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The Undrained Shear Strength of Preconsolidated Boulder Clay

La résistance au cisaillement non drainé d'une argile de moraine préconsolidée

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Summary

This paper describes an investigation into the undrained shear strength of a Danish boulder clay. The undrained shear strengths measured in plate tests, vane tests and laboratory tests are compared and some possibilities of error in the standard laboratory tests as well as the use of 'smooth' pressure heads are mentioned. A test series of unconfined compression tests with axes in different directions is described.

Résumé

Une recherche de la résistance au cisaillement non drainé d'une argile de moraine danoise est décrite. Les résistances mesurées dans les essais de chargement sur plaques, dans les essais au scissomètre et dans les essais de laboratoire sont comparées, et quelques possibilités d'erreurs dans les essais standards de laboratoire sont indiquées. En outre l'utilisation des pistons lisses est traitée. Une série d'essais de compression simple avec différentes orientations de l'axe relatives à la position in situ est analysée.

Introduction

In the present paper different ways of measuring the undrained shear strength in the field and in the laboratory are discussed. Some possibilities of error in performing tests on preconsolidated soils are mentioned, and some suggestions given as how to avoid them.

The tests were carried out on Danish glacial boulder clays. The natural water content was 8–20%. The boulder clay consisted of 40–60% sand, 25–50% silt and 15–25% clay. There are normally some small stones (0–20%) with diameters from 2–20 mm in the samples; in natural deposits they can be much bigger.

The clay is located in the space between the sand and silt grains and is not orientated. The clay, therefore, is heterogeneous, but isotropic.

1. Undrained Tests in the Field

Vane Tests

The vane used at DGI has a height twice as large as the diameter.

It measures mainly the strength on a vertical cylindrical surface. This surface is enforced, and stones, even small ones, in this surface will increase the shear strength c_v above that of the soil proper.

Plate Tests

The most appropriate method of measuring the strength is to perform plate tests directly on the surface of the undisturbed soil.

The plates are normally circular with diameters $D =$ 5–15 cm and are placed on a practically plane, horizontal surface with a diameter greater than $7D$. Gypsum or concrete is deposited between the plate and the surface of the soil to prevent local ruptures.

The results of plate tests are compared with vane tests in Table 1, and it will be seen that there is sufficient agreement between these two methods. The average value is

$$c_u^p = 0.90 \times c_v \qquad \text{(Plate tests)}$$

TABLE 1. *Undrained plate tests compared with vane tests.*
Essais de plaque non drainés comparés aux essais au scissomètre.

P_f t/m²	c_v t/m²	$\frac{P_f}{6.2 \cdot c_v}$
35.7	6.1	0.94
30.0	6.2	0.78
36.0	5.7	1.02
30.4	5.0	0.98
31.7	5.7	0.90
35.0	5.8	0.97
119	22	0.87
122	23	0.86
363	70	0.84
392	70	0.90
460	70	1.06
366	70	0.84
330	70	0.76
400	70	0.92

2. Laboratory Tests

Undrained Compression Test with Fixed Ends

Undrained compression tests are normally carried out with specimens of a height twice as great as the diameter. The specimen is placed between two brass pistons in the unconfined compression test, and in the undrained triaxial compression test between two filter discs. This type of test is called 'test with fixed ends'.

If the sample consists of preconsolidated clay as e. g. boulder clay, this testing method is not very suitable.

A preconsolidated clay expands under failure conditions. This means that when a locally weak zone in the specimen is at failure, its water content will increase, and the zone will become still weaker. The shear plane which is subsequently formed starts developing in this part of the specimen. The normal shape of the sample at failure is shown in Fig. 1. The water content in the shear plane is much greater than that in other parts of the specimen. The failure condition in this very narrow zone corresponds nearly to a drained state.

The undrained shear strength corresponds to a water content somewhat greater than measured, and the measured strength is therefore smaller than the natural one.

The above-mentioned failure type is similar to that in a plane shear-box test. These remarks are thus also valid for this type of test.

