Large Scale Shear Tests

Essais de Cisaillement à Grande Échelle

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Summary

Direct shearing tests with a plane of shear of 1 m^2 were carried out in an open-pit of a lignite mine during 1953 in order to explore *in situ* the shearing strength between the lignite and the underlying beds.

An apparatus for large scale triaxial compression tests has been set up which permits the insertion and the shearing off of samples 1·25 m long and 0·5 m diameter. The lateral pressure is produced by exhausting the air out of the specimen and may be increased up to 0·9 kg/cm^2. The tests were started with gravel (density 1·96 t/m^3) for which also parallel experiments with the usual measuring of the triaxial pressure apparatus of 3·6 cm diameter and 9 cm height, as well as tests with the direct shearing apparatus by Casagrande (controlled shearing load) and a shearing motorized apparatus (controlled shearing displacements) for various compactness are available. A further series of large scale tests dealt with a broken slatey greywacke at various compactions (densities 1·55 and 1·87 t/m^3). With a very cohesive material (weathered silty greywacke schist) similar tests were carried out with three compactions (densities 1·86, 2·11 and 2·36 t/m^3). Comparative experiments with the normal apparatus dimensions are available. Finally a silty sandy gravel (density 1·79 t/m^3) was tested.

The special problems which arise from the tests are explained and the usefulness of such experiments is critically examined.

Sommaire

Des essais directs de cisaillement, avec une surface à cisailler de 1 m^2, furent exécutés au cours de l'année 1953 dans une exploitation de lignite à ciel ouvert. Il s'agissait d'étudier la résistance au cisaillement entre la lignite et la base d'un gisement.

Au cours de l'année 1954 fut mis en marche un appareil pour des essais de pression triaxiale à grande échelle, qui permet de monter des essais de 1·25 m de hauteur et 0·5 m de diamètre. La pression latérale est obtenue par aspiration de l'air de l'échantillon; cette aspiration peut être poussée jusqu'à 0·9 kg/cm^2. Les essais ont été entrepris avec du gravier d'éboulement (poids par unité de volume: 1·96 t/m^3) pour lequel on connaît déjà, pour différentes densités de gisements, des essais faits parallèlement avec les mesures habituelles des appareils à pression triaxiale de 3·6 cm de diamètre et 9 cm de hauteur, ainsi que des essais avec l'appareil à cisaillement direct de Casagrande (avec surface à cisailler contrôlée) et un appareil à cisailler à moteur (dont le déplacement du cisaillage est également contrôlé). D'autres séries d'essais entrepris à grande échelle furent faits avec une grauwacke concassée (poids par unité de volume: 1·55 et 1·87 t/m^3). Avec un matérial très cohérent (grauwacke schisteuse et limoneuse effritée) on fit des essais identiques, avec 3 densités de gisements (poids par unité de volume 1·86, 2·11 et 2·36 t/m^3). On connaît les essais comparatifs obtenus avec les mesures faites au moyen des appareils usuels. Enfin on examina un gravier sablonneux et limoneux (poids par unité de volume 1·79 t/m^3).

Les problèmes spéciaux qui se présentent à l'occasion de telles recherches sont commentés et leur utilisation pratique est examinée.

Introduction

Shear tests are normally carried out by direct shear instruments of 6 × 6 cm base and 2·5 cm height or 10 × 10 cm base and 2 cm height, or in triaxial instruments of about 3·6 cm diameter and 9 cm height. It is known that these dimensions, which are very seldom exceeded, are so small that soils over a certain grain size cannot be exactly tested, even though the precise relationship between maximum grain size suitable for testing and instrument diameter is not yet settled. This does not apply only to coarse grained soils for which an exact determination is unnecessary since the shear resistance value is known approximately. With fine grained soils one is not certain whether the dimensions of the instrument have a noticeable influence on the magnitude of the shear resistance; certainly one gets variations in magnitude. In spite of this, large shear tests have very seldom been carried out in the field or in the laboratory because handling of the instruments under the heavy loads required is laborious; for this reason they are seldom considered for routine tests although sometimes such large tests are necessary. Since these large shear tests most probably have to be carried out with simple instruments, they cannot possess the same versatility in application as the smaller instruments. The items of equipment described, however, have fulfilled their purpose.

Review of Tests Carried Out

As far as is known, outdoor shear tests with shear planes of 1 × 1 m and more were carried out in 1948 in Germany by LEUSSINK (1948). Movements during the shear operation were accurately recorded but there was no graph of shear lines. For gravel BRETH (1951–52) used shear planes of 1 × 1 m with a sample height of 25 cm and obtained well defined shear strength diagrams: a similar instrument was used in Yugoslavia (NONVEILLER, 1954). In the U.S.A. clay has been sheared in the field on a surface of about 5·7 × 0·7 m (THORFINNSON, 1954).

Before 1936 large triaxial tests using specimens 0·3 m diameter and 0·9 m height, loaded by water pressure, had been used by COLLORIO (1936) for building the dams in the Harz mountains. After the last war BRETH (1951–52) wrote about an instrument of 0·5 m diameter and 1·0 m height with lateral pressure brought about by evacuation. Similar tests on specimens of 0·45 m diameter and a height of 0·90 m were carried out in Yugoslavia (NONVEILLER, 1954).

Direct Large Shear Tests

The reason for carrying out new large shear tests arose from an investigation of a lignite dam which was to keep an opencast mine secure. Only as much coal as would leave the remaining dam strong enough to withstand the laetral water pressure could be taken away.

