

ROYAL SWEDISH
GEOTECHNICAL INSTITUTE
PROCEEDINGS

No. 16

MECHANICAL DISTURBANCES
IN CLAY SAMPLES
TAKEN WITH PISTON SAMPLERS

By

TORSTEN KALLSTENIUS

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Ivar Haggströms Boktryckeri AB
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Preface

The question of undisturbed sampling is of major importance both in Sweden and elsewhere where one has to deal with soft sensitive clays and loose soil formations, since theories or analyses based on disturbed samples result in uncertain values and are thus of little use. Furthermore, greater knowledge of the factors affecting sample disturbance lead to a better understanding of soils.

In its Proceedings No. 8 (JAKOBSON, 1954), the Swedish Geotechnical Institute published details of a comparison between a number of piston samplers. Continued research has been deemed useful and a second report—in which the results are judged from other aspects than in Proc. No. 8—has been drawn up. During the course of this recent research some of the factors involved have been reassessed.

The investigations described were planned and conducted by Mr. Torsten Kallstenius, Head of the Mechanical Department of the Institute. Mr. Dag Almstedt, Research Engineer, was in charge of the main part of the field and laboratory investigations, while Mr. Nils Flodin—who also acted as editor of the report—and Mr. Anders Hallén led certain of the field experiments.

The field work at Ultuna was carried out in collaboration with the Norwegian Geotechnical Institute, the Geotechnical Department of the Swedish State Railways and the Geotechnical Section of the Street Department, Public Works of Stockholm. The handling of the equipment supplied by these institutions was done by technicians from them. The Institute expresses its gratitude to these institutions for their valuable cooperation.

The investigations have made actual the design of a standard sampler for routine purposes. In Sweden a special committee, in which the Institute is represented, is now dealing with the question of working out the specifications necessary for that purpose. International contacts have also been established.

Stockholm, September, 1958

ROYAL SWEDISH GEOTECHNICAL INSTITUTE

I. Synopsis

This publication deals mainly with a comparison made between six current types of piston sampler near the town of Uppsala in a deep layer of post-glacial clay. Additional investigations have been made in another area, Skå Edeby, where a large airfield was planned.

The conclusions to be drawn are that sample quality is mainly influenced by the sampler in the following ways:

a) Disturbance of soil outside the sampler caused by displacement when pushing the sampler down to sampling depth (or when preboring to this depth).

b) Disturbance of soil outside the sampler during punching caused by displacement from the sampler wall.

c) Disturbance of soil inside and outside the sampler caused by friction between soil and sampler wall.

The disturbance as per (a) can be decreased either by remoulding the soil above sampling depth before pushing the sampler or by making the sampler sufficiently long (about 20 radii) to get away from the initially disturbed zone. The necessary length of sample is dependent on the depth and the type of laboratory test.

The disturbance as per (b) is mainly influenced by the edge angle and this should therefore be smaller than 5° . The outer wall profile may be slightly concave.

The disturbance as per (c) can be reduced by inside clearance, but could also be reduced in other ways. In principle, it seems better to reduce the friction by lubrication, proper selection of wall material, or by means of foils, as the amount of inside clearance ought to be adjusted to the type of soil and sampling depth. Nevertheless, a moderate clearance (0.5-1.0 % of the inner radius) can be recommended for piston samplers.

The investigations have further shown that the scatter of test results is smaller for high quality samplers, which means safer determination of soil strength. Furthermore, disturbances of the samples have been shown to affect different testing methods differently.

The above conclusions have been verified by rechecking earlier tests, by tests performed by the Swedish State Railways and finally by tests with a new research sampler (SGI IX) which was designed to give extremely little sample disturbance in accordance with the above conclusions.

In soils other than Swedish post-glacial clays, the influence of different factors may differ, and this may in certain cases lead to different conclusions. The principles given above should, however, still be valid.

Damage during shipment of samples is known to be an important factor, especially in sensitive clay. Such damage was avoided in our investigation, and a study of this influence is therefore not included here.

2. General Considerations

2 a. Need of Undisturbed Sampling

Much has been said and written about the "undisturbed" sampling of soils, but still both opinions and routines are at great variance.

The reason for the variety of opinions as to the answer to a given question may either be lack of knowledge of the subject or, alternatively, it may be that the problem has no unequivocal solution and is dependent on a number of local or temporary factors. Both these possibilities appear to be valid when related to the undisturbed sampling of soils. Since sampling is influenced by many factors, it will be realized that research into the matter must be comprehensive and that it will call for a great deal of time and money and the services of a skilled staff. This, and the fact that there is a lack of understanding of the necessity of taking good samples, may be the reason why comparatively little research has been performed in this field.

The basic source of knowledge in the field of soil mechanics is, of course, practical experience. However, progress is leading towards stricter requirements and new construction methods and fresh building sites appear frequently. Therefore, it is often necessary to extrapolate from existing knowledge to a greater or lesser degree by theoretical judgment, in most cases based on soil investigation including soil sampling. The greater the extrapolation the greater the demands on sample quality. The nature of the soil (especially its sensitivity), of course, has a great influence on the sampling requirements.

As these demands variate, the word "undisturbed" in connection with samples is interpreted in different ways, and it would normally rather mean "sufficiently little disturbed for the actual strength tests". There exists an "optimum" sample disturbance which is largely an economic consideration. As a rule, sampling costs rise with the quality required. On the other hand, a small variation in the test results obtained with samples of high quality enables small safety factors to be employed. This may result in cheaper foundations.

The Author would, in principle, divide undisturbed sampling into three main classes, viz:

Research class—Highest possible quality of samples—little regard to costs. (Research, important buildings, expensive foundations.)

Routine class—A fairly good quality of samples, with some attention to costs. (Routine cases for specialists in soil mechanics.)

Simple class—The samples must not be seriously disturbed, but most consideration is given to simplicity of operation and low sampling costs. (Sampling by non-specialists, often in accordance with standard instruction.)

There can, of course, be no sharp division between these classes.

As regards this report, most of the investigation refers to routine class samplers but a research class sampler is also described (The Foil Piston Sampler, SGI IX).

2 b. Causes of Disturbance in Clay Samples

Changes in the mechanical properties of clay samples may be due to mechanical, physical, chemical, or other reasons. They may be either local or distributed throughout the sample.

In a specimen of saturated clay, the volume of liquid may increase and the "grain skeleton" may expand and thereby lose part of its strength. An increase in volume of this kind may be caused by excess pore pressure in the neighbourhood (*e.g.* caused by sampler displacement). Similar effects may probably also be caused by changes in temperature, freezing or osmotic pressure due to differences in the chemical composition of a sample and its surroundings.

A disturbance may also result from deformation of the grain skeleton. This happens when clays are subjected to shearing stresses. If the shearing stresses are great, flaky mineral grains orientate themselves parallel to the flow and rearrange. When this happens, most clays lose a part of their strength—they are thus "sensitive".

Quite obviously, sample disturbance must be dependent on the relative density and permeability of the soil and its degree of saturation. If a loosely packed soil of low permeability is subjected to shear, it will, owing to increased pore pressure, lose much of its strength. On the other hand, if the pore liquid can escape owing to high permeability or long-term loading, the disturbed soil may show a higher strength than the natural.

Regardless of the presence of the pore liquid, cementation between the soil grains will be broken when the soil is subjected to shear. This will tend to reduce the strength of all such soils.

Chemical changes in a soil sample, with accompanying change in its mechanical properties, may occur if the sample container corrodes, *etc.*

2 c. Determination of Mechanical Disturbance in Samples

Mechanical disturbance in a soil sample may be manifest in many different ways (as indicated by CASAGRANDE, 1932, RUTLEDGE, 1944, HVORSLEV, 1949, and others). Even if none of the following criteria are generally valid, a good background will be obtained if as many as possible are applied to actual cases. This has been done in the investigations presented in this report.

Deformation criterion

Visible deformations often indicate great inside friction in a sampler. In piston samplers, the piston helps to keep the strata in position. Nevertheless, soft strata between rigid strata may have been squeezed out without it being possible to detect this phenomenon (sometimes, by using a sharp pencil as a primitive cone test, one can detect such layers).

Fig. 1 shows the appearance of samples after 20 % deformation in an unconfined compression test. Distortion of the layers can hardly be detected. Obser-

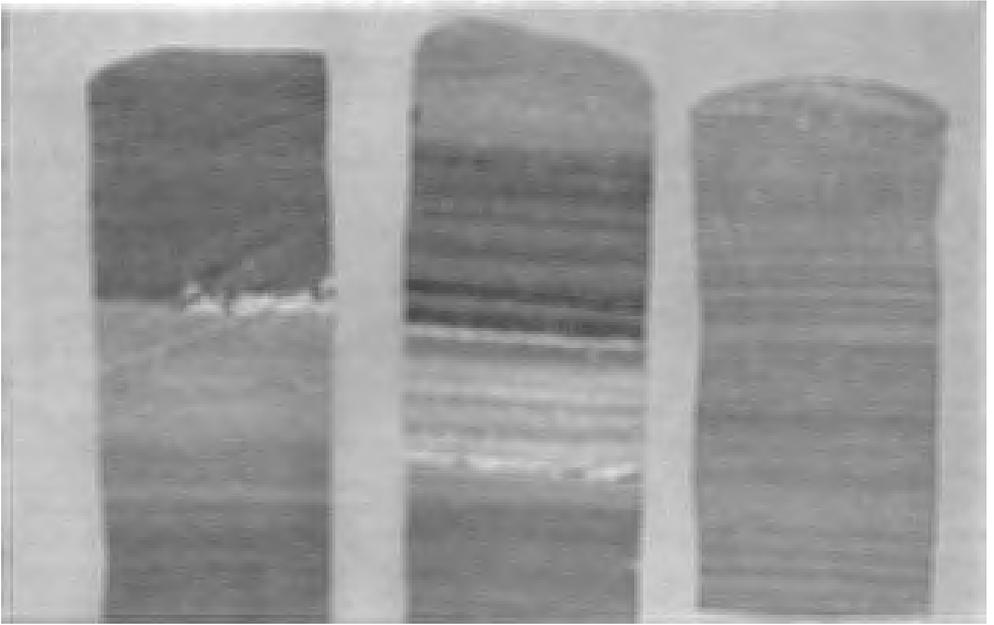


Fig. 1. Soil samples after great axial deformation in compression test.

vation of the strata (even after drying) indicated that practically all the samples in this report could be regarded as undisturbed, but their mechanical properties were, nevertheless, very different. Thus, this criterion must be regarded as rough.

Stress-strain curve criterion

The slope of stress-strain curves obtained with undisturbed clay is straight and steep for small strains up to a certain stress. Thereafter, the slope is very flat. When disturbed, the clay shows more gentle stress-strain curves. Thus, when making unconfined compression tests, the strain at failure ought, for undisturbed clay, not to exceed a certain value (3-10 per cent) and, as regards small strains, the stress-strain relation ought to be as straight as possible. The failure-strain criterion can be applied to individual samples but it is not possible to give a definite value serving as an overall criterion. Organic clays may show large strain at failure, even though little disturbed. The same may be true if the clay has been disturbed *in situ* by geological events. The straightness of the curves for small strains is probably somewhat more significant.

In consolidation tests on disturbed samples, the graphical plot of void ratio versus stress in a semi-log-scale is said to result in gentle curves near the "pre-consolidation" stress. However, the pre-consolidation stress is not always easy

to determine. Besides, such curves do not seem to differ much for the differences in sample quality actual in this report. Consolidation tests are time-consuming, and are very much dependent on variations in soil strata and sample trimming.

Shear strength criterion

When judging strength test results from specimens taken with different samplers, it seems logical to deem samples of higher shear strength to be less disturbed. When doing so it is presumed that the water content has not decreased and that no chemical action has occurred. To allow for variations, a number of samples is generally required. However, Swedish experience indicates that disturbance may increase the shear strength of varved clays with layers of silt due to change in water content.

Strength scattering criterion

It is recommendable to study the scatter, or variation, of strength test results. The more sources of disturbance, the more the sample will differ from the ideal undisturbed state and the greater the scatter of results. However, very heterogeneous soils make assessment difficult, as does also the fact that certain homogenization may occur if the disturbance has been very considerable. Thus, some care must be shown also when applying this valuable criterion.

2 d. Background to Piston Sampling Investigations

2 d 1. Development of First Swedish Samplers

A piston sampler mainly intended for peat was reported by KELLGREN as early as 1894.

When, in the first decades of this century, engineers at the Gothenburg Harbour studied the stability of quays, they attempted to take undisturbed samples of clay. Sampling was done with open samplers working inside 4" casing pipes (PETTERSON, 1916, 1955).

The Geotechnical Commission of the Swedish State Railways 1914-22 also used an open sampler for most of its sampling work, the cylinder sampler. The fall-cone test was applied to the samples, and the results were thoroughly correlated to practical experience from slides. Later, John Olsson, who was secretary of the Commission, designed a piston sampler for clay (OLSSON, 1925). The John Olsson sampler has since been a standard sampler used by both the Swedish State Railways and other institutions. It is shown in Fig. 2 and is referred to in this report as Sampler SJ.

Using the Sampler SJ as the prototype, the Gothenburg Harbour made a sampler similar to Olsson's but with a refinement in that the sample was retained in liners (PETTERSON, 1933, 1955). This is referred to in this report as Sampler

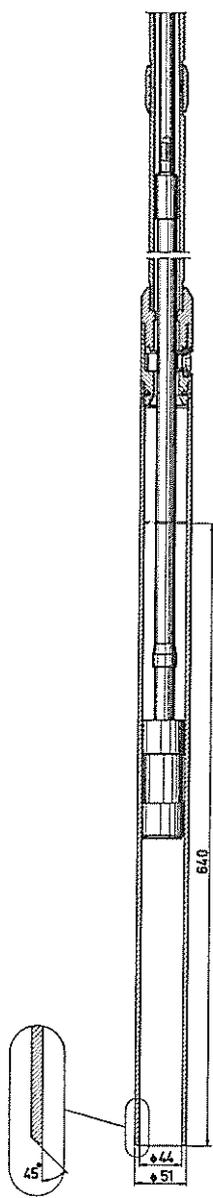


Fig. 2. Sampler SJ.

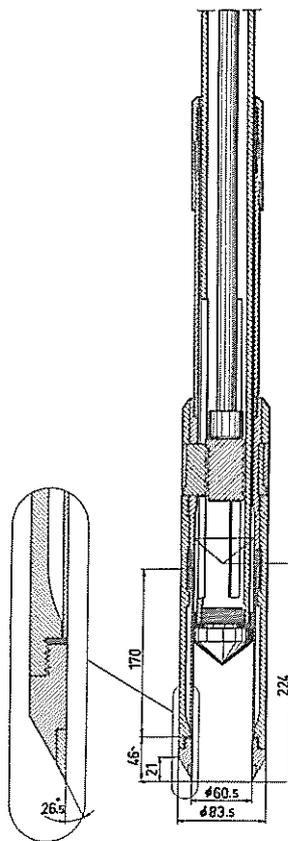


Fig. 3. Sampler SGI IV.

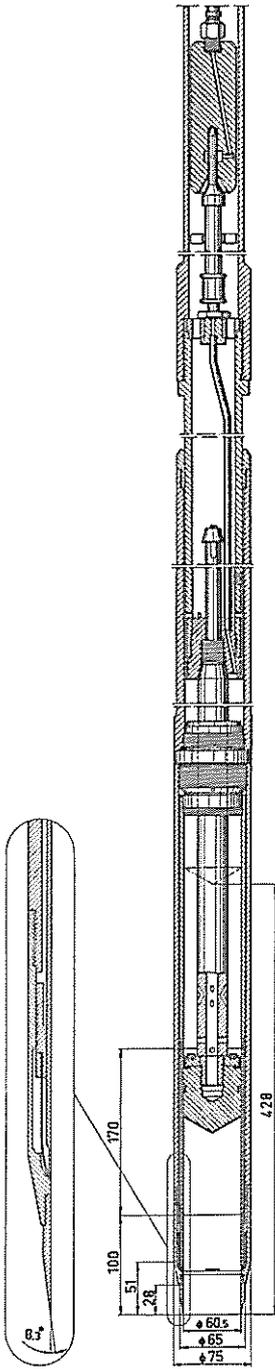


Fig. 4. Sampler SGI VI.