The height of the specimen gives another possibility of error. Any inhomogeneity will make the upper piston tilt and the specimen will break as a column. It is necessary to trim the ends of the sample very carefully.

In Table 2 are given some results with very carefully cut specimens (block samples), and also some results with normally cut specimens (borehole samples), compared with the vane test.

In the best tests	$c_u \sim 0.6\ c_v$	(U.C. tests)
In an average test	$c_u \sim 0.4\ c_v$	(U.C. tests)

The triaxial test naturally shows the same errors. Furthermore, the rubber membrane produces some additional errors. Spaces between the rubber membrane and the specimen are normally filled with water and during the test this water enters the sample. Air dissolved in the cell-water can pass through the rubber membrane into the specimen.

This gives too high a water content, too weak a suction in the pore water and thus too small a shear strength.

Another difficulty is that the connection between the pore water and the outside system is rather difficult to establish, even by washing water through the filter discs.

TABLE 2. *Undrained compression tests with fixed ends compared with vane tests.*
Essais de compression non drainés à extrémités frétées comparés à des essais au scissomètre.

c_u t/m²	c_v t/m²	c_u/c_v
24.5	29.2	0.84
15	44	0.34
12	42	0.29
13	40	0.33
6.1	29	0.21
14.1	22	0.64
6.4	21	0.30
16.3	26	0.63
13	40	0.33
1.4	5.5	0.25
0.8	6.5	0.12
1.2	7.0	0.17
2.2	12.0	0.18
4.5	11.0	0.41
3.8	11.0	0.35
Special, carefully-made specimens.		
12	20.4	0.59
12.3	20.4	0.60
12.5	20.4	0.61
12.7	20.4	0.62

New Unconfined Compression Tests

The solution to the above-mentioned problems is to enforce the correct conditions at failure. By giving the specimen a height equal to the diameter one prevents the creation of a single shear plane. By using smooth pressure heads uniformity in stress and strain distribution, and thus in water content, can be obtained (Fig. 2).

The smooth pressure head consists of a glass plate with silicone grease and a rubber membrane (Fig. 3), as proposed by Rowe and Barden (1964).

The first thing to be done is to check up on the effect of the pressure heads. The proposed system is naturally not quite frictionless, but it is sufficient if the influence of the roughness is negligible.

For this purpose a test series consisting of 15 tests has been carried out. The cross-sectional area was 10 cm² and the following heights were used: $H = 2D$ (2 tests), $H = D$ (8 tests), $H = 0.5D$ (4 tests)and $H = 0.4D$ (1 test).

The two tests with $H = 2D$ had a peak strength corresponding to the increasing water content in a rupture plane.

Three of the tests with $H = D$ also had a maximum value of the deviator stress. Radial cracks transform the specimen into a series of smaller specimens with $H > D$.

The other tests had uncracked cross-sectional areas.

The tests with $H = D$ showed vertical tangents at rupture (Fig. 5).

The tests with $H < D$ showed no peak point but increasing stresses corresponding to the measureable influence of the pressure heads (Fig. 5).

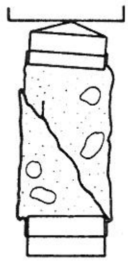


Fig.1

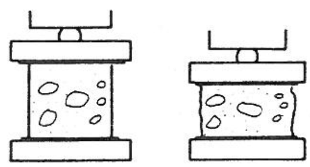


Fig.2

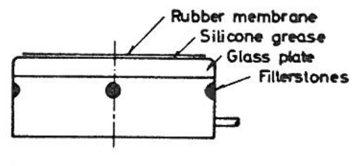


Fig. 3

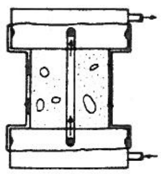


Fig. 4

Fig. 1. *Unconfined compression test with fixed ends shown after rupture. Line-rupture.*
Essai de compression simple à extrémités frétées, après rupture. Rupture plane.