As lignite is very water-porous and has a low bulk density the pressure of the dam on its foundation is very low and it can only be held in place essentially by cohesion between the clay on which it rests and the lignite. To determine this value exactly both small and large shear tests were carried out. For the latter, pits were dug until they reached clay. The coal was kept together by a sheet metal box covered with a pressure distribution plate of steel (Fig. 1) loaded with steel plates packed into an old boiler. To obtain a pressure of at least 1·5 kg/cm^2 on the foundation of 1 × 1 m a maximum applied load of 15 German tons had to be produced.

The box with lignite was displaced by a hydraulic jack as soon as no further settlements were noticed under the vertical applied load. The shearing force was also increased when there appeared to be no further displacements. Vertical and horizontal movements were measured by dial gauges at ten points. The plane of shear was kept under water. Altogether four tests, with vertical applied loads of 0 to 1·5 kg/cm², were carried out. Only one test result was astray, the other three lay on one line. The result of the large tests was somewhat unfavourable compared with the mean values of several small tests (Fig. 2). In particular the large test produced only half the cohesion shown by the small tests, which was important in the design of the dam. The failure values of the large shear tests were obtained after displacements of between 1 and 3 cm, depending upon the magnitude of the applied load. In the normal laboratory tests these displacements were, on the other hand, between 0·1 and 0·3 cm.

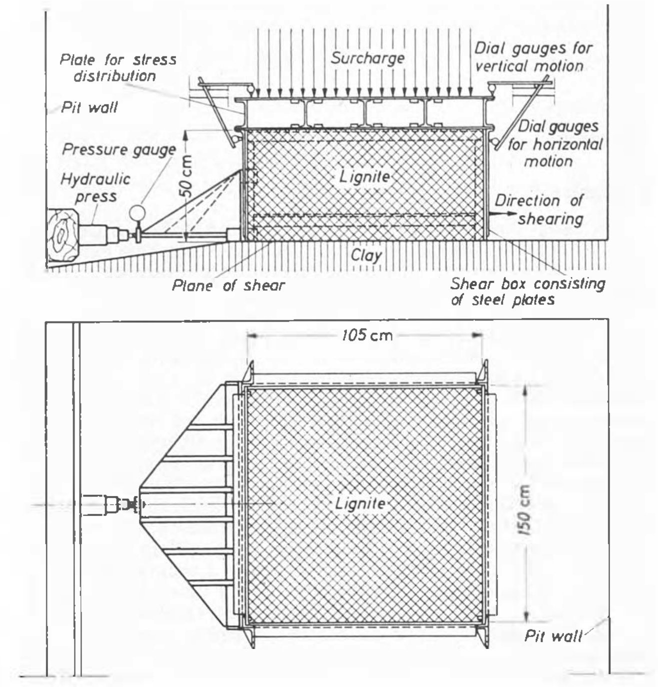

Fig. 1 Large shear test, cross-section and plan of the testing apparatus

Essai de cisaillement à grande échelle section et schéma en plan de l'appareil d'essai

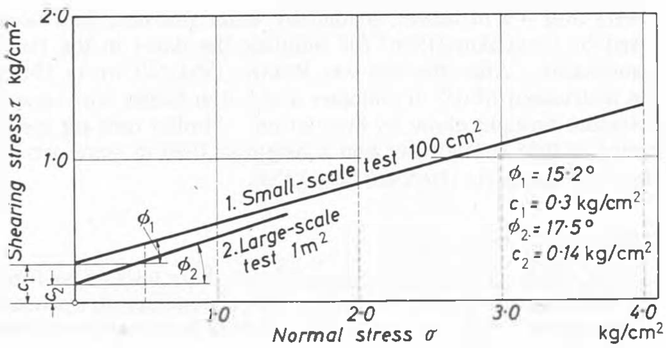

Fig. 2 Shear test for the coal-dam Hubertus, Brüggen/Erft. Shear lines from large and small tests with soil from the layer between the lignite and the clay

Essai de cisaillement au barrage des charbonnages Hubertus, Brüggen/Erft. Lignes de cisaillement pour essais à grande et petite échelle sur terres provenant de la couche située entre la lignite et l'argile

By Hookes law we have:

$$\frac{\Delta l}{l} = \frac{\tau}{G}$$

where Δl = displacement; l = length of shear plane; τ = shear stress; and G = modulus of rigidity.

This equation gives a fair approximation to the stress–strain line (Fig. 3). Differences in displacements of individual points of the coal block were not very large; they remain within the shaded areas shown. The box tipped forward a little during displacement.

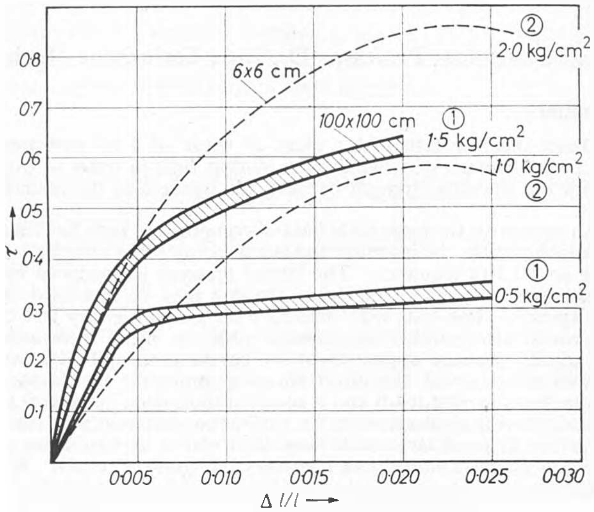

Fig. 3 Shear tests for the coal-dam Hubertus, Brüggen/Erft. Shear displacement lines for large and small tests

Essais de cisaillement au barrage des charbonnages Hubertus, Brüggen/Erft. Lignes de déplacement produit par le cisaillement au cours d'essais à grande et petite échelle