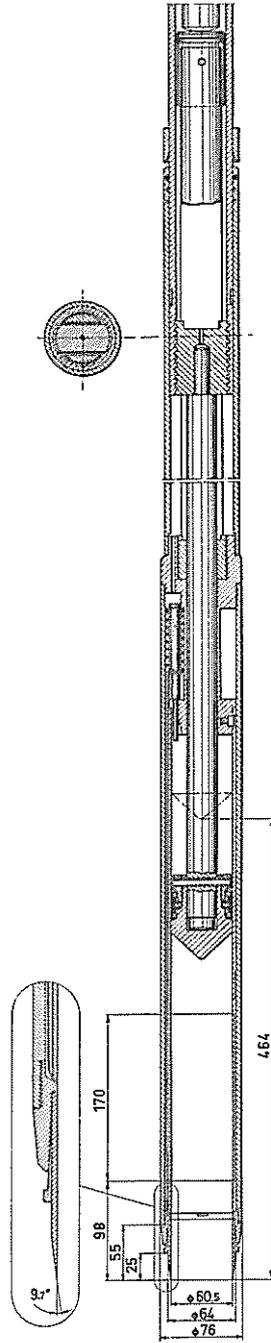


Fig. 5. Sampler SGI VIII.



Fig. 6. Hvorslev's sampler.

GH (sampler "h" in SGI Proceedings No. 8 and there erroneously referred to as the Swedish State Railways piston sampler). This sampler is still used by the Gothenburg Harbour.

Both the SJ and GH samplers are simple, light and cheap and have been correlated to the work of the Geotechnical Commission of the Swedish State Railways and to other practical experience in Sweden and Norway (except by J. OLSSON, also by SKAVEN HAUG, 1931, T. HULTIN, 1937, and CALDENIUS, 1938).

When W. Kjellman—the former head of the Institute—started his geotechnical work, he wanted to be able to determine consolidation, permeability and shear strength (by means of the unconfined compression test and the direct shear test). This was deemed to require the use of a sampler of larger diameter.

His sampler (Fig. 3)—referred to in this report as Sampler SGI IV—was adopted as the standard sampler by the Institute when it was established in 1944 and is still in use. It was found that the results of tests made with the SGI IV sampler could be reasonably well correlated to the experience gained with the SJ and GH samplers. It has been used for some 5,000 routine jobs, each comprising a number of samples.

2 d 2. Experiments at the Swedish Geotechnical Institute

It was soon realized that the SGI IV sampler was too short and bulky, and steps were taken to develop an improved sampler. It was appreciated that exhaustive tests would have to be made on a new sampler before it could be accepted as a successor to such a well-known model as this sampler.

To start with, small modifications were made to the sampler head in that it was lengthened (sampler SGI V—Fig. 8 in Proceedings No. 8) or provided

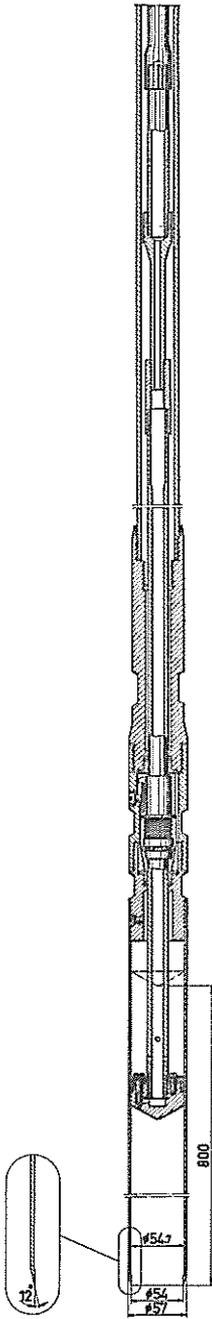


Fig. 7. Sampler NGL.

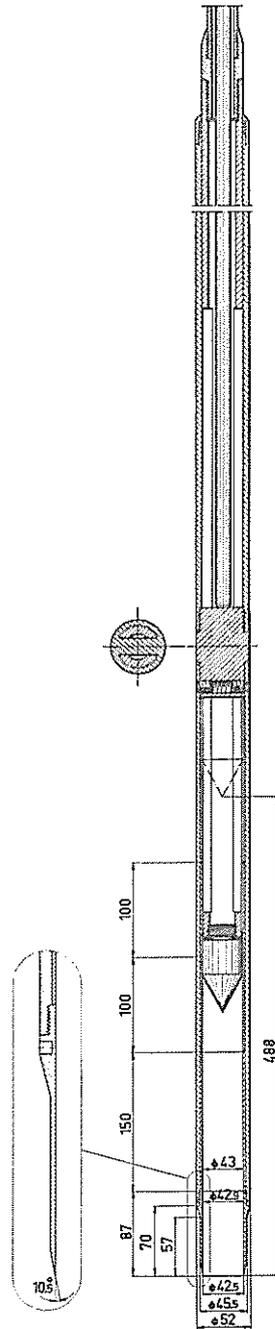


Fig. 8. Sampler Gk.

with different types of shutters (SGI IV_w—Fig. 5 in Proc. No. 8; SGI IV_A—Fig. 6 in Proc. No. 8). It was deemed that the slight improvement in sample quality obtained by some of these measures did not offset the added trouble in sampling.

The next step was to design new sampler heads utilizing, as far as possible, the existing equipment. After tests with a thin-walled sampler, made in accordance with Hvorslev's recommendations (HVORSLEV, 1949; referred to as sampler T—Fig. 7 in Proc. No. 8), had shown no improvement, a composite pneumatic sampler—the SGI VI—was designed (Fig. 4). This gave much better samples. It was longer than the SGI IV, had a sharper edge and punched out the sample more rapidly. Besides, the sample was cut off automatically and the vacuum below the sample broken by means of compressed air. The maximum punching force (1,000 kg) was, however, found to be too small for hard soils. A similar sampler (SGI VII) with a punching force of 7,000 kg was also tested, but even this force was at times insufficient. It was also difficult to arrange earth anchors providing the requisite reactionary force and yet not yielding too much.

Hvorslev's findings were utilized when designing the SGI VI sampler but no great attention had been paid to the "area ratio" conception (since the distance from the cutting edge should also have some influence, as proved by the development of the Steel foil sampler). Hvorslev's conception of "inside clearance" was accepted by the Author who provided the SGI V and SGI VI samplers with moderate inside clearance. Using clearance was, however, contrary to the official opinion of the Institute (*cf.* Proc. No. 1 p. 13 and Proc. No. 8 p. 18) and changes had to be introduced later.

Sampler SGI VIII (Fig. 5) was then designed. This model could be pressed or hammered while sampling. The dimensions were largely the same as for the SGI VI, which had proved to be the best of the types tested at Enköping (Proc. No. 8) and other sites. We tried to make SGI VIII equally sturdy and as well suited to all-round conditions as the SGI IV.

2 d 3. *Other Piston Samplers Tested at the Institute*

When Hvorslev made his well-known sampling tests (HVORSLEV, 1949), he dealt mainly with open-drive samplers but, to some extent, piston samplers were also employed. He designed a piston sampler (Fig. 6) with very thin walls, moderate inside clearance and similar proportions to samplers SJ and GH. This type has been adopted by many institutions and a modification of it by the Norwegian Geotechnical Institute. The Norwegian sampler is referred to in this report as the NGI sampler (Fig. 7). This sampler was stated to be good and we therefore wished to try it out on soils in Sweden.

Since 1950 many Swedish institutions and firms have interested themselves in soil mechanics. When they started, they were not committed by investments already made in equipment, nor by staff adapted to a given routine, and some

of them designed samplers of their own. An example is the sampler designed by the Geotechnical Section of the Street Department of Stockholm. It is referred to in this report as sampler Gk (Fig. 8) and is a compromise between samplers SJ, GH, SGI IV and Hvorslev's.

2 d 4. *Aim of New Tests*

The Institute decided to check the current position by comparing samples from the old prototypes and certain typical modern samplers. It was hoped that such tests would aid a future discussion of a standard sampler for routine application.

Such a comparison had, of necessity, to be made under field conditions and in natural soil as it is important to keep the natural soil texture unchanged. Moreover, laboratory tests do not permit the same depth reaction to displacement as do field tests. As the test results were available, the investigations were extended by special tests in order to throw light upon different problems. Since the tests have revealed certain important factors as regards sample quality and, especially, as final results cannot be expected for some years yet, it was considered that a report on the investigations hitherto performed now was justified.

3. Tests at Ultuna 1956

3 a. Test Site and Soil Conditions

The test site is situated about 50 km north of Stockholm and near the town of Uppsala. It was examined by geologists and the soil was considered to be fairly homogeneous and typical for soil conditions in Middle Sweden.

Fig. 9 shows a plan of the bore holes, arranged in a circle, and with every sampler tested in at least two diametrically opposed holes. In four holes the shear strength of the ground was determined by means of vane boring. The results (Fig. 10) indicate that, as regards small depths, the shear strength was approximately 20 % greater in holes lying in a north-south direction (samplers Gk and SGI VIII). At greater depths the soil was more homogeneous.

The space between the bore holes was at least 2 metres. Vertically, the samples were spaced at 2.5 metres intervals to eliminate, as far as possible, reciprocal disturbance between holes and samples. In the centre, at a depth of 10 metres, the pore pressure was measured to check test conditions.

JÄRNEFORS (1955) describes the soil profile in the following words: "...to a depth of 1.5 metres an oxidized, grey dry crust penetrated by permanent fissures, below this a sulphidous clay replaced at a depth of about 14 metres by a grey and soft clay. Below a thin layer of sand at a depth of slightly over 19 metres follows the so-called 'dotted zone'—a layer of clay about 0.1 metre thick dotted with small fragments of lime. This zone is typical of the site around

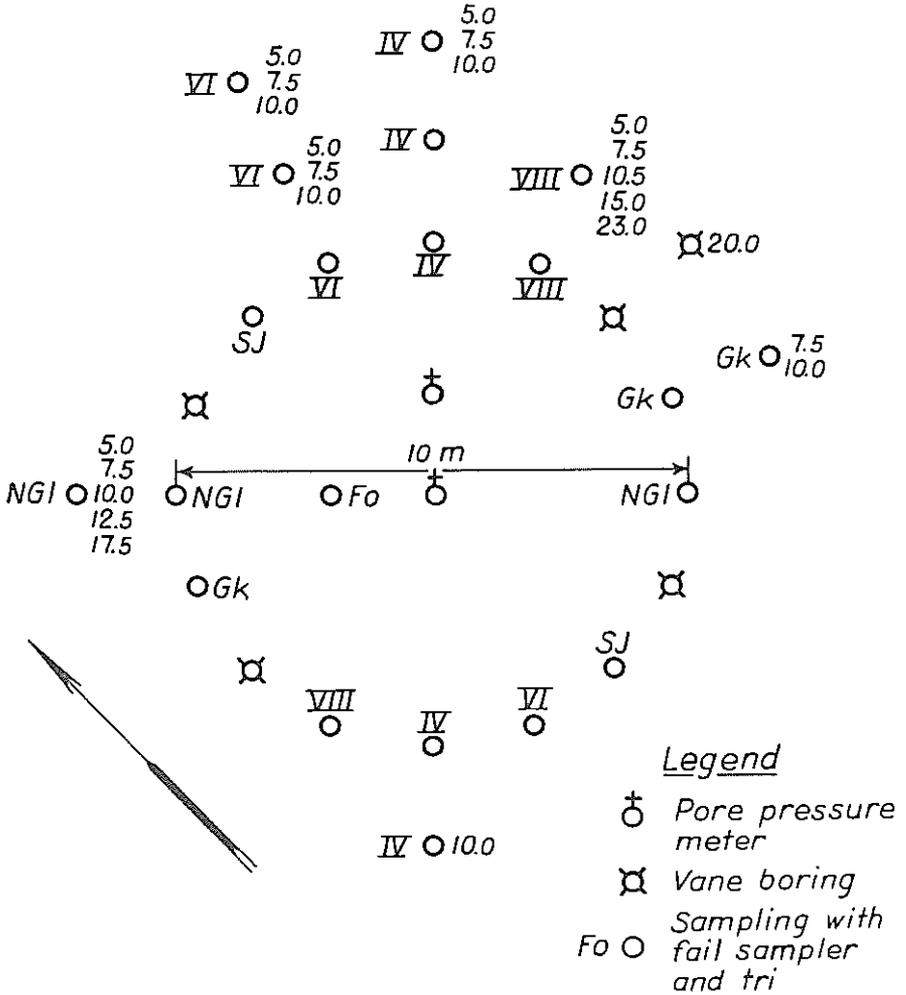
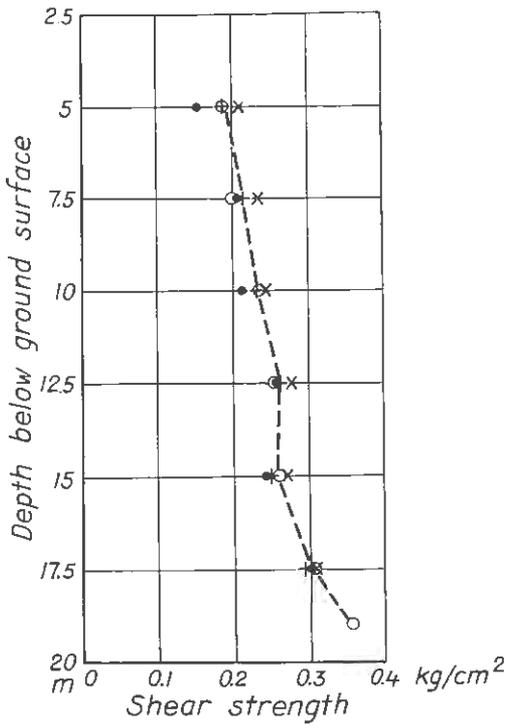


Fig. 9. Arrangement of bore holes. (Figures to the right of the additional bore holes outside of the circle indicate sampling depths.)

Uppsala and normally lies immediately above the first visible micro-layers of glacial clay." Fig. 11 shows some samples taken with the NGI sampler.

Fig. 12 shows the general data of the soil.

The soil contained gases to a depth of at least 10 metres and swelled slightly when left free. The gas was dissolved in the pore water but filled also some voids and fissures.



Bore hole North ○
 " " South ●
 " " East †
 " " West ×

Fig. 10. Shear strength at Ultuna according to field vane boring.

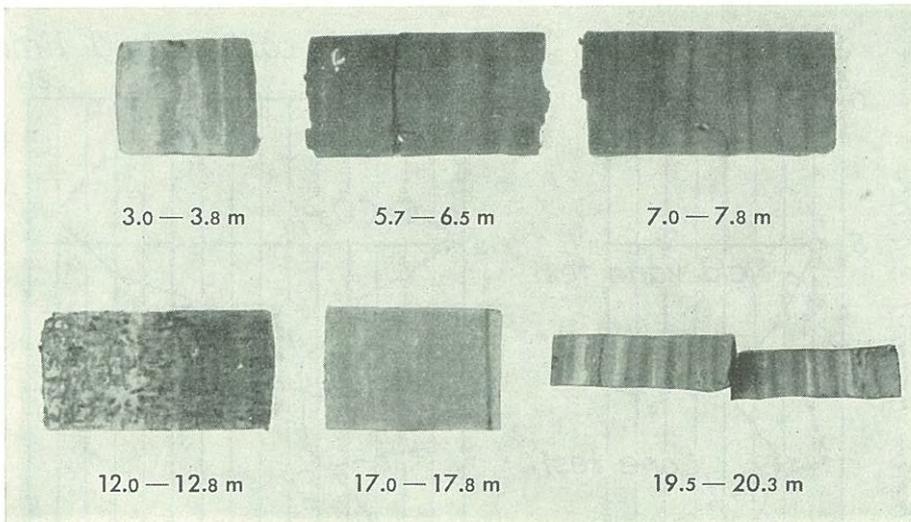


Fig. 11. Typical specimens of soil from Ultuna.