Fig. 2. *Unconfined compression test with smooth pressure heads before and after the test. Zone-rupture.*
Essais de compression simple à pistons lisses, avant et après l'essai. Rupture de zône.

Fig. 3. *A smooth pressure head.*
Le piston lisse.

Fig. 4. *De-airing of the filter system. Only surface drains.*
Dégazage du système filtrant. Drainage de surface seulement.

The test results are shown in Fig. 6, and a curve has been drawn through the average values. This curve has at any point for $H_f/D < 1$ (zone-rupture) the same inclination as the ultimate inclination at failure in the corresponding stress-strain curve (e.g. $H_0/D = 0.5$ and 1 in Fig. 5). This means that the undrained strength of a sample at certain H/D ratio is independent of whether the sample has been prepared by compressing a larger sample, or simply by cutting out a sample of this height.

The curve, therefore, represents the influence of the 'smooth' pressure heads. The conclusion is that the influence is negligible if the initial height of the specimen is about equal to the diameter.

It is obvious that in this type of test all parts of the specimen are in a state of failure (Fig. 2).

Comparing the results of the new testing method with the vane test one gets:

$$c_u \sim 0.93 \times c_v \text{ if } H \sim D \qquad \text{(N.U.C. test)}$$

This method has now been used several times with quite consistent results and up to maximum values of $c_u = 70$ t/m² (examples in Table 3).

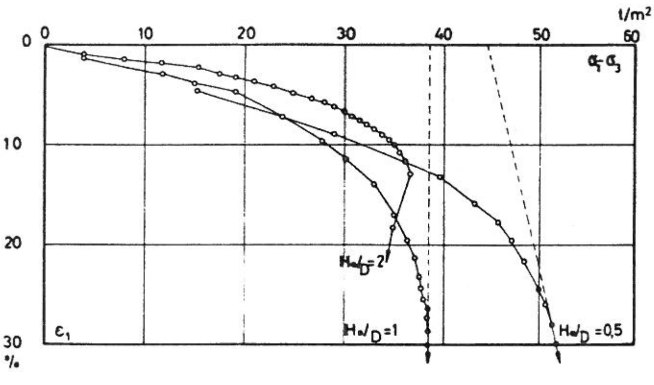


Fig. 5

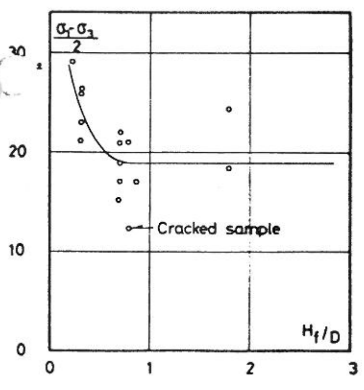


Fig. 6

Fig. 5. *Stress-strain curves for unconfined compression tests with smooth pressure heads. H_0 is the initial height of the sample.*
Courbes contraintes-déformations pour essai de compression simple à pistons lisses. H_0 est l'hauteur initiale de l'échantillon.

Fig. 6. *The effect of 'smooth' pressure heads.* H_f *is the sample height at failure.*
L'effet des pistons lisses. H_f est l'hauteur à la rupture de l'échantillon.

The Undrained Triaxial Test

Boulder clay contains stones, some of which are located at the surface of the specimen. Normally the stones are removed and replaced by remoulded material, so producing locally weaker regions in the material. If the stones are located in the ends it is of course necessary to remove them, but the holes can be filled with gypsum. If not, it is better to let the stones remain.

In order to avoid having water between the membrane and the sample around the stones and in the corners between the pressure heads and the specimen, the rubber membrane is moulded directly over the specimen.

To ensure an effective connection between the pore water and the outer system, the filter system consists of four surface drains extending from the lower to the upper pressure head. The drain is made of filter paper with a small strip of sand. It is rather incompressible. The water can be washed through this system outside the specimen and the air bubbles can be effectively removed (Fig. 4).