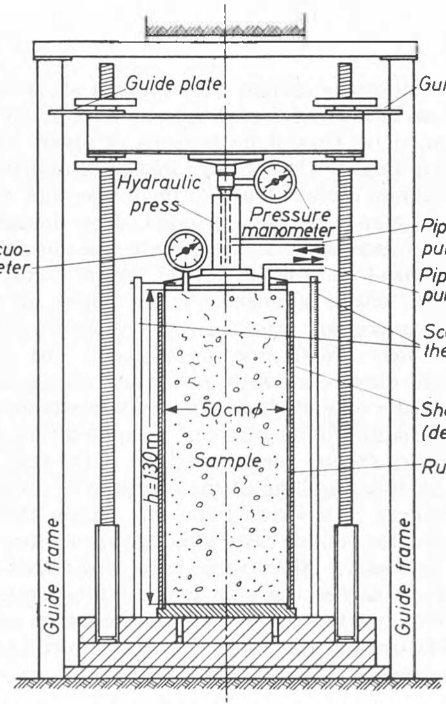

Fig. 4 Drawing of the large triaxial shear apparatus

Schéma de l'appareil pour les essais de cisaillement triaxial à grande échelle

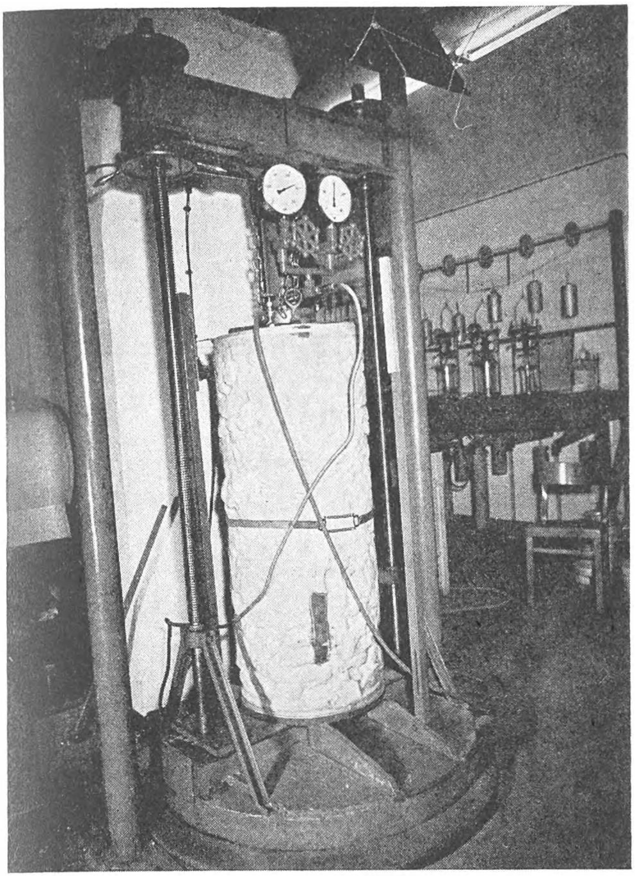

Fig. 5 Large triaxial test for the determination of shear strength of rubble, broken stones or broken rock

Essai de cisaillement à grande échelle pour la détermination de la résistance au cisaillement de moellons pierres ou roches concassées

Large Triaxial Shear Instruments

The large triaxial shear instruments of the Institute of Soil Mechanics at Aachen (Fig. 4) consist of a guide frame (which is to prevent the sample acquiring an oblique position) and two spindles with a traverse between, supporting the hydraulic ram and the test sample of 0·50 m diameter and 1·30 m height. The soil is filled into a rubber membrane which is protected by a sheet metal cylinder and by tamping or vibration it is compressed to a desired size. Air is removed from the sample after placing the end cap on by a water-jet pump: with the pump any lateral pressure up to 0·9 kg/cm² may be applied in three minutes and during this operation the compression and increase of circumference at midheight can be measured (Fig. 5).

The upper-size limit of material used was fixed at 10 cm diameter. When packed loosely this sometimes produces an irregular cylindrical surface. Material which binds easily together stands after compression. Depending on the lateral pressure and the type of soil, the sample, when compressed, either bulges out, or shows a distinct slip plane.

The disadvantage of the instrument is that it can only be used for lateral pressures up to about 0·9 kg/cm². Parallel tests, however, carried out with a small triaxial pressure instrument and fine-grained soils have shown that the failure envelope may almost always be determined by the use of lateral pressures of 0·3, 0·6 and 0·9 kg/cm². There appeared to be no essential deviation from the curve at higher lateral pressures. An increase of lateral pressure will only be possible if the instrument is re-built with a pressure cylinder for water. However, the cost would rise so much and handling become so laborious that it is doubtful whether the increased expense would be worth while.

Evaluation of Tests

Stress curves are produced from the applied pressures making allowance for enlargement of the sample diameter with increased compression. Only with dense and coarse material is a distinct failure point observed (Fig. 6); otherwise soil material