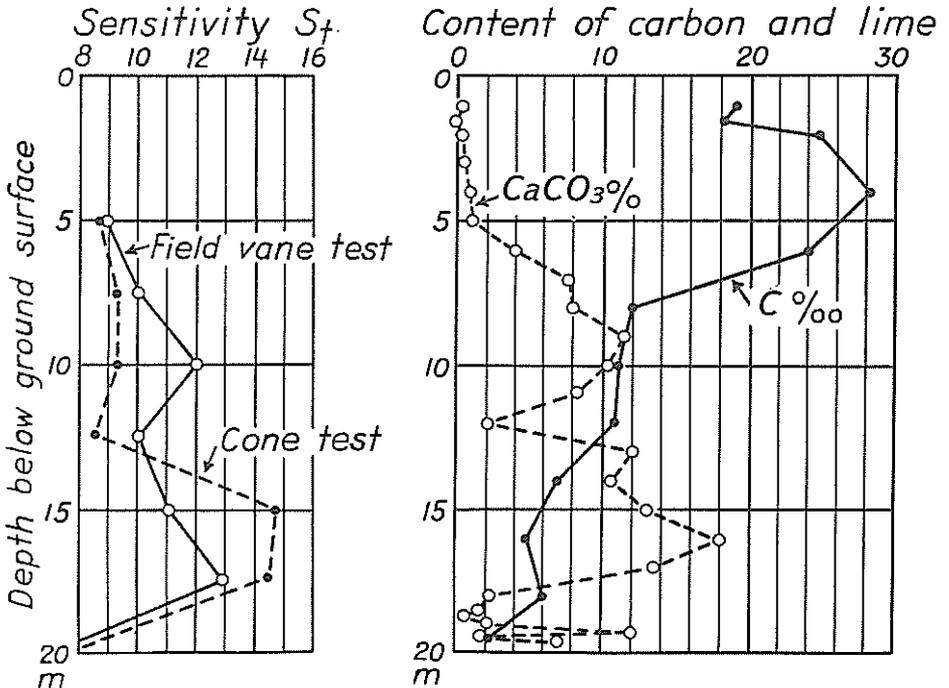
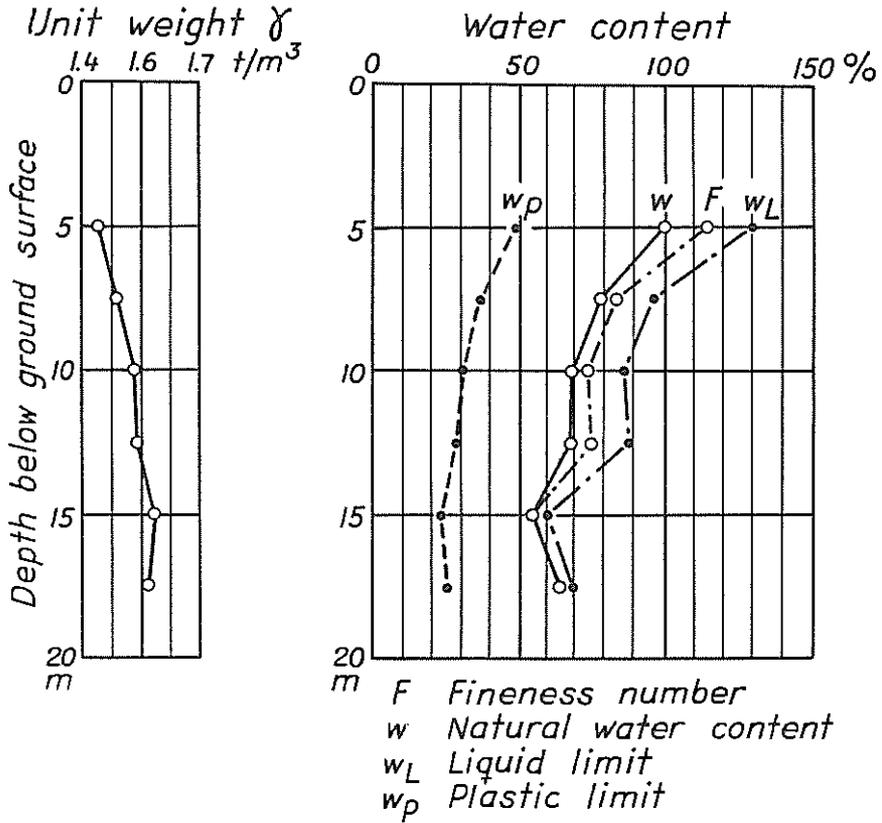


Fig. 12. Soil data from Ultuna.

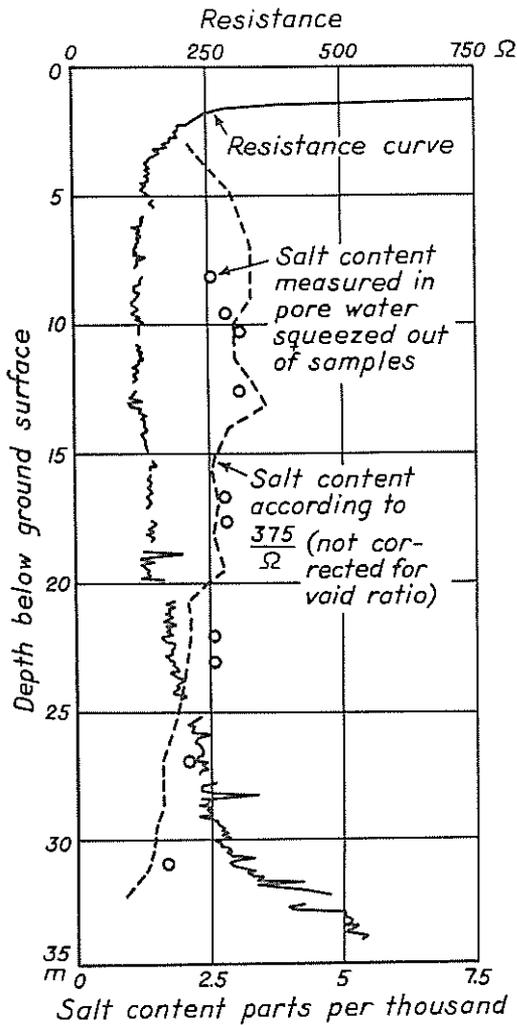


Fig. 13. Salt content in a profile at Ultuna (from analysis and electrical resistance tests).

The water table was near the ground surface. At a depth of 10 metres there was slight excess pore pressure. A few months after the samples had been taken this pressure had disappeared.

The salt content was determined by measuring the electrical resistance of the soil and by analysis of the pore water squeezed out of soil samples, as part of the total weight. Fig. 13 indicates that the salt content is low and that it decreases with depth. Consequently, the danger of osmotic disturbances during sampling ought to be small.

3 b. The Samplings

3 b 1. Sampler Data

The samplers have already been introduced in § 2. Their main data are given in the table below.

Sampler	SJ	SGI IV	SGI VI	Gk	NGI	SGI VIII
Type	Simple	————	Composite	————	Simple	Composite
Area ratio ¹ , per cent	34	91	53	50	12	59
Edge angle, degrees	45	26.5	8.3	10.5	12	9.7
Inside radius R_i , cm	2.2	3.02	3.02	2.12	2.7	3.02
Sample length L , cm	64	22.4	42.8	48.8	~80	46.4
Relative sample length, L/R_i	29.1	7.4	14.2	23.0	~30	15.3
Inside clearance, per cent of R_i	—	—	—	1.2	1.3	—
Sample shutter	—	—	Yes	—	—	Yes

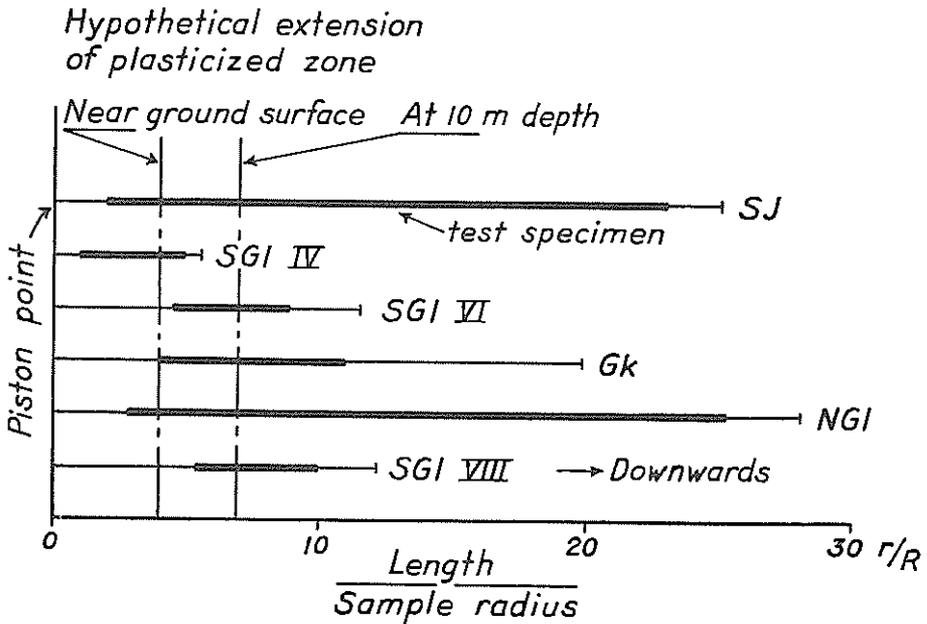


Fig. 14. Relative position of samples taken at Ultuna.

¹ Computed as the ratio between the wall section area and the gross area of the sampler.

Samplers SGI and Gk are composite samplers with exchangeable cutting edge and liners, and permit the use of simple shutters. Sampler SJ is thick-walled and NGI thin-walled.

The area ratio should not, according to Hvorslev, exceed 10 %, and we can see from the table that only sampler NGI approaches this value. The others have thicker walls owing to the requirement of a sturdy construction.

From the relative punching stroke it can be said that all SGI samplers are short and the others long.

Only samplers Gk and NGI were, when making the actual test, provided with inside clearance. (These samplers showed a tendency to lose samples, not evident with the others.)

The liners of sampler Gk were very smooth inside, while those of samplers SGI were old and therefore not quite smooth on the inside. In the beginning the tubes of the NGI sampler were smooth and oiled but, to prevent loss of samples, the inside had to be cleaned and roughened with emery cloth.

Fig. 14 shows a comparison of the parts of the samples accepted as test specimens (in relation to the external radius R_e). In the case of sampler SJ, test specimens were taken near the lower end at depths of 7.5, 12.5 and 17.5 metres and near the upper end for other depths. This has apparently not influenced the results very much (*cf.* Fig. 21 a).

3 b 2. Sampling Operations

Every sampler was handled carefully by persons familiar with its use. The procedure was principally the same as for routine sampling. The operations were carefully supervised and recorded. Some sampling data are given below.

Sampler	SJ	SGI IV	SGI VI	Gk	NGI	SGI VIII
Number of sampler heads used for one equipment ...	1	1	1	1	2	1
Number of operators employed	3-4	2-3	2-3	2	2-3	2-3
Piston travel upwards during punch, mm	1-25	0	0	-1	0-4	0
Punching speed, metres/min	0.3-4	3-5	10-13	3-5	4-6	10-13
Number of samples taken a day	6-7	7-9	7-8	9-11	6-8	7-8
Greatest depth for manual press, m	20	15	15	20	—	15
Aid for punch	Lever	None	Compressed air	None	Jack	Compressed air
Cutting of sample after punch by	Turning	—	Shutter	—	Turning	Shutter

It was possible to press down samplers SJ and Gk manually, even to 20 metres depth. The SGI samplers could be pressed down manually to 15 metres depth and were then carefully rammed. Sampler NGI was pressed with a special jacking device.

During the punching operation, the piston of sampler SJ travelled upwards to begin with and then, at the end of the stroke, down a little. The upwards travel was 1-2 mm at a depth of 5 metres and 25 mm at 20 metres depth. The piston of sampler NGI had a similar tendency, but its travel was only one fifth as much. There was no observable travel in the pistons of any of the SGI samplers. Sampler Gk had great friction between the piston rod and its guide and consequently the piston moved slightly downwards when punching started.

The figures on sampling capacity should not be regarded as being too generally valid as no great attention was paid to the capacity. Sampler SJ is not normally used at greater depths than 15 metres and was thus operating beyond its normal depth. Even if this is to a certain degree true also of the other samplers, sampler SJ seemed to be most affected by depth.

The most time-consuming task when using the simple samplers SJ and NGI was the preparation of samples for shipment. The SGI samplers had the greatest diameter, and their penetration resistance and the fixing of their pistons caused the main loss of time. The quickest and most economical sampler was the Gk, but even this could be improved as to sampling capacity.

In spite of the different means used to separate the samples from the underlying soil (rotation, tension, shutters), all samples were cut off at the edge. Most of the surfaces of rupture were fairly flat, but in the case of sampler SGI IV the surface of rupture was cone-shaped with the point directed downwards (cf. § 4 a 9).

For samplers SGI IV and NGI a pause of a few minutes was made before the withdrawal to get better adhesion between the sample and cylinder wall because of the shortness of the former sampler and the great clearance of the latter.

3 b 3. *Preparation of Samples for Shipment*

After extraction to the ground surface the test specimens were cut out with great care. The samples taken with sampler SJ were pressed out on the site, transformed into loosely fitting brass cylinders and stored in airtight glass jars.

Samplers SGI and Gk had brass liners protected by tight-fitting rubber caps. As regards sampler Gk, the edge was simply turned until the sample had been separated immediately below the lowest liner. Between the liners, the sample was cut off with a wire saw, which meant that the liners had to be separated a little in the axial direction. All the SGI samplers were dealt with in the same way except that the sample in the lower end was removed with a special cleaning tool before the edge was screwed off.

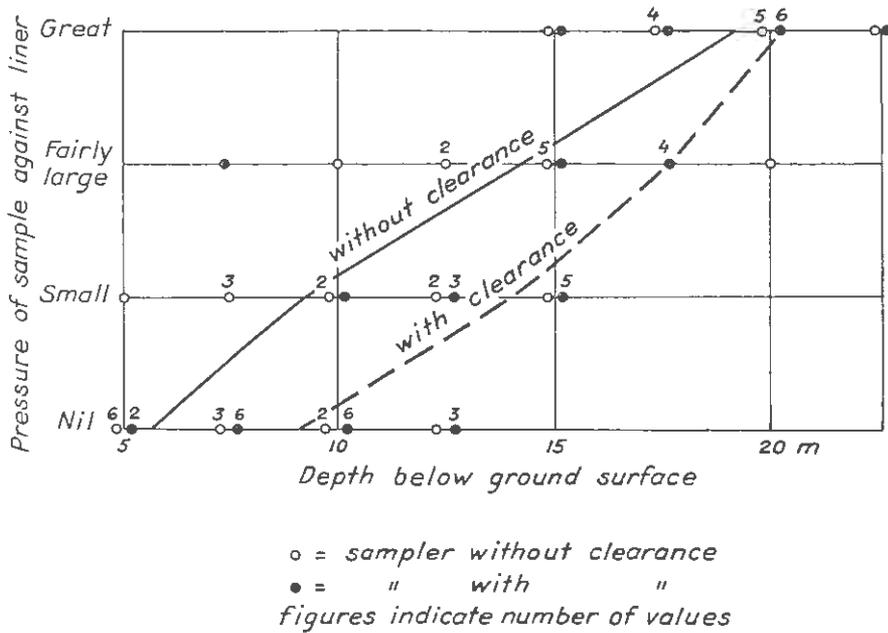


Fig. 15. Radial pressure against liner versus depth (Uttuna).

The stainless steel tube containing the sample extracted with sampler NGI was sealed with melted wax and rubber covers. The samples were kept in the shade when taken. When shipped to the laboratory they were protected from shocks and vibration.

3 c. Laboratory Tests

3 c 1. General

The laboratory was situated about 50 km from the test site. The samples were shipped with great care in the evening of the day on which they had been taken and, as a rule, were tested the following day. In a few cases testing was performed two days after sampling.

The normal extraction procedure was to push the samples out of their liners with the aid of a simple piston. If they were firmly fixed to the cylinder, a pneumatic extruder was used.

When pressing out the samples a note was made as to whether the samples were firmly or loosely fixed in their liners. By personal judgment, the radial pressure between sample and liner was assessed as *nil*, *small*, *fairly large* or *great*. No such assessment was possible in the case of the samples from the SJ sampler since those had been pressed out on the site. For sampler NGI, it

was only stated that the samples taken at depths of 5 and 7.5 metres showed almost no side pressure and that the radial pressure tended to increase with the sampling depth.

