with test path in $\tau - \sigma'$ co-ordinates; (e) shear diagram with test path in $\frac{1}{2}(\sigma_1 - \sigma_3) - \frac{1}{2}(\sigma'_1 + \sigma'_3)$ co-ordinates.

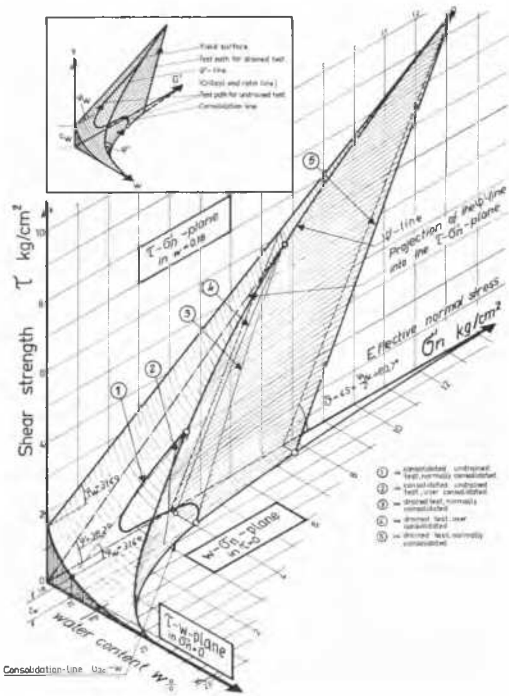

FIG. 3. Representation of the shear strength of silt in three-dimensional co-ordinates.

Effect of the water content. Both the true cohesion, c_w, and the cohesion, $c_u = ½(\sigma_1 - \sigma_3)$, of the undrained tests depends on the all-round consolidation pressure σ_{3c} (Fig. 4b).

Yield surface. By the boundary surface of the shear strength (Fig. 3) all the properties of the silt, which are related to the shearing, are given. All the tests can be reproduced by curves in this co-ordinate system; this is true for both the test paths and the shear lines.

Size of the shear parameters. The effective angle of friction φ' and the true angle of friction φ_w depend on the plasticity of the soil. For the three silts investigated, the angles of friction φ' for the failure criterion $(\sigma_1 - \sigma_3)_{max}$ varied slightly between 36.0 deg. and 36.6 deg. In contrast, the true angles of friction φ_w ranged from 26.4 deg. to 31.4 deg.

The relation between c_w and w is a parallel to the consolidation curve. With overconsolidation c' is also zero in the drained test, due to the sucking in of water by the dilatation of the soil. c_u and c_w depend on the water content (Fig. 4b).

Test Programme

A very simple programme of investigation for the determination of the shear parameters of silt can be derived from the above experimental results. The advantage of such a programme is that all the properties relating to the shear strength can be determined by the triaxial consolidation test and a single consolidated undrained shear test with constant, yet randomly chosen, lateral pressure.

In the undrained test (Fig. 4) the test path is similarly plotted (Fig. 4f). Firstly, it gives a piece of the true shear curve between the maximum of (σ'_1/σ'_3) and the maximum of $(\sigma_1 - \sigma_3)$. By extension of the same the true shear parameters c_w and φ_w are obtained. The effective angle of friction φ' appears in this diagram as a straight line between the origin and the maximum of $(\sigma_1 - \sigma_3)$.

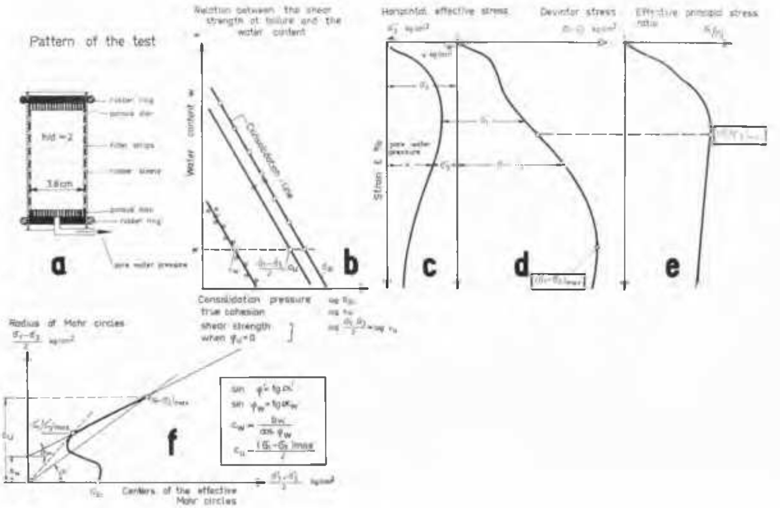

FIG. 4. Test programme for the undrained test for the determination of the effective angle of friction φ', the true shear parameters φ_w and c_w and the cohesion c_u.

If one wishes to ascertain the values c_w and c_u for other values of the water content it is sufficient at first to plot the all-round consolidation test with the ordinates w and log σ_{3c} as a straight line (Fig. 4b). By means of the values of c_u and c_w already determined, one can then draw parallels which make the dependence on the water content quite clear.

REFERENCES

AKAI, K. (1960). *Die strukturellen Eigenschaften von Schluff.* Mitteilungen aus dem Institut für Verkehrswasserbau, Grundbau und Bodenmechanik, TH Aachen 22.

BRAND, W. (1962). Der Einfluss von Kalziumhydroxyd auf die Eigenschaften schluffiger Böden im Strassenbau. Dr.-Thesis, Technische Hochschule, Aachen.

FRANK, A. (1965). Einfluss der Bodenkennziffern und der Wärme auf die Verfestigung schluffiger Böden mit Kalkhydrat im Strassenbau. Dr.-Thesis, Technische Hochschule, Aachen.

HORN, A. (1964). *Die Scherfestigkeit von Schluff.* Forschungsberichte de Landes Nordrhein-Westfalen, Nr. 1346. Westdeutscher Verlag Köln und Opladen.

——— (1964). Wärmetechnische Verfestigung bindiger Böden, insbesondere von Schluff. *Baumaschine-Bautechnik,* 11. p. 367.

KOTZIAS, P. (1963). *Die Zusammendrückbarkeit von Schluff.* Mitteilungen aus dem Institut für Verkehrswasserbau, Grundbau und Bodenmechanik, TH Aachen, 28.

KRAUSE, J. (1965). Untersuchungen über die eindimensionale Konsolidation eines gestörten, wassergesättigten Schluffs. Dr.-Thesis, Technische Hochschule, Aachen.

MENZENBACH, E. (1959). *Die Anwendbarkeit von Sonden zur Prüfung der Festigkeitseigenschaften des Baugrundes.* Forschungsberichte des Landes Nordrhein-Westfalen, Nr. 713, Westdeutscher Verlag Köln und Opladen.

SCHULTZE, E., and P. KOTZIAS (1961). Geotechnical properties of Lower Rhine silt. *Proc. Fifth International Conference on Soil Mechanics and Foundation Engineering,* Vol. 1, p. 329.

SCHULTZE, E., and J. KRAUSE (1964). Pore-water pressure and creep in one-dimensional compression of silt. *International Symposium Rheology and Soil Mechanics* (Grenoble), Vol. 2, p. 3.