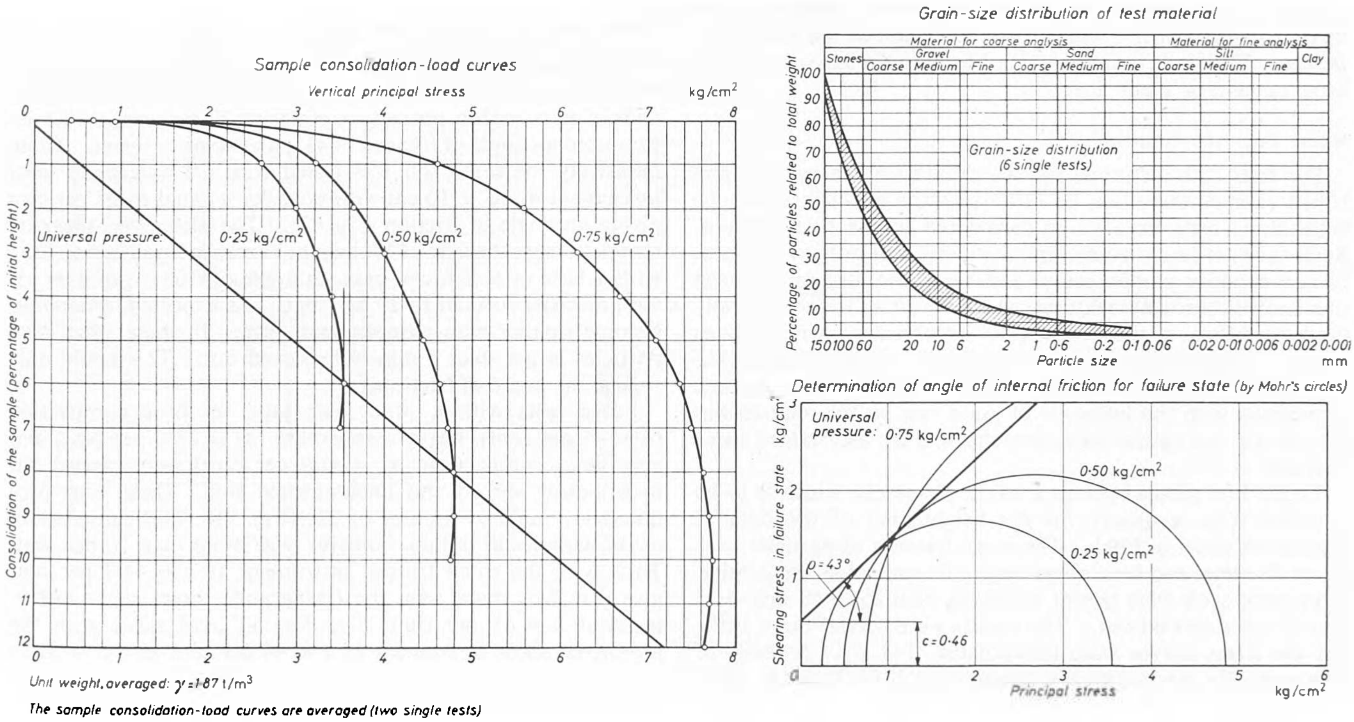

Fig. 6 Heightening of the Schwammenauel Dam. Triaxial pressure test with a slatey greywacke. Final bulk density 1·87 t/m³

Rehaussement du barrage de Schwammenauel. Essai de pression triaxiale sur une grauwacke schisteuse. Densité volumétrique final 1·87 t/m³

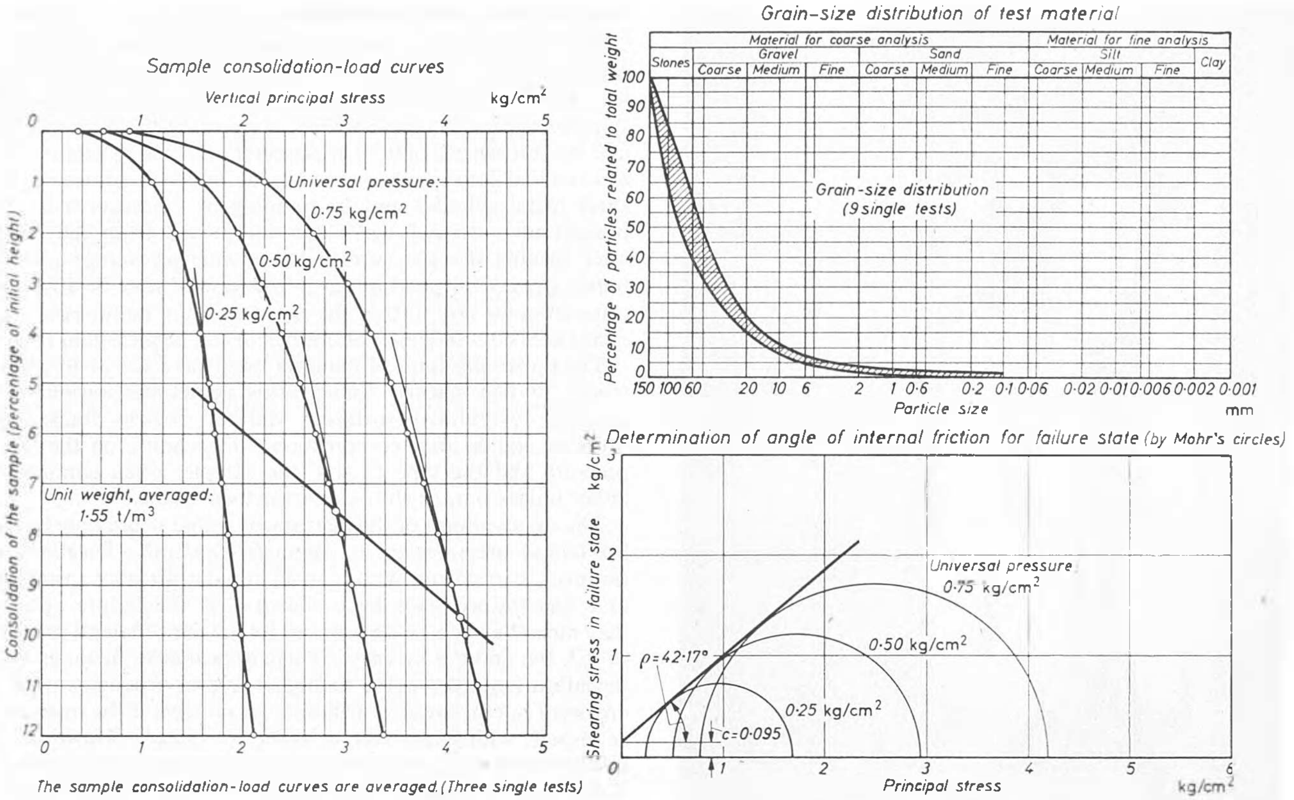

Fig. 7 Heightening of the Schwammenauel Dam. Triaxial pressure test with silty greywacke. Final bulk density 1·55 t/m³
Rehaussement du barrage de Schwammenauel. Essai de pression triaxiale sur une grauwacke schisteuse. Densité volumétrique finale 1·55 t/m³