Fig. 15 shows the pressure data collected in respect of the SGI and Gk samplers. The tendency for the radial pressure to increase with the depth is obvious. A comparison between sampler Gk, which had inside clearance, and the SGI samplers, which in this case had no clearance, indicates that the clearance reduced the radial pressure. This reduction is greatest at shallow depths (*cf.* also Figs. 45-47).

After the samples were pressed out of their liners they were first examined visually. Certain samples showed nearly vertical fissures. This was true for all samplers and all depths. Certain samples also contained small cavities. When the samples were still in the ground, these cavities may have been filled with gases and water (gas bubbles had been observed when boring). The samples often contained shells.

A few samples taken with samplers SGI VI and NGI were obviously disturbed and were therefore rejected. The cause of this disturbance was probably excess air pressure at the time of or after punching in the case of the SGI VI, and too large an inside clearance at shallow depths in the case of the NGI sampler.

3 c 2. Tests Performed

Determinations of water content were made on all samples. For certain samples the liquid and plastic limits, and also the Swedish "fineness number", which is closely related to the liquid limit, were determined (CALDENIUS and LUNDSTRÖM, 1956).

Chemical tests were performed on a core taken with the Steel foil sampler (KJELLMAN, KALLSTENIUS and WAGER, 1950). The results of these tests have already been given in § 3 a.

Shear strength was determined by means of three different methods, *viz.* the fall-cone test, the unconfined compression test and the laboratory vane test.

The fall-cone test (Fig. 16) was carried out and evaluated in accordance with the old standard Swedish procedure (*cf.* STATENS JÄRNVÄGAR: GEOTEKNISKA KOMMISSIONEN, 1922, and CALDENIUS and LUNDSTRÖM, 1956). No correction was made for the fineness number (see above). Three cone tests were made on each sample.

The fall-cone test has recently been revaluated and modernized (HANSBO, 1957, where also a comparison between samplers SGI IV and SGI VIII is made). In this publication the older interpretation was used because the new one was not quite ready at the time of testing. The old interpretation gives the most direct, even if not the best connection to older experience.

The unconfined compression test was made in the Institute's recording compression test machine (Fig. 17). The part of the sample used as the test specimen

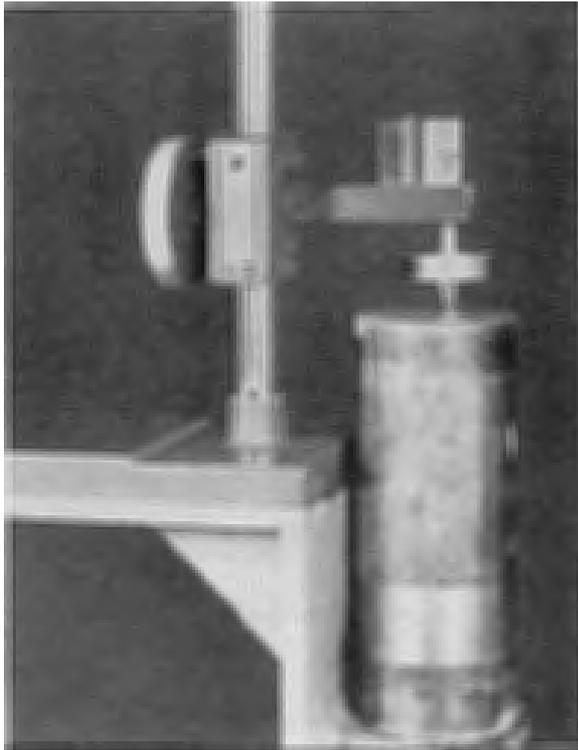


Fig. 16. Fall-cone tester.

was taken out near the lower end of most samples, and pieces with visible fissures were avoided. Since samples of different diameters were to be tested and trimming avoided, the length-to-diameter ratio was kept constant. Also the increase in stress with time was kept constant (0.02 kg/cm^2 per minute in the axial direction) for all sample dimensions. This was done by changing the gearing in the machine. Stress-strain curves were plotted for each test.

The laboratory vane apparatus is shown in Fig. 18. It consists of a vane body with two transverse blades $15.3 \times 30 \text{ mm}$, fastened to a shaft and fitted with resistance wire strain gauges for measuring the torque. The specimen is mounted on a rotatable table, which can be raised to allow the vane to be inserted into the specimen until the upper end of the vane has reached a depth of 20 mm. Electrical contacts on the electric motor used to rotate the table actuate a counter indicating the number of $1/6$ degree increments of the rotary movement. From the readings a stress-angular-deformation curve can be plotted. The rate of rotation of the vane during testing was about 2 degrees a minute.

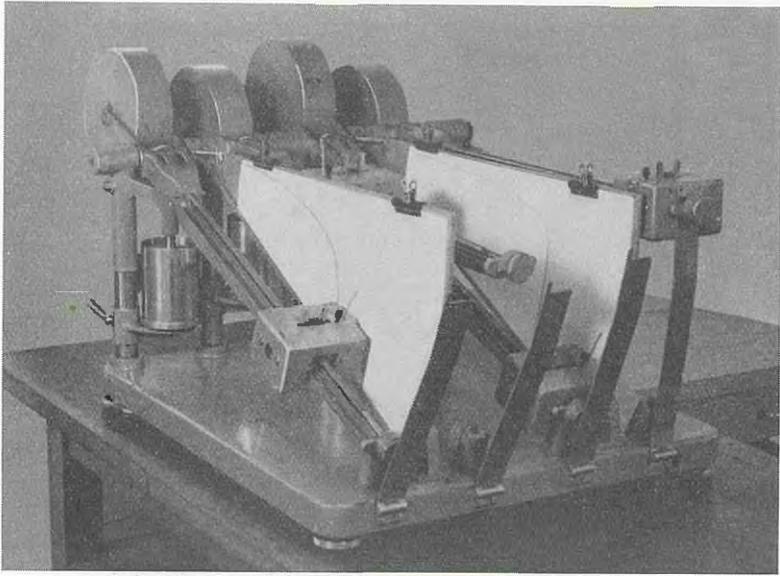


Fig. 17. Unconfined compression tester SGI.

The vane apparatus requires the specimen to be rigidly fixed in a liner. The samples taken with the SJ sampler were so loose in their containers that they had to be secured by means of sticks pushed in between the sample and the container. In spite of this arrangement a few samples slipped at times during the tests. This could be easily seen on the curves, but curves showing such slips have not been accepted as reliable. Half of the number of samples taken with the Gk sampler and all those taken with the NGI were prepared in the following manner. The specimen was wrapped in a very thin metal sheet and placed in a cylinder a few millimetres wider. Plaster of Paris was poured into the annular space between the specimen and the cylinder. Of the SGI-samples all remained in their original liners when being tested. Consequently, when making comparisons between the different samplers with respect to laboratory vane results, it must be remembered that the radial pressure was not strictly the same in all cases.

Radial fissures were sometimes found when the vane was pressed into the specimens. This tendency was twice as great in the case of small diameter samplers (SJ and Gk) as for the others. This has probably to do with the diameter (as the samples taken with the NGI sampler were treated in the same way as those from sampler Gk). The strengths of samples with and without fissures were compared, but the results were varying and did not permit any conclusions.

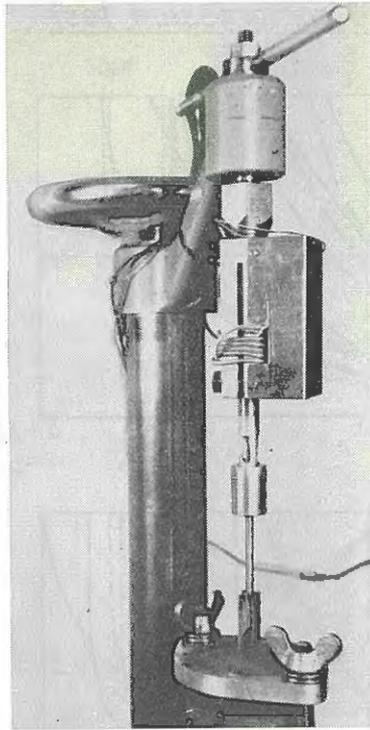


Fig. 18. Laboratory vane tester. Torque measuring device.

3 c 3. Test Results

Some typical stress-strain curves from unconfined compression tests are shown in Fig. 19. Appreciably greater strain is evident in the case of SJ and SGI IV samplers than in more recent models.

In Fig. 20 similar curves for laboratory vane tests are given. In this case the largest strain is shown by samplers with the smallest diameter (*cf.* also Fig. 24).

Fig. 21 indicates the individual values of fall-cone test strengths and of stresses for certain strains, and for failure for the unconfined compression test and the laboratory vane test. To facilitate comparison, the averages have been plotted in Fig. 22. Especially for the unconfined compression test it can be seen how the short samplers exhibit their best qualities at shallow depths and the long samplers at greater depths.

A comparison is made between the above results and those from the field vane tests, Fig. 23.

The fall-cone test in Fig. 23 has not, as mentioned before, been corrected for "fineness number". When this is done, the curves become almost parallel with

Unconfined compression test

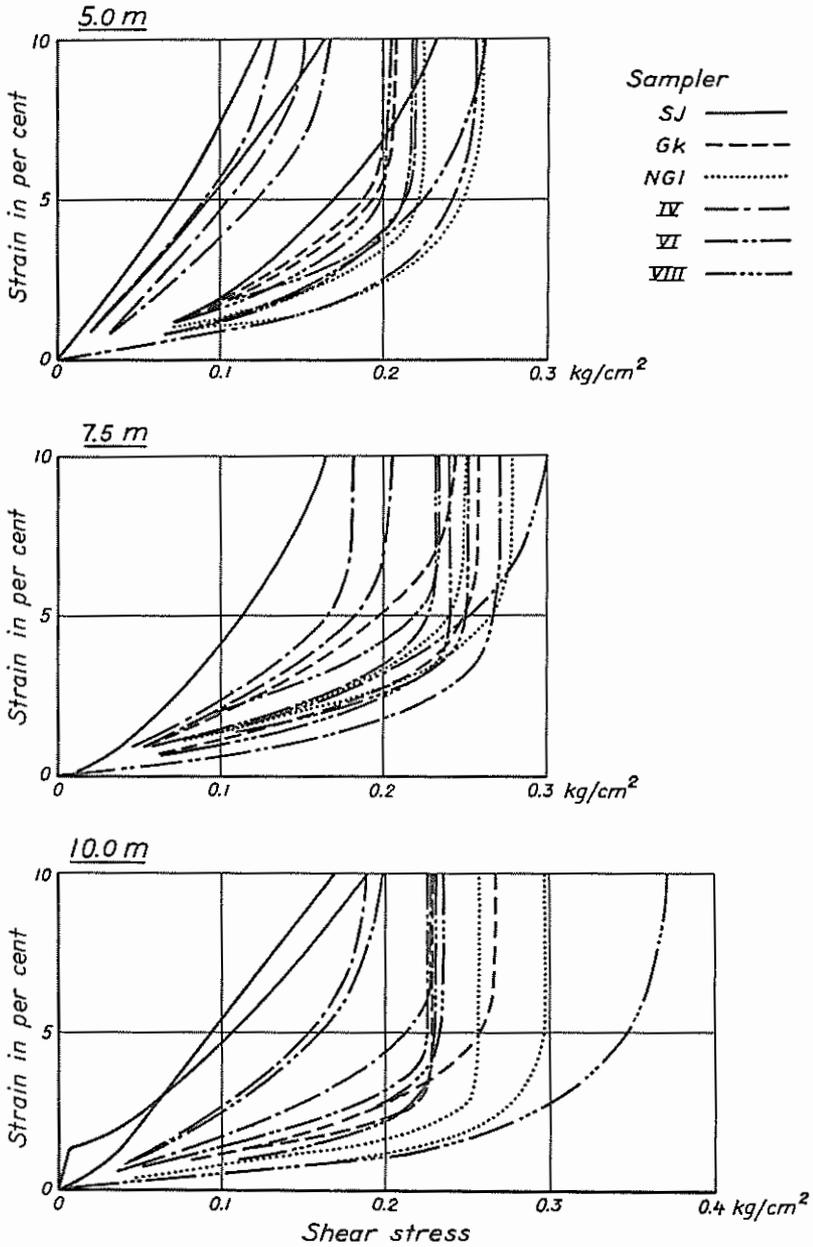
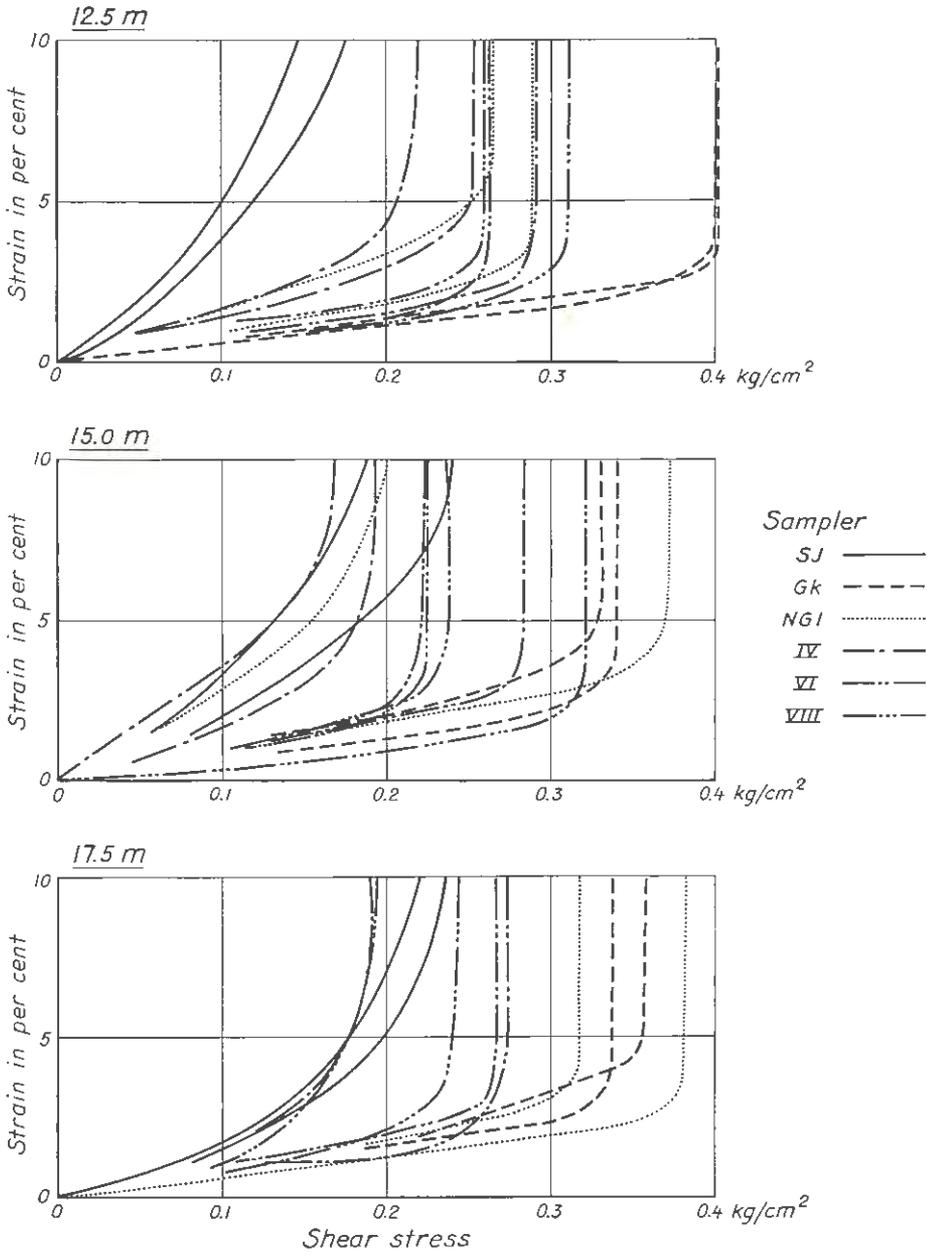


Fig. 19 a. Unconfined compression test. Stress-strain curves (Ultuna)
(5, 7.5, and 10 m depths).