The diameter of the specimen is 7 cm, that of the pressure head 8 cm.

The first part of the test is a reconsolidation of the specimen. No cracks have been observed in this kind of test.

The test procedure used at DGI is different from the one normally used. Instead of measuring the pore pressure at constant cell pressure, the cell pressure is varied at constant volume. It is neccessary to de-air the system completely and to use a very fine capillary tube in measuring the changes of volume.

The test is undrained because it is carried out at constant volume. The stresses measured are, however, the effective ones.

A typical test result is shown in Fig. 7–8. There is neither a peak point nor a shear plane but a uniform passive zone.

In the last part of the test the specimen is almost in a failure state. The final rupture takes place without changes of strength, i. e. the so-called 'critical state.'

The results of a multiple-stage triaxial test on a lightly preconsolidated boulder clay are given in Fig. 9. The vane tests give $c_v = 7$ t/m² at $\sigma_3 \sim 3$ t/m² and obviously the mean normal preconsolidation pressure is near 12 t/m².

The Variation of Undrained Strength with Direction of Shear Plane

The above-mentioned laboratory tests were all carried out on axi-symmetric specimens with vertical axes.

A comparison between the vane test and the unconfined compression test is therefore only relevant if the influence

TABLE 3. *Undrained compression tests with smooth pressure heads compared with vane tests.*
Essais de compression non drainés à pistons lisses comparés à des essais au scissomètre.

c_u t/m²	c_v t/m²	c_u/c_v
11.9	13	0.92
11.7	13	0.90
11.2	13	0.86
12.3	13	0.95
22.0	20	1.10
19.7	20	0.99
15.5	20	0.78
17.2	20	0.86
21.3	20	1.07
20.9	20	1.05
17.3	20	0.87
12.2	20	0.61
71	70	1.01
74	70	1.05

of the orientation of the shear plane is negligible. A variation in shear strength with direction of the shear planes may cause a difference in the values measured in these two ways.

Therefore, a series of unconfined compression tests with different directions of the axes relative to the in-situ position was carried out. The dimensions of the samples were

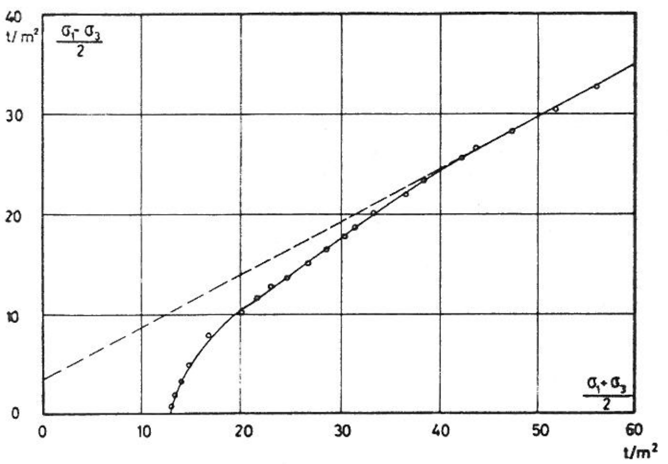


Fig. 7. *Stress path for a consolidated undrained triaxial test.*
Essai triaxial à consolidation complète et non drainé; variation des contraintes.

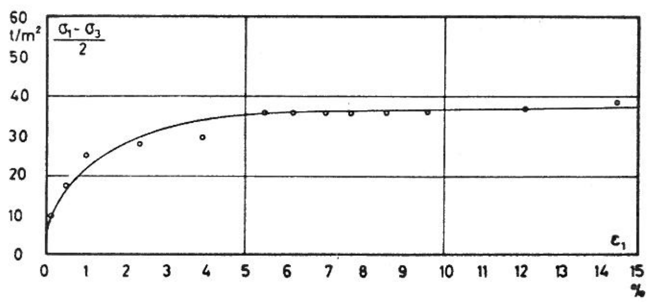


Fig. 8. *Stress-strain curve for a consolidated undrained triaxial test.*
Essai triaxial à consolidation complète et non drainé; courbe contraintes-déformations.