flows (Fig. 7), so that we must define clearly our criterion of failure. Our observations have shown that all these stress curves merge into a single straight line and that the points at which this line begins, for the various lateral pressures, again lie on a straight line. These points we regard as the strength at failure. The three corresponding Mohr circles have nearly the same tangent or shear line.

Shear Test with Stones

For tests with disturbed soil which contain coarse parts and which cannot, therefore, be fitted into the small instruments, large shear tests have to be considered in the first instance. Such soils are found when building dams, not only in the form of non-cohesive stones, gravel and sand, but also in the form of cohesive stone clay mixtures, which are either found naturally (and, therefore, a cheap material) or produced artificially as earth concrete (soil cement) (Fig. 6). In addition we investigated sand without a coarse fraction in order to become acquainted with the influence of grain size on the relationship between the instrument measurements and the ascertained shear strength.

To the first group belongs a slatey greywacke which is to be obtained from a quarry for the heightening of the dam at Schwammenauel in Eifel. The small fraction of particles over 10 cm diameter had been sieved out. To control its uniformity, three tests each with lateral pressures of 0·25, 0·50 and 0·75 kg/cm² were carried out. The results were spread out a little, but the stress curves were interpolated (Fig. 7). A series of nine tests was made with low compaction (Fig. 7) and a series of six tests with higher compaction (Fig. 6) (bulk densities of 1·55 and 1·87 kg/m³ respectively). In both cases the angle of friction was nearly 43°. The cohesion caused by the binding of particles rose from 0·1 to 0·2 kg/cm² and the compressibility was reduced. The accuracy of the results was confirmed by slipping tests on a large scale on the site.

Shear Tests with Gravel and Sand

Large tests with gravel at a porosity of 25 per cent from a lignite waste tip (Fig. 8) gave an angle of friction of 35°. Small triaxial tests with a porosity n equal to 29 per cent, however, produced an angle of friction of 41°; an excessive result. Comparatively the same soil was tested with a Casagrande shear instrument of 10 × 10 cm with porosity n equal to 28 per cent giving an angle of friction $\phi = 42°$. The motorized shear instrument from the firm of Wykeham Farrance Engineering Ltd., with a base of 6 × 6 cm, gave an angle of friction of $\phi = 45°$ with porosity n equal to 29 per cent. As expected, differences become smaller with reduced grain size. In these small tests particles larger than 5 mm were sieved out. This could only reduce the angle of friction.

Large tests with a little finer sand in loose compaction ($n = 45$ per cent), heavy compaction ($n_d = 28{\cdot}0$ per cent) and very loose compaction ($n_o = 46{\cdot}9$ per cent) were carried out in a loosely spread and uncompacted soil. These tests produced an angle of friction of 32° (Fig. 9). The compression of the samples at failure, however, was more than 20 per cent. Tests with the small triaxial instrument at $n = 44{\cdot}3$ per cent give $\phi = 28°$, those with the Casagrande direct shear instrument at $n = 45$ per cent, give $\phi = 34°$ and those with the motorized shear instrument at $n = 44$ per cent give $\phi = 31°$.

Shear Test with Loam

A loamy scree and loamy debris containing a coarse fraction were to be used to build the Riveris earth dam near Trier.