Unconfined compression test



*Fig. 19 b. Unconfined compression test. Stress-strain curves (Ultuna)
(12.5, 15, and 17.5 m depths).*

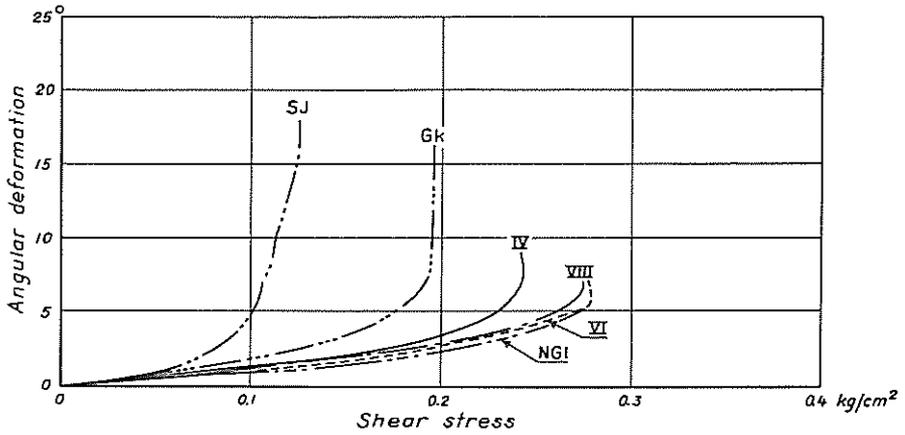


Fig. 20. Laboratory vane test. Stress-angular deformation curves (Ultuna).

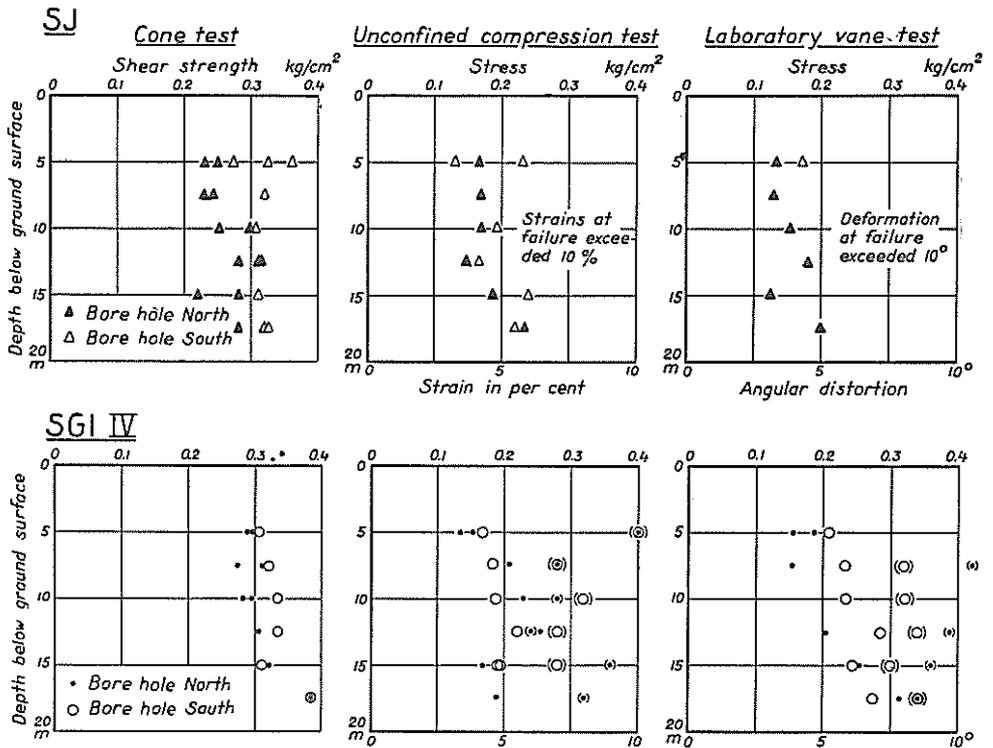


Fig. 21 a.

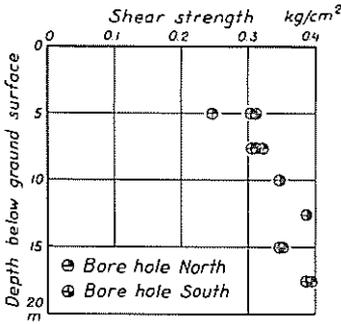
Fig. 21. Shear strengths (Ultuna), individual values (signs in parentheses indicate strains).

a. Samplers SJ and SGI IV.

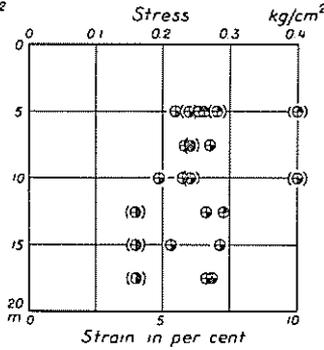
b. Samplers SGI VI and Gk.

c. Samplers NGI and SGI VIII.

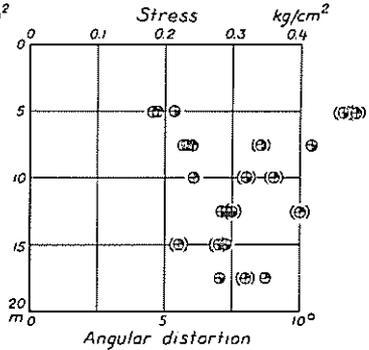
SGI VI Cone test



Unconfined compression test



Laboratory vane test



Gk

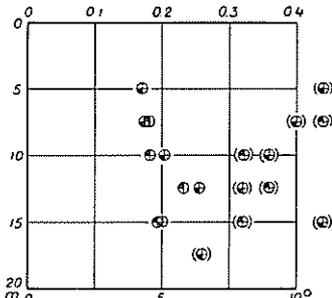
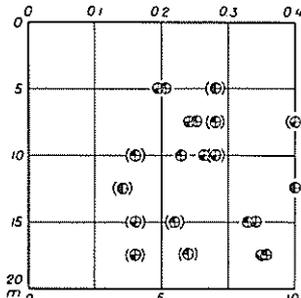
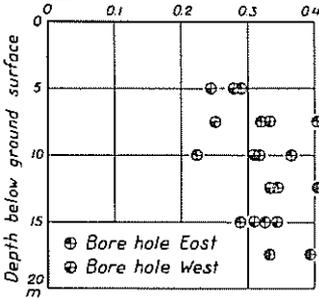
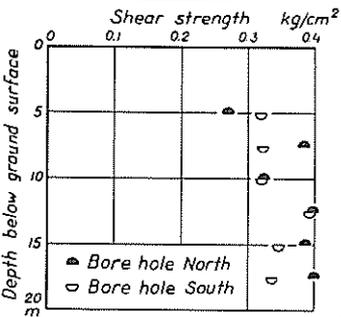


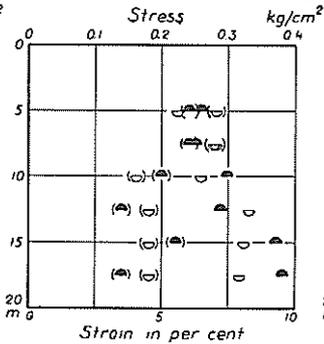
Fig. 21 b.

NGI

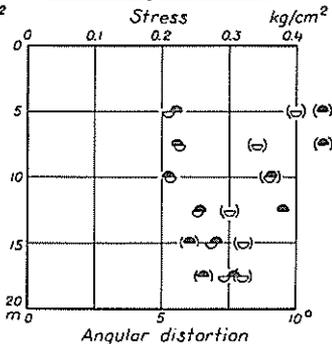
Cone test



Unconfined compression test



Laboratory vane test



SGI VIII

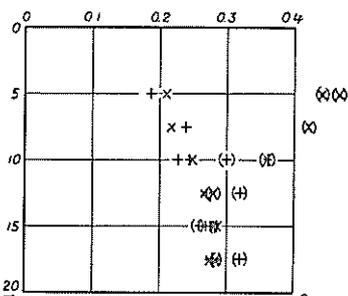
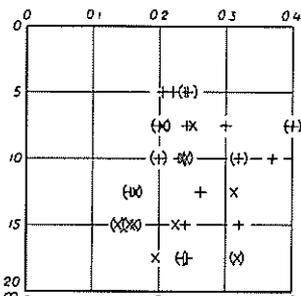
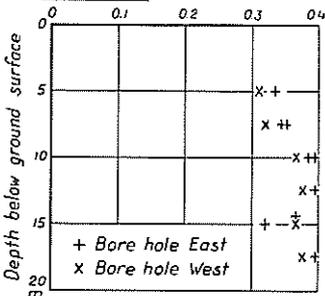


Fig. 21 c.

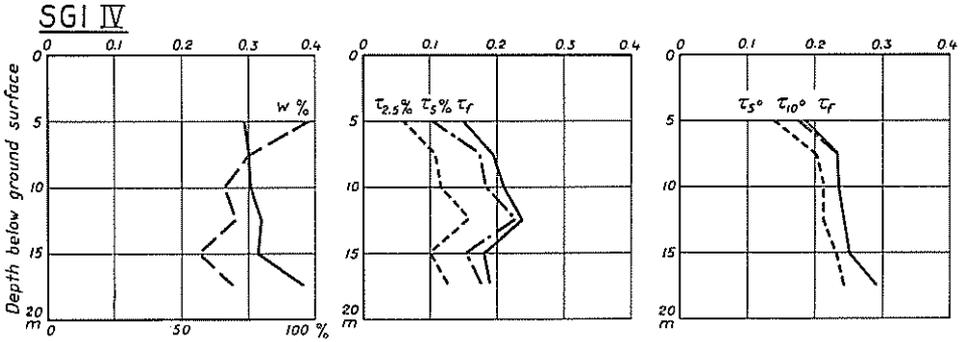
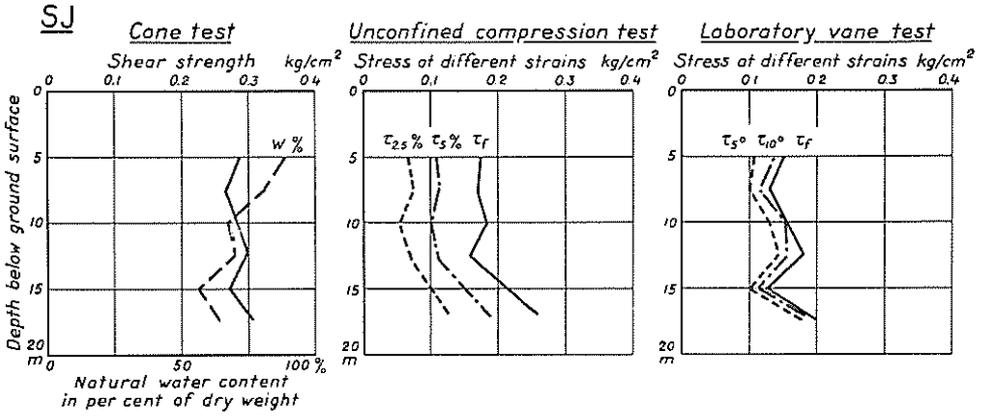


Fig. 22 a.

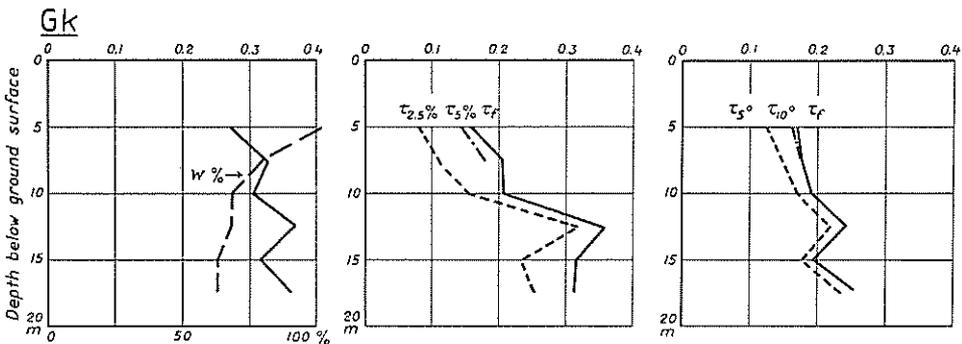
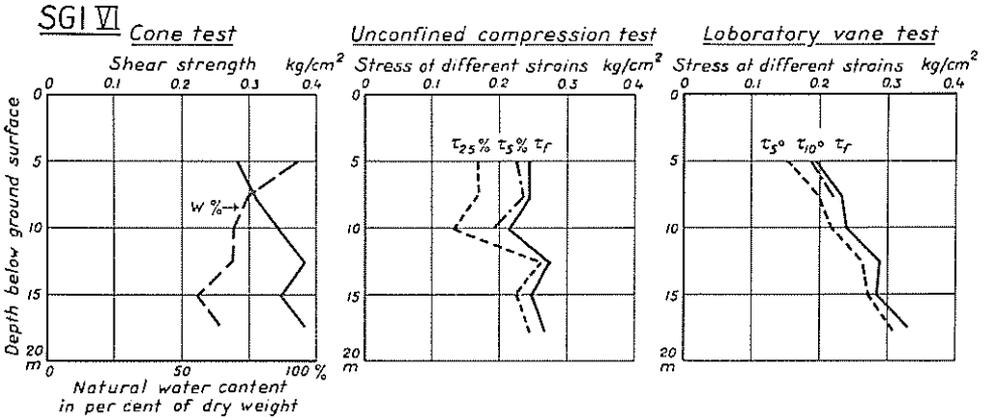


Fig. 22 b.

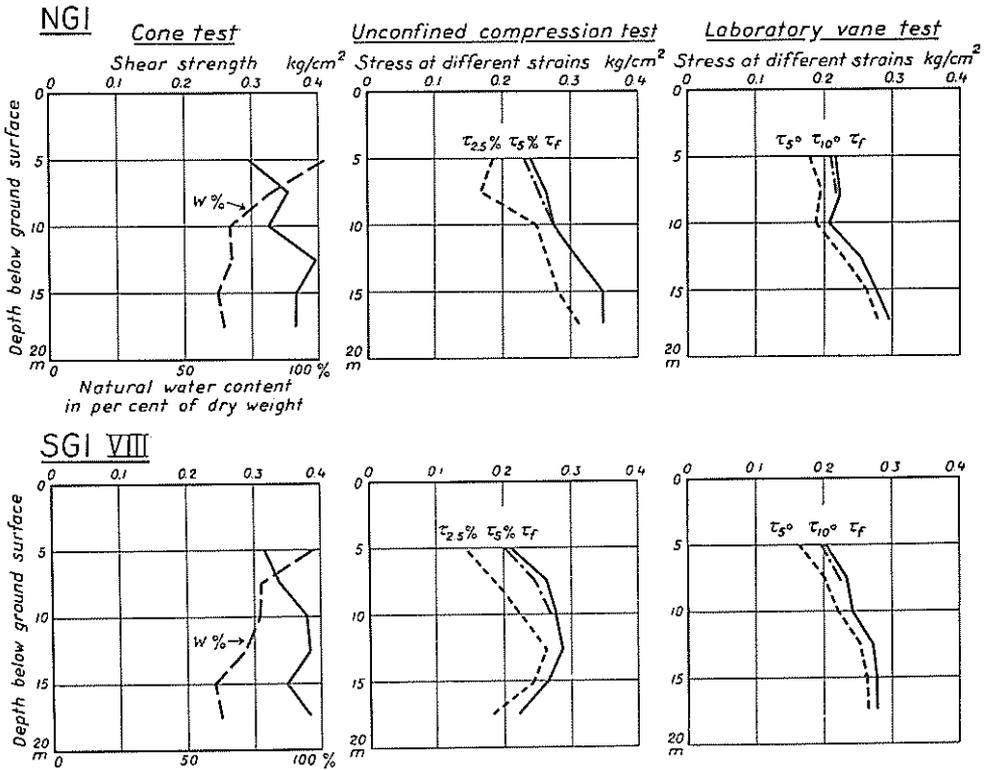


Fig. 22 c.

Fig. 22. Shear strengths (Ultuna), average values.