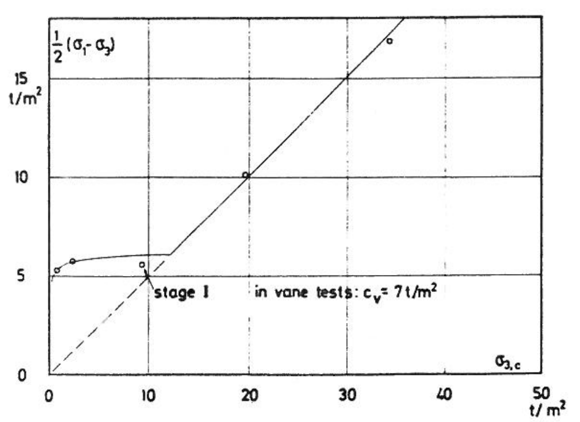


Fig. 9. *Relationship between strength and preconsolidation pressure.*
Relation entre résistance au cisaillement et pression de préconsolidation.

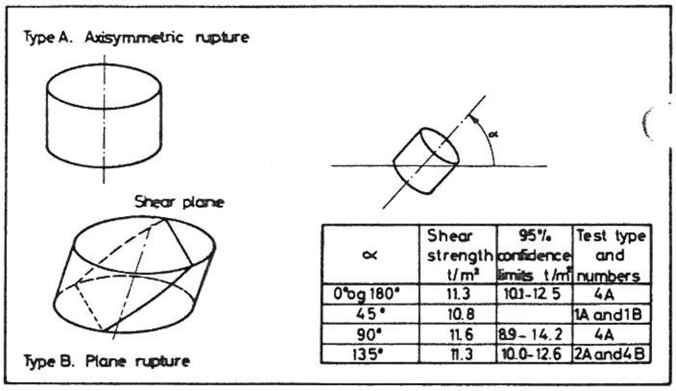
$H = D = 3.5$ cm, and the average water content was 12.5%. The results are given in Fig. 10.

By using smooth pressure heads one causes the normal shape of the specimen at failure to be cylindrical (Type A). The so-called shear planes are in this case shear cones. The angles between the tangent planes and the direction of the main normal consolidation stress have thus only a constant value if the axis of the specimen has the above-mentioned direction. Tests with axes perpendicular to this direction have no special orientation.

A tangent plane to the shear cone coinciding with a plane of minimum shear strength may cause an almost plane rupture. The shape of the specimen at failure is of the type B.

It will be seen that the shear strengths are not significantly different at a 95% confidence level.

Some of the tests, however, have ruptures of type B, perhaps indicating a direction in which the shear strength is a minimum. But in the tests with uncracked samples it is nevertheless impossible to measure any difference.



α	Shear strength t/m²	95% confidence limits t/m²	Test type and numbers
0° og 180°	11.3	10.1-12.5	4A
45°	10.8		1A and 1B
90°	11.6	8.9-14.2	4A
135°	11.3	10.0-12.6	2A and 4B

Fig. 10. *Undrained strength for various directions of sample axis in unconfined compression tests.*
Résistance au cisaillement non drainé pour diverses directions de l'axe de l'échantillon dans les essais de compression simple.

Conclusion

It has been shown that the undrained shear strength of preconsolidated boulder clay is nearly independent of the direction of the shear plane.

It has also been shown that the different methods measuring the undrained shear strength give almost the same results. There is excellent agreement between the compression tests with smooth pressure heads ($H \sim D$) and the undrained plate tests.

The vane tests give a somewhat higher value (10%), probably because the measurements are taken in an enforced shear surface.

The best standard compression tests with fixed ends and a height twice as great as the diameter give only 65% of the true value.

Reference

Rowe, P. W. and Barden, L., 1964. *Importance of free ends in triaxial testing*. Proc. ASCE, Vol. 90, SM 1, p. 1–27.