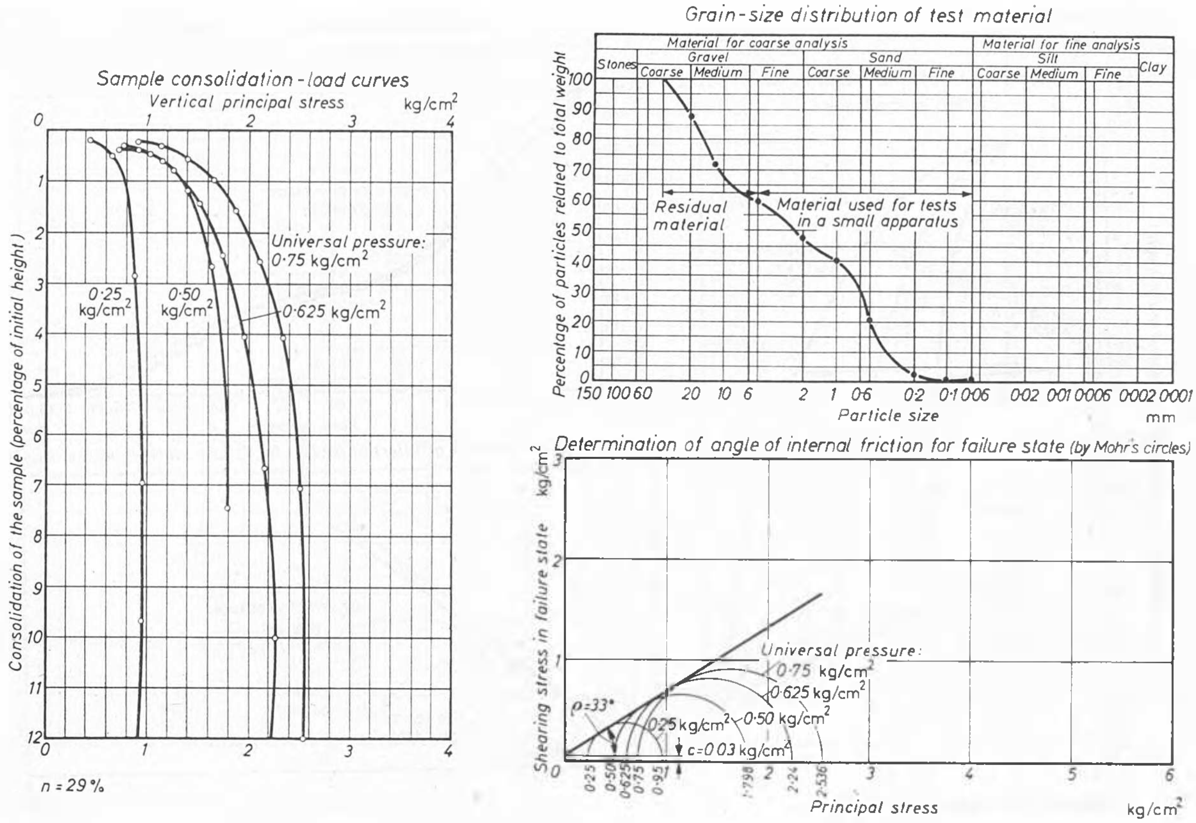

Fig. 8 Large triaxial tests with gravel. Bulk density 1·98 t/m³
Essais de pression triaxiale à grande échelle sur gravier. Densité volumétrique 1·98 t/m³

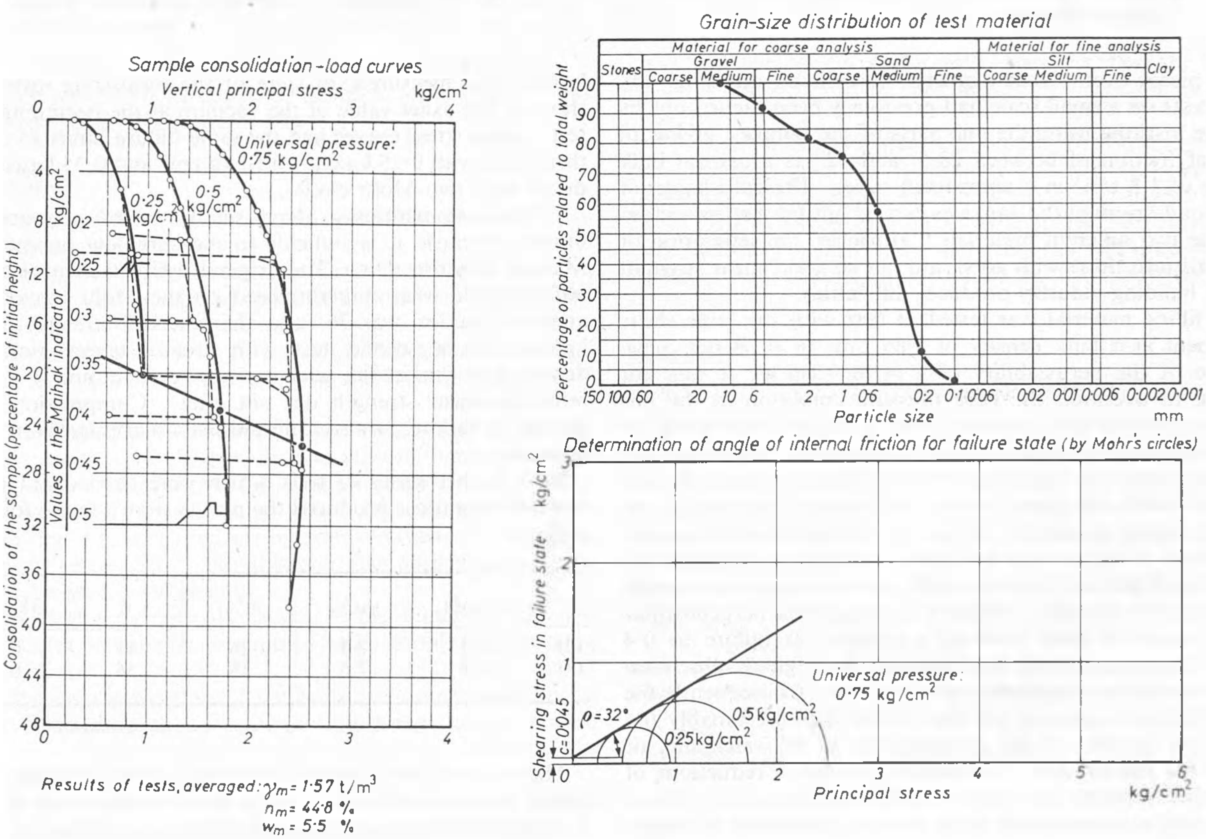

Fig. 9 Large triaxial tests with gravelly sand. Bulk density 1·57 t/m³
Essais de pression triaxiale sur gravier sablonneux. Densité volumétrique 1·57 t/m³