- a. Samplers SJ and SGI IV.
- b. Samplers SGI VI and Gk.
- c. Samplers NGI and SGI VIII.

the 100 per cent line. (Compare also the revised interpretation of the fall-cone test—HANSBO, 1957, p. 34 Fig. 22—which shows a constant relation between the fall-cone test and the field vane test for the depths in question.) It is interesting to note that sampler SJ, on which the fall-cone test was once calibrated, gives an almost identical result with the field vane test, except that the results scatter much more. Samplers NGI and SGI VIII give about 30 per cent greater strength values than the SJ sampler.

The unconfined compression test shows the greatest differences in Fig. 23. The long samplers give results parallel with the field vane at all depths, but the short samplers show a decrease with depth. This will be discussed later on.

The laboratory vane agrees well with the field vane at all depths. It is interesting in this connection to note that the old and short sampler SGI IV is, in

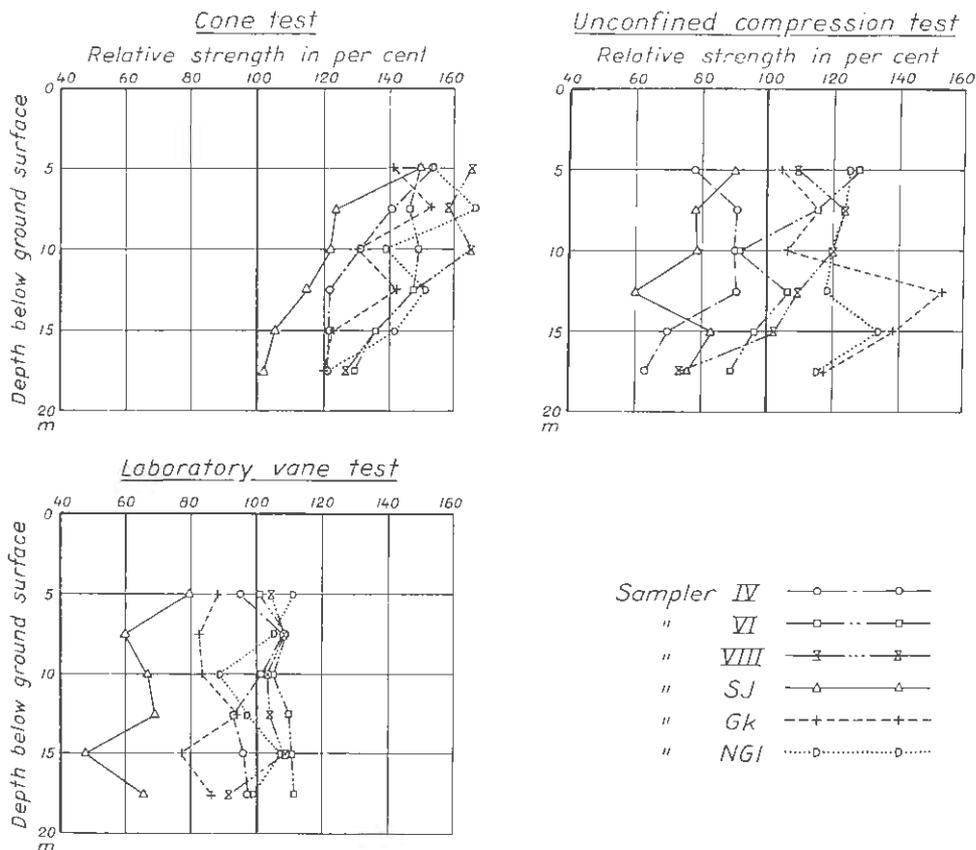


Fig. 23. Shear strengths from laboratory tests as percentage of field vane tests at Ultuna.

this case, equal to the long and modern NGI, while samplers Gk and SJ give smaller strength values. The diameter of the samples seems to have had an effect on the results (cf. Fig. 20).

Fig. 24 gives a general statistical summary of all the results. Using a common base, the average strength values have been plotted upwards, while the average scatter of the individual values from the mean value at each depth has been plotted downwards. As a rule, great strength and small scatter are combined.

It is remarkable how differently the three laboratory methods indicate the quality of the different samplers, and how great the differences are between the samplers.

One can, however, deduce a tendency for larger diameter samplers to give better results. This is directly visible for the fall-cone tests and the laboratory vane tests, but not for the unconfined compression tests. However, in Fig. 22

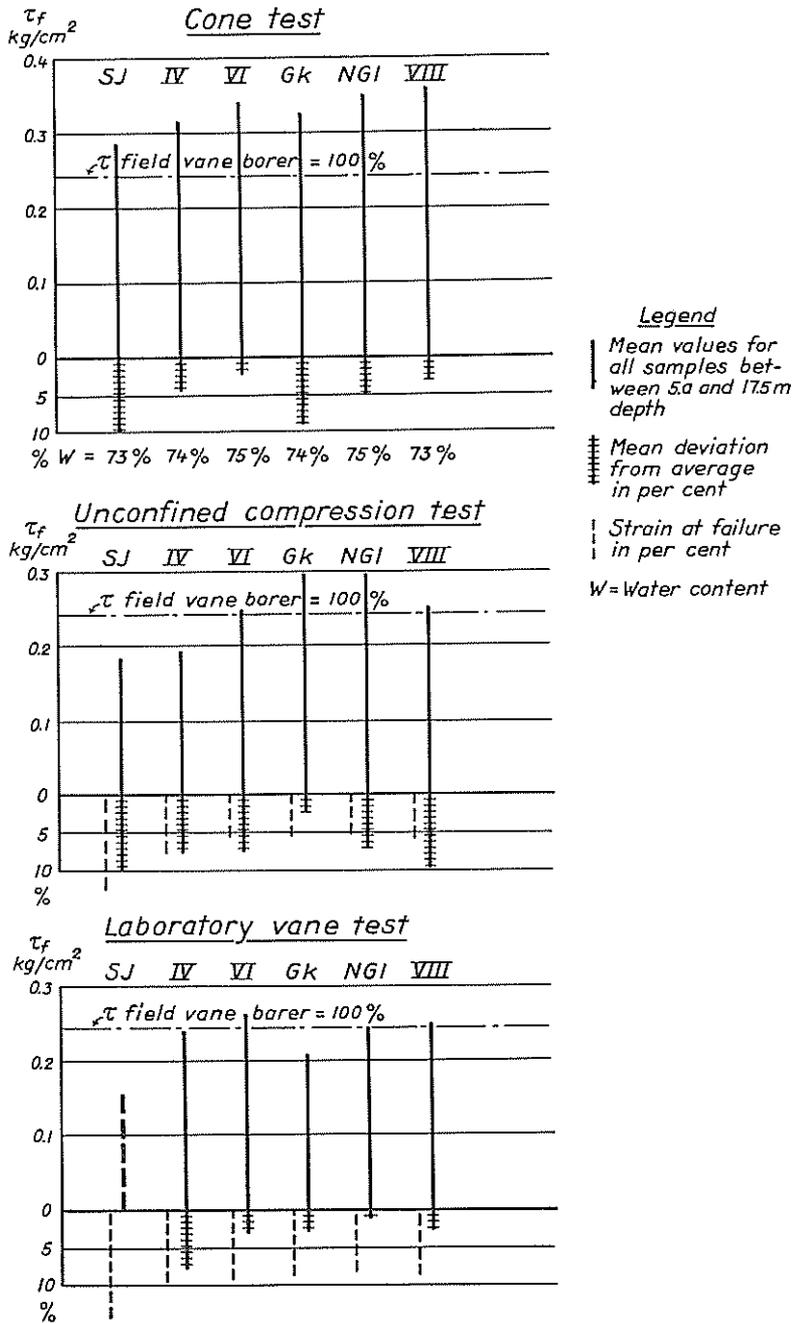


Fig. 24. Summary of test results (Ultuna).

it can be seen how the strengths in the unconfined compression test decrease with increasing depth for the short samplers, whereas this is not the case with the long samplers. If a comparison is made only for shallow depths (5-10 metres) one can find the same tendency towards increasing strength with increasing diameter as indicated by the cone test and the laboratory vane test.

The average water content of the different samples has also been indicated in Fig. 22. No great differences were noted.

A number of samples taken with sampler NGI were shipped to the Norwegian Geotechnical Institute and tested there. The test values obtained were in good agreement with our results.

3 d. Tests on Influence of Sample Size

In § 3 c the influence of the sample diameter on the disturbance of samples is mentioned as being a possibility. It was decided to check if this dependence was influenced by the specimen-diameter as such. If so, a correction must be made when discussing the influence of sampling.

3 d 1. Influence of Sample Size in the Unconfined Compression Test

HABIB (1953) has performed tests with remoulded and reconsolidated clay. He found that the results from the unconfined compression test were largely independent of sample size.

As his tests did not show how undisturbed natural clay behaves, we made supplementary tests on clay taken up with the Steel foil sampler from the test site at Ultuna. Pieces of core from 11-15 metres depth were cut into specimens and carefully trimmed to prisms of various size with a square cross-section and a height twice the side of the square. The unconfined compression tests were performed with the same rate of stress-with-time as was used for the main unconfined compression tests.

The results are shown in Fig. 25. A minimum of strength and a maximum of scatter is noticeable for the 25 mm side length. This could be the result of a texture in the clay which could be studied by breaking the clay into pieces. However, it cannot have had considerable influence on our comparison of samples with diameters 42-60.5 mm.

3 d 2. Influence of Sample Diameter in the Laboratory Vane Test

The angular deformation of a cylindrical specimen caused by the torque of the vane can be computed (CADLING and ODENSTAD, 1950, p. 38). Such a calculation gives the following values.

Sampler	SGI	NGI	SJ	Gk
Relative angular deformation	1.0	0.98	0.94	0.93

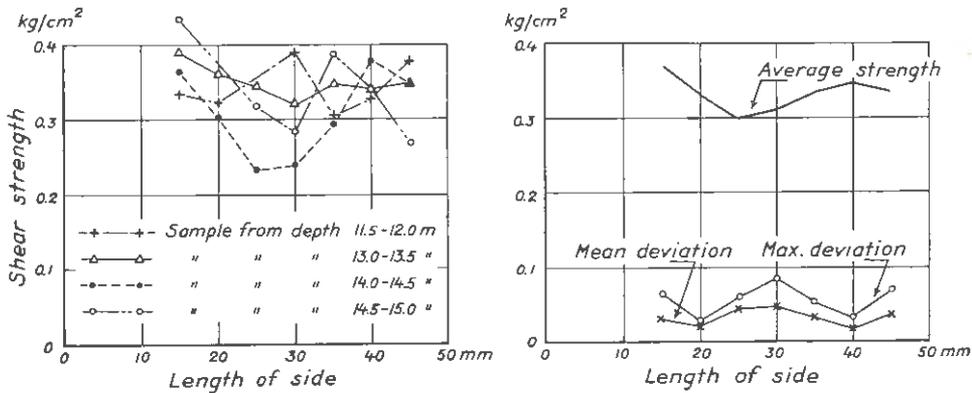


Fig. 25. Influence of sample size on unconfined compression test strength.

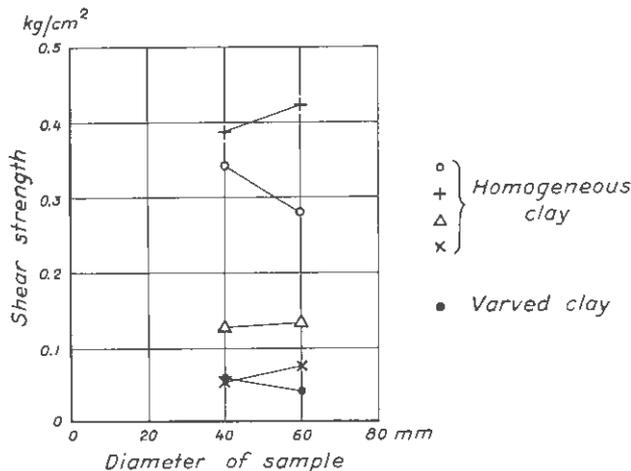


Fig. 26. Influence of sample diameter on laboratory vane test strength.

The differences are small, as can be seen, and have the opposite tendency to the deformation curves from the Ultuna tests (Fig. 20). The above will therefore not influence our coming conclusions.

A test series was performed to study whether specimen-diameter as such would influence the shear strength obtained in the laboratory vane test. Seven SGI IV samples were used and two specimens were taken from each sample. One of the specimens was trimmed down to 40 mm diameter and the other was kept at its original diameter of 60 mm. The specimens were wrapped in metal foil and fixed in plaster of Paris.

The strength values obtained are given in Fig. 26. The influence of the diameter is small.

4. Analysis of Disturbance due to Sampler Shape

As many factors may have influenced the test results, any analysis must be made with care. To this end, a theoretical analysis and some additional tests were made in order to study the influence of sampler shape. These investigations sought merely to give a qualitative idea of what happens during sampling, as such knowledge will be helpful when treating test results and performing more detailed tests.

4 a. Disturbance below Sampler Pushed down into Soil

4 a 1. Metallurgical Analogy

Although metal in many respects differs much from soil, a certain similarity between these materials may be expected in the plastic state.

When metal is punched, the material deforms plastically. A plasticized zone can be observed if the test specimen is cut and the cut surfaces are polished and etched. Fig. 27 *a-b* shows photographs taken from NÁDAI (1931, p. 253). Fig. 27 *a* demonstrates how the plastically disturbed zone near the punch forms an even bulb for small displacements, and Fig. 27 *b* shows how, for larger displacements, additional zones of more local shear extend the bulb.

Fig. 27 *c* is taken from Swedish experiments. Here the surface hardness has been measured. Increase in hardness gives an indication of plastic deformations, and one can also observe such disturbance outside the zone of directly visible flow. It must be remembered that this zone lies comparatively near the surface where punching was started and will probably have a different shape deeper in the material.

4 a 2. Use of the Theory of Plasticity

In a soil, when theoretically treated as a material having a modulus of elasticity E and a shear strength $\frac{K}{S_t} \cdot \tau_f$, expressions for stresses and strains caused by an expanding cavity can be derived (NÁDAI, 1931; HILL, 1950; MÉNARD, 1956). (Here τ_f is the undisturbed shear strength, S_t the sensitivity, and K a factor depending on the degree of disturbance.)

The equations (1-3) below are based on some expressions derived at the Institute (ODENSTAD, 1950).

It may be considered that a cylindrical or spherical cavity expands radially by a distance indicated by R . The body tends to resist expansion and additional radial stresses then arise, as do also tangential stresses. After a small expansion the counter-pressure reaches a certain value σ_{\max} .

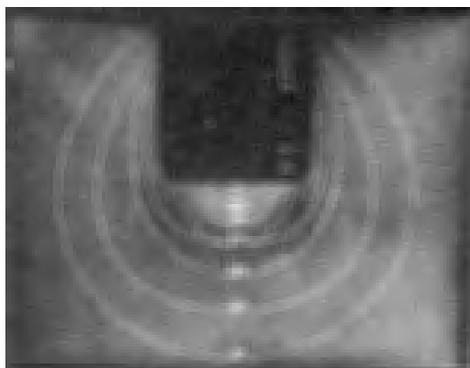
Around the cavity a plasticized zone is formed in which the shear strength is equal to $\frac{K}{S_t} \cdot \tau_f$. Assuming the material to be incompressible, a radius q can be calculated where the deformation is just sufficiently small to permit the material to behave elastically.



a.



b.



c.

Fig. 27. Disturbance in metal below a punch.

a. Small displacement (Nádai).

b. Greater displacement (Nádai).

c. Extension of disturbed zone (Thehning).

We obtain the following equations:

$$\frac{\sigma_{max}}{\tau_f} = A \left(\frac{K}{S_t} \ln \frac{E}{B \cdot \tau_f} + 1 \right) \dots\dots\dots (1)$$

$$\frac{\rho}{R} = \sqrt[3]{\frac{E}{B \cdot \tau_f}} \dots\dots\dots (2)$$

$$\frac{\sigma_r}{\tau_f} = \frac{\sigma_{max}}{\tau_f} - D \frac{K}{S_t} \ln \frac{r}{R} \dots\dots\dots (3)$$

$$\frac{\sigma_t}{\tau_f} = \frac{\sigma_r}{\tau_f} - 2 \frac{K}{S_t} \dots\dots\dots (4)$$

σ_r and σ_t are radial and tangential stresses at radius r .