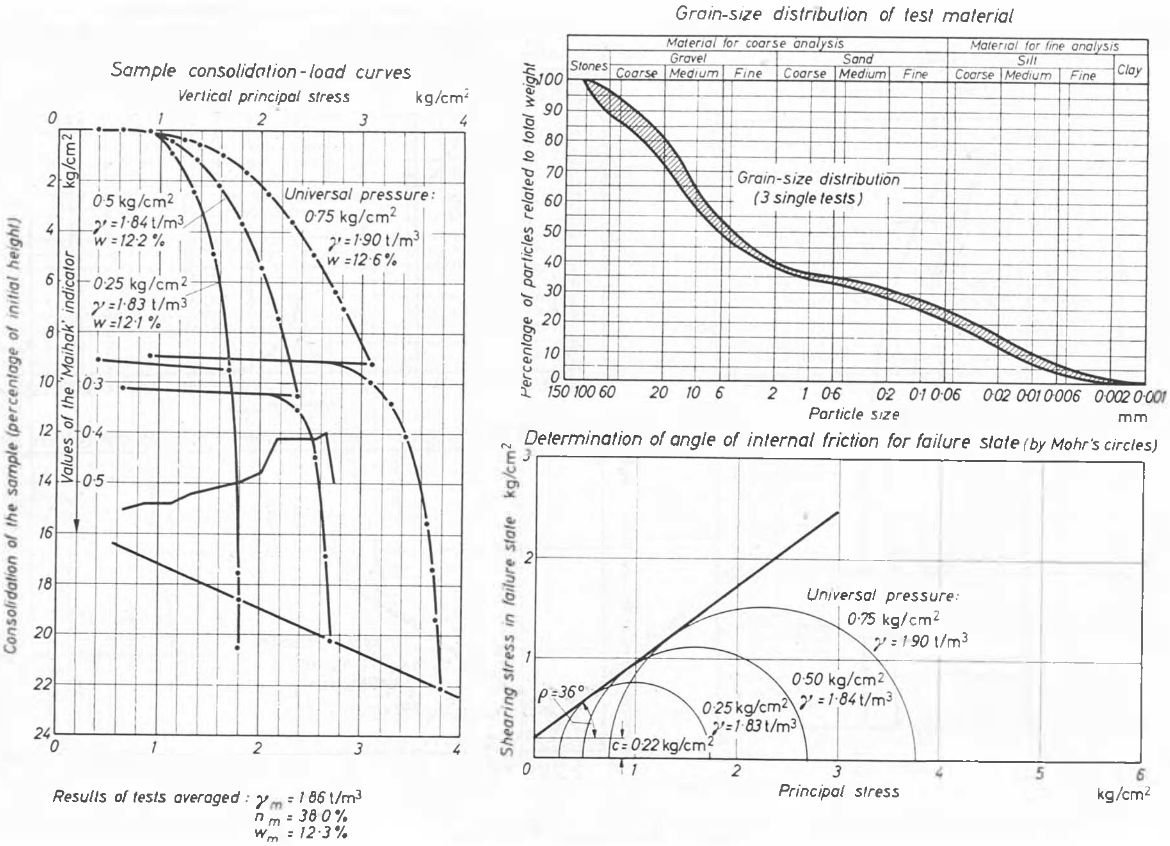

Fig. 10 Riveris reservoir. Triaxial pressure tests with material from Thielenbachtal (silty greywacke slate). Bulk density 1·86 t/m³
Réservoir de Riveris. Essais de pression triaxiale sur un matériau de Thielenbachtal (grauwacke schisteuse et limoneuse). Densité volumétrique 1·86 t/m³

Again pieces over 10 cm diameter were sieved out (Fig. 10). Shear tests on a small scale had previously been carried out by another Institute using the fine parts of the samples, giving an angle of friction of between 28·5° and 32° at a natural bulk density of 1·8 t/m³ in a compacted state. The calculation of static equilibrium of the dam was carried out for a cross-section with the two different materials. However, the separation of materials into those with good and not so good shear strength for the building industry produces difficulties.

The filling material was tested at first with the large shear instrument at a bulk density of 1·86 t/m³ ($n = 38$ per cent). Because of the permeability of $k = 10^{-5}$ cm/sec it was not possible to overlook the pore pressure condition in the unsaturated sample and an electric pore pressure meter from the firm of Maihak was built into the test sample. This was also used in the previous mentioned test with sand and showed a low pressure which was equal during the whole of the test to the vacuum (lateral pressure). From the application of the lateral pressure of 0·5 kg/cm² to the loam, one gathers that from the beginning of the test the pore water pressure meter very nearly agrees with the vacuum. With the increase of the perpendicular major stress the pore pressure is reduced at failure to 0·4 kg/cm² and immediately rises again to its original value even though the vacuum has been kept constant. Consequently the real hydrostatic pressure on the sample was presumably 0·4 kg/cm² on account of the counter pressure of water and air against the rubber skin. Substantial numerical reductions of pore water pressure are shown in tests carried out by BRETH (1955) with less permeable earth concrete, especially at higher lateral pressures. Here at failure for a vacuum of 0·5 kg/cm² as well as for a vacuum of 0·75 kg/cm² in the sample only 0·65 kg/cm² was measured, in spite of the measuring instruments showing the exact value of the vacuum at the beginning of the test. Both stress curves had the same failure limits so that the three tests with 0·25 kg/cm², 0·50 kg/cm² and 0·75 kg/cm² produced only two Mohr circles.

In the case mentioned above smaller lateral pressures were omitted because it is difficult to measure low pressure with Maihak pressure cells. The original hydrostatic pressure was unfavourable when superimposed on the Mohr circles. The angle of friction was 36° and the cohesive strength was 0·2 kg/cm². In a second test with greater compaction (bulk density 2·10 t/m³ at the same moisture content and $n = 31$ per cent) the shear strength did not alter. Compression of the samples at failure, however, diminished on average from 20 to 8 per cent.