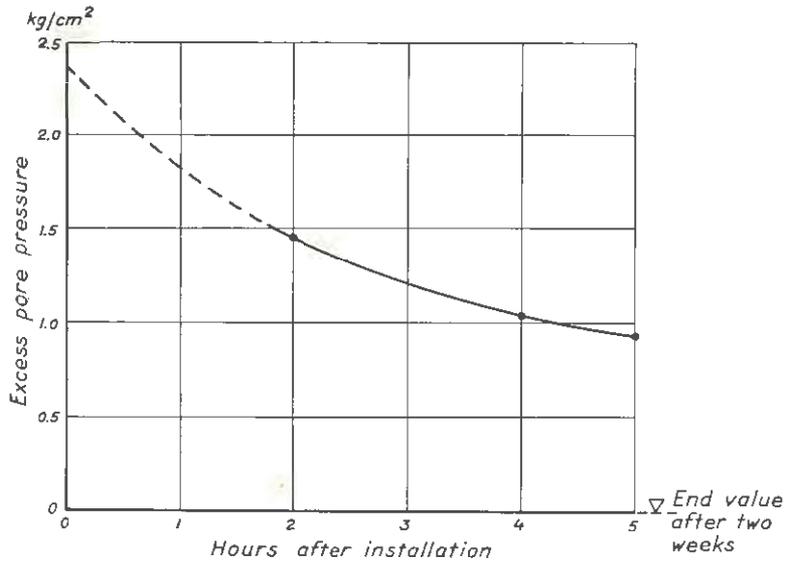


Fig. 28. Excess pore pressure below meter pushed down 5 m into clay.

For the cylindrical case $A = 1$; $B = 2(1 + \nu)$; $C = 2$; $D = 2$;
 " " spherical " $A = 4/3$; $B = 3$; $C = 3$; $D = 4$;

For a rod, penetrating into a soil, the cylindrical case would roughly correspond to conditions along the rod at great depth and the spherical case roughly to the conditions below the point.

As pore water and soil may flow away radially or upwards along the rod during penetration, one would certainly obtain an upper limit for q from the formulas, but the secondary zones of shear failure go beyond the bulb (cf. Fig. 27 b). The formulas can only give the right magnitude of the plasticized zone if they are calibrated in accordance with practical observations.

4 a 3. Soil Data for Computing Plasticized Zone

To be able to apply Eqs. (1-4), the ratio between the modulus of elasticity and the shear strength, E/τ_f , and the ratio between the maximal radial stress and the shear strength, σ_{max}/τ_f , or rather their apparent values, must be known.

A reasonable value of the latter can be deduced from tests. If a closed pipe fitted with a porous point is pushed down into saturated clay, and the excess pore pressure then produced is measured, it ought to lie only slightly below σ_{max} . Fig. 28 shows the results from such a test made at a depth of 5 metres in a post-glacial clay with $\tau_f \approx 0.25$ kg/cm². The measurement indicates a σ_{max}/τ_f -values of the order of 10.

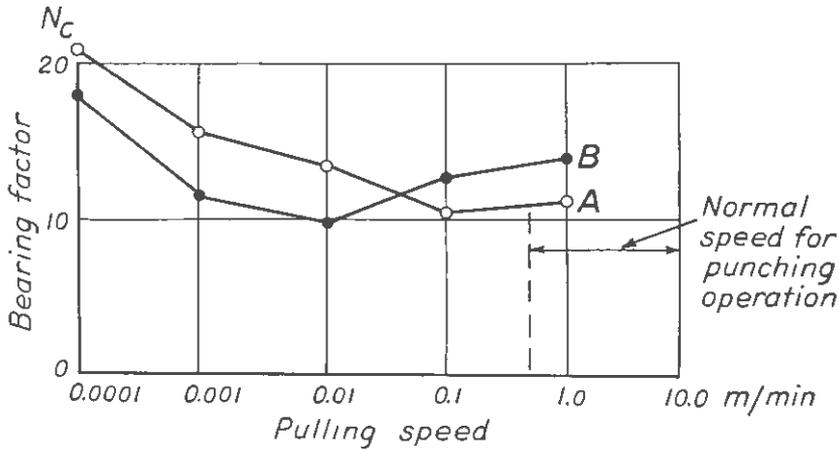


Fig. 29. Approximate N_c -values versus speed of pull obtained with *iskymeter* in Gôta River Valley clay.

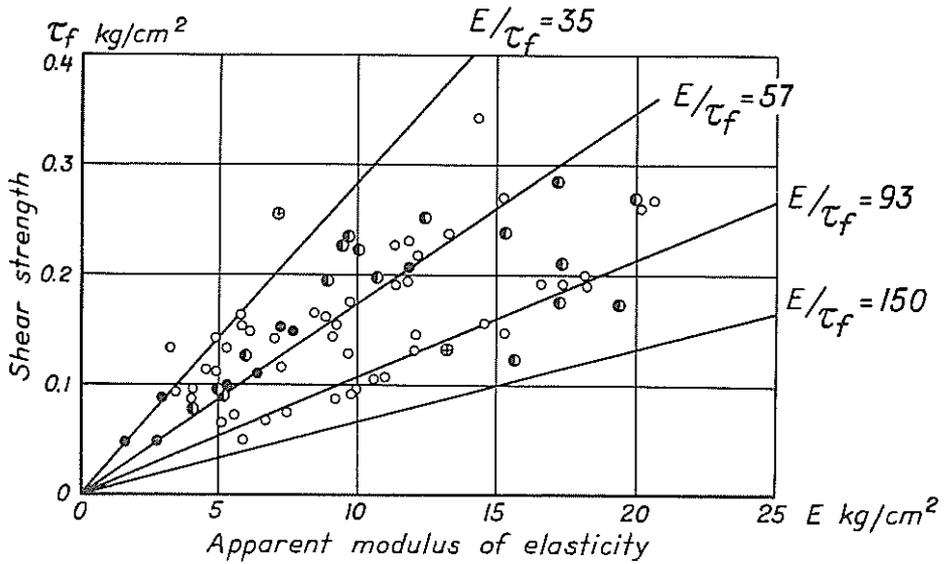
In another case we got 1.1 kg/cm^2 excess pore pressure at 3 m depth in a clay with τ_f about 0.25 kg/cm^2 , which means a σ_{max}/τ_f -value of at least 4-5.

Fig. 28 is a typical curve for most installations of pore pressure meters in Swedish clays, and the above experiences may be said to show that σ_{max}/τ_f is 4 to 6 at 3 metres depth and increases for 5 metres depth to 8 to 10 and further at greater depth.

The increase with depth is logical as the boundary condition given by the free soil surface must have an influence. As a result of leakage along the pipe, of influence of fissures or by upwards displacement, the soil must resist a certain radial displacement less at shallow depths than at large depths.

MÉNARD (1956, p. 20 and Fig. 5) has studied σ_{max}/τ_f in bored holes and at 0-8 ft depths. For saturated clays and for conditions most corresponding to the cylindrical case, he found values of the order 1 to 4. For the spherical case, the values ought to be about 30 per cent higher. This seems to correspond reasonably well with the general picture given above.

Although the stress conditions are much different, it may be of interest to compare the above with the bearing capacity (N_c) of embedded plates. The factor N_c (cf. MEYERHOF, 1951), the ratio between the maximum normal stress on a plate and the shear strength of the soil, ought to be of the same size as σ_{max}/τ_f . It is found that this value has the order 5 to 12 depending on depth. Fig. 29 shows how the N_c -value depends on speed. (The values in the figure were obtained with an apparatus called *Iskymeter* [earlier called *Insitu Apparatus*, see HVORSLEV, 1949, p. 43 and 44] which measures the resistance against a resistor body pulled out of the soil by means of a wire rope.) One can observe how the minimum values lie at pulling speeds 0.01 to 1.0 m/min. This may be compared with the driving speeds used at sampling.



Legend

- Mud
- ⊖ Varved clay
- ⊕ Muddy clay
- Clay

Fig. 30. Ratio of apparent modulus of elasticity versus shear strength (τ_f for unconfined compression test on samples from SGI IV).

When the values of σ_{max}/τ_f are known, we can, by means of Eq. (1), compute the corresponding E/τ_f . The effect of disturbance within the plasticized zone, which is indicated by the average value K/S_t in the equation, can be assumed to be slightly below unit. Estimating $K/S_t \approx 0.9$ we obtain:

σ_{max}/τ_f	5	6	7	8	9	10	12
Computed E/τ_f	23	69	135	240	312	339	710

Some experimental evidence for E/τ_f is also available. Fig. 30 shows values E/τ_f for unconfined compression tests on samples taken with sampler SGI IV in different soils (cf. also SKEMPTON and HENKEL, 1957). The vane test gives similar values. We find that values of E/τ_f between 50 and 150 are common for conditions where shear is the main resisting factor. On the other hand, the dynamic modulus of elasticity would give E/τ_f the order of magnitude of 10,000 to 50,000 (cf. DENISON and RELTOV, 1957), whilst the compressibility of water divided by its "shear strength" would give infinitely large values. At

large depths, where soil density is increased and surface influence decreases, the apparent E/τ_f ought to be higher than 50 to 150. Values of 350 to 700 or still more are not improbable for depths below 10 m in our case where the volume of the sampler is added to that of the soil.

4 a 4. Reduction of Strength in Plasticized Zone

The reduction of strength in the plasticized zone has no great influence on stress distribution. It is, however, of interest for the judgment of sampler disturbance. Conditions are complicated, and therefore one has to simplify.

As before, we assume at first the plasticized material to be incompressible. Further, we disregard the conditions very close to the sampler as we are most interested in the peripheral parts of the plasticized zone.

When the small spherical cavity expands radially by the distance R , the displaced volume is $\approx \frac{4}{3} \pi R^3$. At a radius r , this volume gives a radial displacement u_r , which for large values r/R is approximately:

$$u_r \approx \frac{R^3}{3r^2}$$

An element of soil situated at radius r moves through a distance u_r in a radial direction and is subjected to the tangential strain:

$$-\varepsilon_t = \frac{u_r}{r + u_r}$$

If u_r is small in relation to r , this expression can be replaced by

$$-\varepsilon_t \approx \frac{u_r}{r} = \frac{1}{3} \left(\frac{R}{r} \right)^3$$

Let us assume the disturbance to be $(1 - \frac{K}{S_t})$ and nearly proportional to the shear strain. This is assumed to be proportional to $-\varepsilon_t$. We can then write

$$\left(1 - \frac{K}{S_t} \right) \approx f \left(\frac{R}{r} \right)^{3n} \dots \dots \dots (5)$$

which is practically valid for the outer parts of the plasticized zone. This expression means that disturbance should decrease rapidly with increasing radius. MURAYAMA and HATA (1957) have given a relation between the angle of shear and disturbance. The Author is of the opinion that the strain gives a better parameter in our case where the strain is so large.

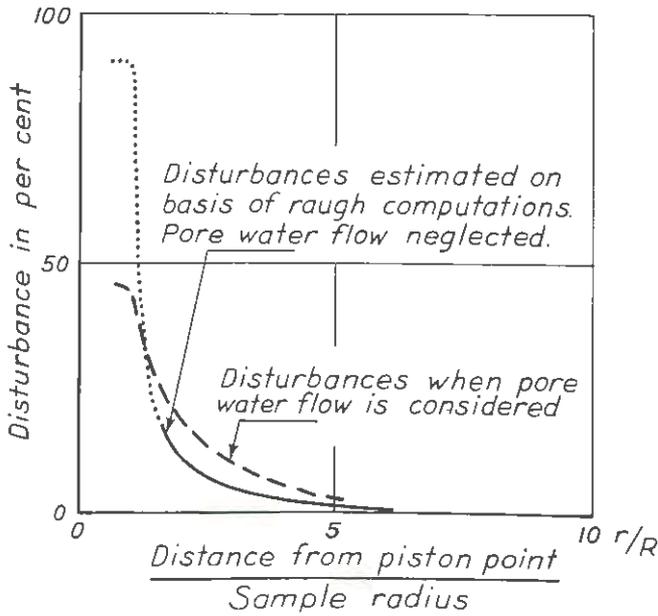


Fig. 31. Estimated size of disturbance within plasticized zone.

For a rough evaluation of Eq. (5) we try:

$$\left(1 - \frac{K}{S_t}\right) \approx \left(1 - \frac{1}{S_t}\right) \left(\frac{R}{r}\right)^3 \dots\dots\dots (5 a)$$

Fig. 31 shows the result of a calculation. Due to pore water flow in a radial direction we may, however, expect higher shear strength near the sampler and greater disturbance at some distance from it than indicated by the calculation.

As the disturbance must be very small at the periphery of the plasticized zone, there will be difficulties in finding its real size by means of strength tests, since these cannot be sufficiently accurate. On the other hand, only about half the radius of the plasticized zone will be of importance in practical sampling.

4 a 5. Computed Stress Distribution below Sampler

By means of Eqs. (1-5) and the empirical values obtained in § 4 a 3, we can now sketch the stress-strain conditions around a sampler before the punching operation has started.

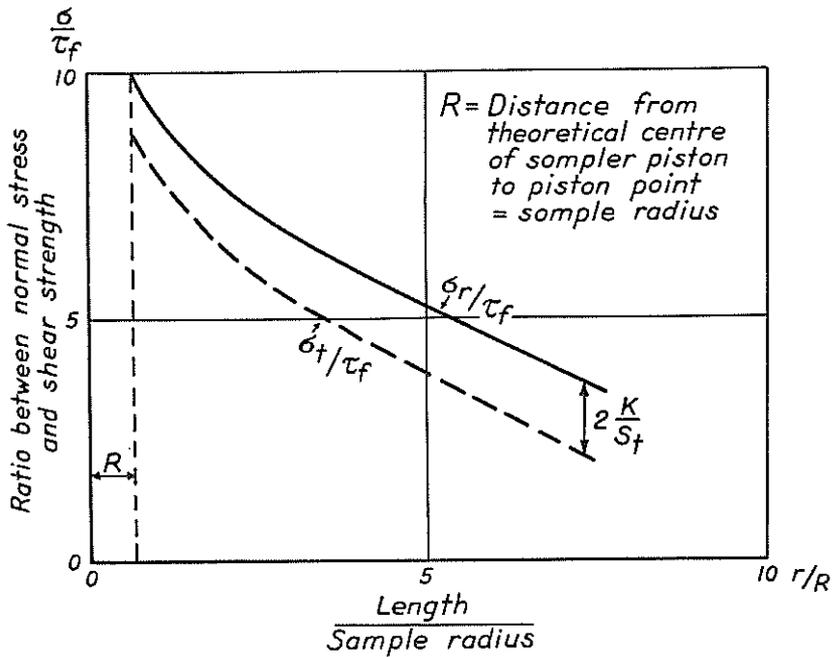


Fig. 32. Computed excess stresses within plasticized zone.

The relative radius (ρ/R) of the plasticized zone as computed for the spherical and cylindrical cases for our conditions is shown below.

Apparent E/τ_f	50	100	200	500	1 000	2 000
ρ/R cylindrical case	4	6	8	13	18	26
ρ/R spherical case	2.5	3.2	4	6	7	9

It may be concluded from § 4 a 1 to 4 a 4 that there is a homogeneously disturbed zone extending 3 to 5 radii at small depths, 6 to 8 radii at 10 metres depth and still more at a greater depth below the sampler. This zone may further be extended by local failure zones in accordance with Fig. 27 b and by changes due to pore water flow radially away from the sampler.

The computed excess stress in the plasticized zone below a sampler pushed down to a depth of 10 m is shown in Fig. 32. This figure is to be compared with the location of samples in Fig. 14.