Two further series of tests which were carried out on soil from other sources produced the results shown in the following table:

	γ(t/m³)	w_n(%)	n(%)	ϕ	c(kg/cm²)
(2)	2·11	7·3	26	41	0·18
(3)	2·36	7·6	18	36	0·70

γ = bulk density, w_n = natural moisture content

These show still higher strengths. This example shows clearly how unproductive are the tests on small test samples. A slightly finer grained material which was washed out of an ore pit and which was to be used as a filling material for settling basins (Fig. 11) had a porosity of $n = 44$ per cent and gave an

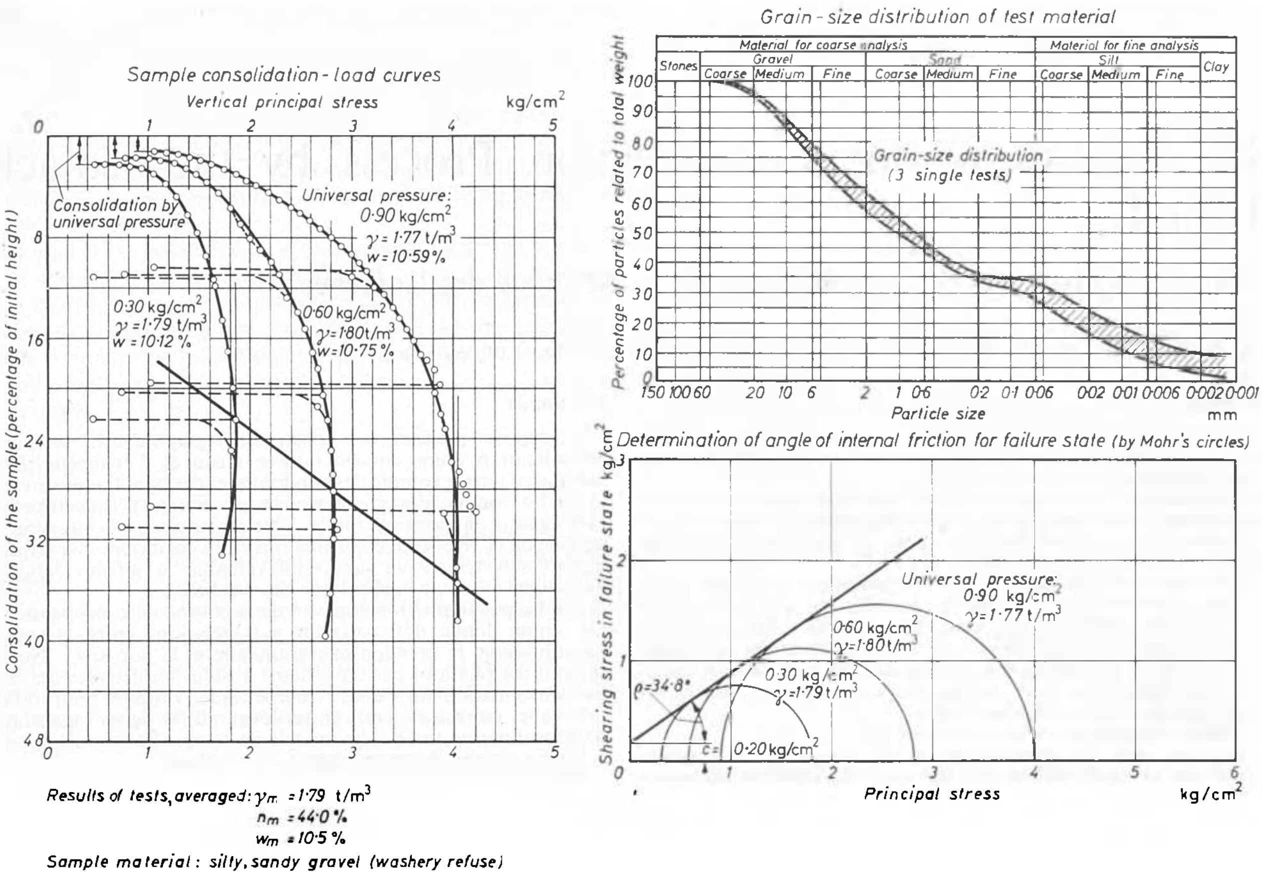

Fig. 11 Large triaxial pressure tests with a deposited material. A silty sandy gravel of bulk density 1·79 t/m³
Essais de pression triaxiale à grande échelle sur un gisement de gravier sablonneux et limoneux. Densité volumétrique 1·79 t/m³

angle of friction of about 35° and a cohesion of 0·2 kg/cm².

Further tests with undisturbed samples of lignite dug out of the ground have been carried out.

Conclusions

As a result of the tests carried out up to now, and which will be continued, one has to remember:

(1) Direct, as well as triaxial, large shear tests make it possible to investigate filling material with coarse particles for earth dams.

(2) If the instrument is to be simple to manufacture and handle, the maximum normal pressures are limited to 1·5 kg/cm².

(3) Whether the shear envelope up to 1·5 kg/cm² is also accurate enough for higher normal stresses depends on the material tested. In general, the shear envelope is not so curved at the beginning, so that large errors do not appear. This question has to be cleared up by comparison tests with large and small instruments. For this only fine grained soil can be used in the small instruments.

(4) With slightly cohesive soils it is recommended that the actual lateral pressure be determined in the sample with pressure cells.

(5) The coarse fraction of the soils mentioned produced a higher shear strength. Consequently sieving out the coarse fraction and testing the remainder in the small instrument is unrealistic.

(6) The density of the soils tested does not affect the internal angle of friction, but it does affect the cohesion and compressibility.

(7) Exact details of the relationship between the largest grain diameter and the instrument diameter have yet to be determined by comparative tests in large and small instruments. Up to now, when using a flakey broken slate, the ratio of the grain size to the instrument diameter has not exceeded 1:5. However, only a small proportion of the whole was made up of coarse particles.

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