As disturbance ought to decrease much with increasing distance from the sampler (Eq. 5), it may for practical purposes suffice to consider a zone where

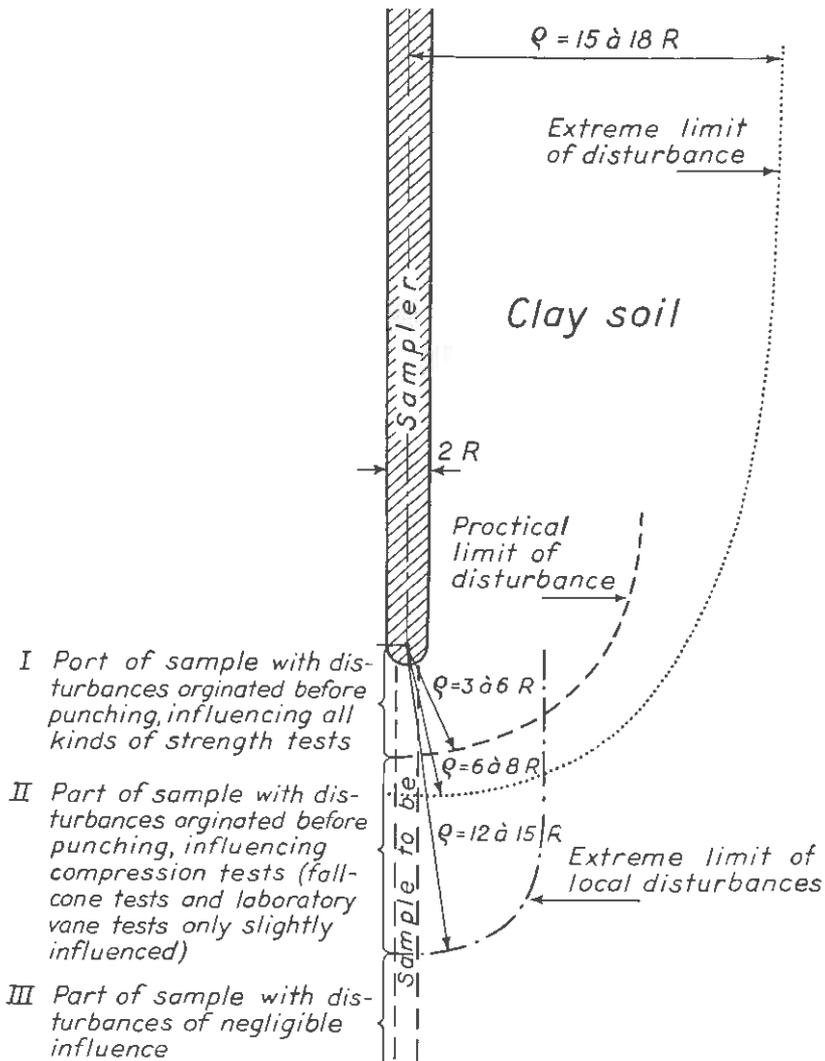


Fig. 33. Type and probable extent of disturbed zones near sampler pushed 10 m into normal Swedish clay soil.

the limiting disturbance has a certain value—say 3 per cent of the undisturbed shear strength. Then the actually important part of the primary plasticized zone would cover only about half the above values of q/R .

Fig. 33 shows how the extension of the disturbed zones may be visualized at a depth of 10 metres. The picture will differ for different soils.

4 a 6. *Experiments with Field Vane on Extension of Disturbed Zone below Sampler*

The adaptability of the theories of elasticity and plasticity on such a complicated material as soil may be questioned. We have therefore performed experiments in order to determine the extension of disturbances. As small scale laboratory tests were not considered adequate, we have tried to make the studies under field conditions.

CADLING and ODENSTAD (1950, Figs. 27 and 28) have shown how the vane test shear strength varies with the distance by which a vane has been pushed out of its protection tube. Their tests were performed in very sensitive (quick) clay and at depths of 10 to 13 metres. There is no doubt but that the resistance to torque decreased with decreasing distance from the tube. However, from their tests it is not possible to determine the extension of the disturbance caused by the protecting tube.

For this reason, new experiments were performed at Ultuna. Two vane borers were constructed with standard vanes of 6.5 cm diameter which could be pushed down 1 and 2 metres, respectively, below the end of the protecting tube (which had a diameter of 7 cm). The height of the vane was 11 cm. The vane shafts were protected against friction by thin, lubricated tubes.

The investigation was carried out in six holes in the immediate vicinity of those used for the piston samplers. After the protection tube had been pushed down to the desired depth, the vane was pushed down in 25 cm stages and a measurement made for each stage.

The results are shown in Fig. 34. The individual curves for the relation between torque and depth below the protection tube appear to have the following characteristics. From a low value close to the end of the tube the torque increases with depth, reaching a maximum after 0.3-0.8 metres. Then the torque decreases again and reaches values pretty well in accordance with the average curve obtained with the routine vane test for the main investigation (Fig. 10).

As the investigation was carried out to a distance of 2 metres below the end of the tube, it is reasonable to assume the values obtained at this distance to be the least disturbed. A conclusion would then be that the maximum torque values are higher than in undisturbed soil, and that the values obtained close to the tube are lower than in undisturbed soil. It might be suspected that the highest torque values were influenced by the friction caused by bending of the long vane shaft. Tests have shown, however, that this influence was not sufficiently great to explain the results, and these must therefore be explained by the varying properties of the soil.

A possible explanation of the shape of the curves in Fig. 34 is that at least two different processes must be considered. One is the plastic deformation of the soil. This is largest close to the tube and decreases rapidly with increasing distance (cf. Fig. 31). In a very sensitive clay this effect may dominate and it would explain the results obtained by Cadling and Odenstad.

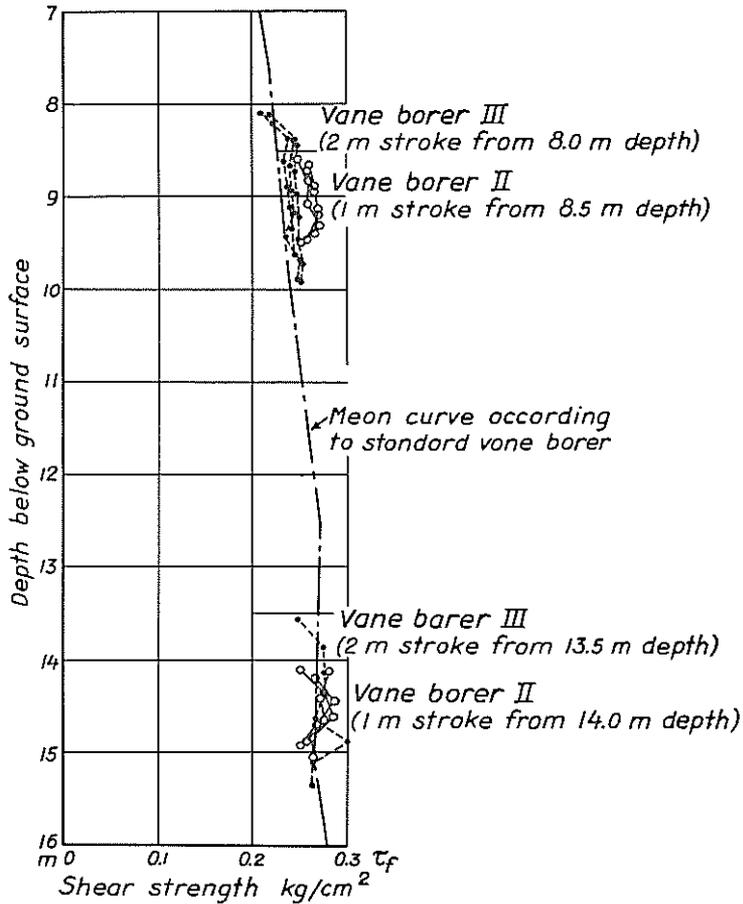


Fig. 34. Attempt to measure the extent of disturbance below a rod by means of field vane tests.

The other process is the flow of pore water away from zones with high pore pressure. There is evidently a general tendency for water to flow in radial direction, and thus the void ratio must decrease close to the tube and increase at some distance from it. This will produce a tendency towards increased shear strength close to the tube and reduced strength further away.

If these two effects are combined, we ought to obtain curves similar to the trend in Fig. 34. It might be concluded from this figure that the zone of plastic disturbance has extended to about 8 tube-radii below the protection tube at 8 metres depth and about 15 radii at 15 metres depth.

Beyond this zone we have a zone where the flow of water may have influenced the shear strength. It may be expected that measurements within this zone will give different results if performed on laboratory samples instead of *in situ*. The flow of water may not be homogeneous but may follow weaker zones, especially where the tangential stresses become negative.

4 a 7. Detailed Study of Samples Taken with Sampler SGI VI

In order to find out disturbances, detailed investigations were performed on some extra samples taken at Ultuna with sampler SGI VI. The fall-cone test and the unconfined compression test were used for these investigations. For both types of tests the sample was cut into discs 2 cm thick.

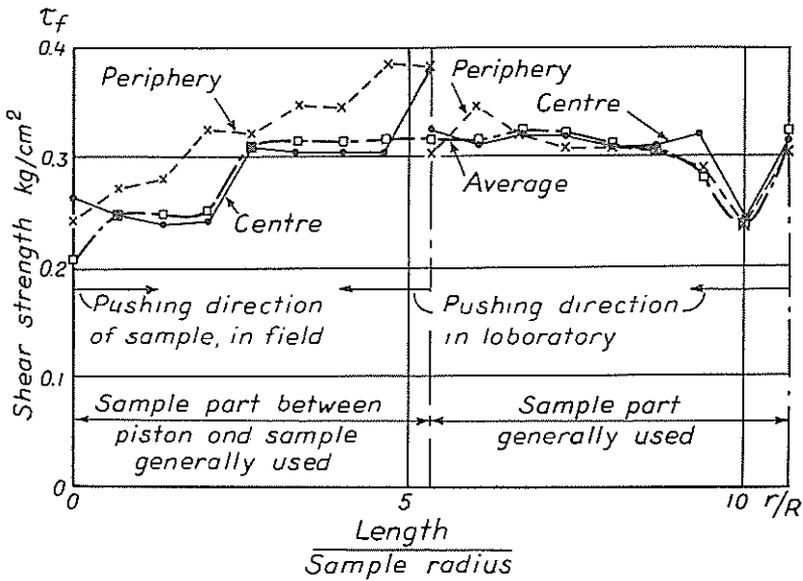
By means of the *fall-cone test* the discs were tested at various distances from the centre (0, 0.75, 1.5, 2.25 and 3 cm). The 3 cm test was made with the cone directed radially and the others axially. The samples proved to be very homogeneous over the cross-section. The strength was highest at the centre and decreased about 2 per cent at radius 2.25 cm. At the periphery the strength was slightly above average, probably caused by drying and chemical action from the brass liners (which showed signs of corrosion). No great influence of inside friction could be detected (cf. § 4 b 3).

Fig. 35 shows the above cone tests on a sample from a depth of 11.3 metres. A decrease in strength can be observed along a length extending about three times the sample radius R_i from the upper end. At the lower end a length of about two times radius R_i was not tested (removed from the cutting edge). The lowest end surface had increased its strength by drying and by pressure from the extruding piston (cf. the middle part of the sample, which had been shipped in two liners). Taking the above into consideration, we find a disturbance at the lower end covering about 5 radii.

The same effect was obtained from a sample taken from a depth of 12.1 metres, whilst samples from 4 to 7 metres depth showed the same range of disturbance at the lower end, but less disturbance at the upper end. This is in agreement with our theoretical discussion.

For the *unconfined compression test* six specimens ($1 \times 1 \times 2$ cm) were cut along the diameter of each disc and tested at a constant rate of strain. Fig. 36 shows the result of unconfined compression testing on a sample taken from the same depth (11.3 m) as that in Fig. 35. It will be seen that the disturbance at the upper end covers a range of about 6 times the sample radius, *i.e.*, more than in the case of the fall-cone test, whilst the disturbance at the bottom end is similar to that of the fall-cone test. Here, too, the strength near the periphery was a little higher than the average.

In this connection the Author would like to refer to HVORSLEV (1949, Fig. 140 a) who has noted that samples taken with a long thin-walled 2" piston



- × Periphery ($R=3$ cm)
- Average for $R=0.75, 1.5$ and 2.25 cm
- Centre ($R=0$ cm)

Fig. 35. Detailed study of SGI VI-sample by means of fall-cone test.

sampler in Boston blue clay showed ranges of disturbance 10 times the sample radius in both the upper and the lower end.

When analyzing Figs. 35 and 36 it is found that Sampler SGI VI was too short to permit a safe determination of a part undisturbed by end influences. This is undeniable for the unconfined compression test.

Furthermore, the differing results obtained with different samplers (Fig. 24) have indicated that even the middle part of the sample is more or less disturbed (seemingly caused by displacement of the soil or by friction during the punching operation as indicated by the influence of the edge angle shown in Figs. 44 and 45). Consequently, the range of disturbance due to the initial deformation was probably larger than that indicated by Figs. 35 and 36 as very small initial disturbances were probably swallowed up by the larger disturbance caused by the punching operation.

The unconfined compression test is apparently influenced by fissures and locally disturbed shear zones (cf. Fig. 37).

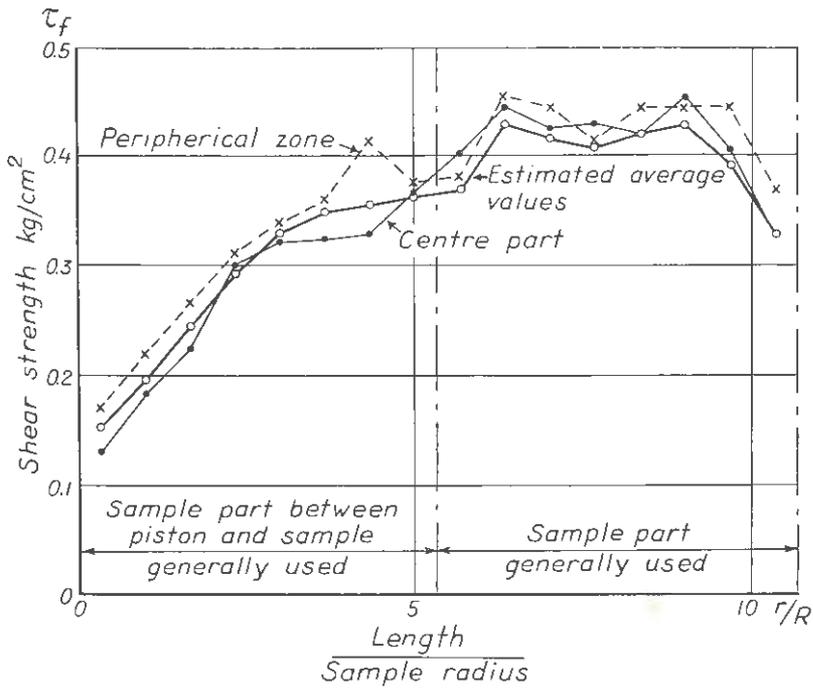


Fig. 36. Detailed study of SGI VI-sample by means of unconfined compression test.

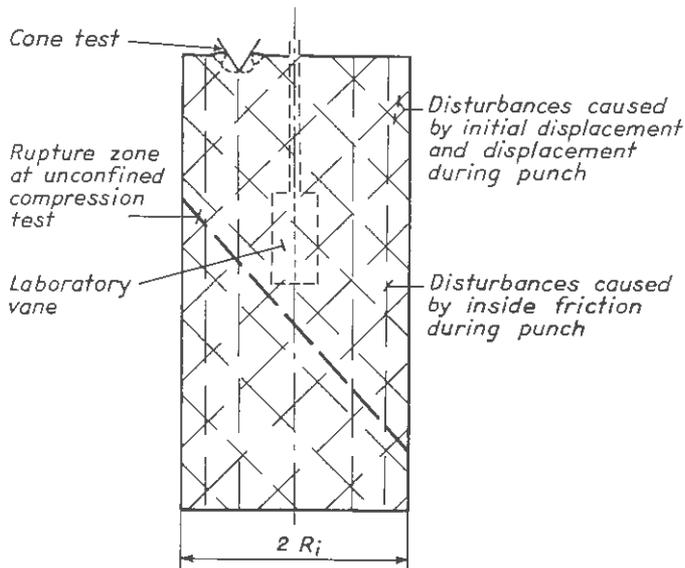


Fig. 37. Explanation in principle why sample-disturbance affects different laboratory tests differently.

Sampler type	$\frac{\tau_f \text{ lab. vane test}}{\tau_f \text{ unc. compr. test}}$ At various depths below ground surface			L/R _i
	5 m	10 m	15 m	
SJ	0.87 Δ	0.85 Δ	0.59 \blacktriangle	29
IV	1.21 \circ	1.13 \ominus	1.37 \bullet	7.4
VI	0.79 \square	1.15 \blacksquare	1.15 \blacksquare	14.2
Gk	0.84 $+$	0.78 $+$	0.59 $+$	24
NGI	0.89 \circ	0.75 \circ	0.80 \circ	29.6
VIII	0.96 \times	0.86 \times	1.06 \times	15.4

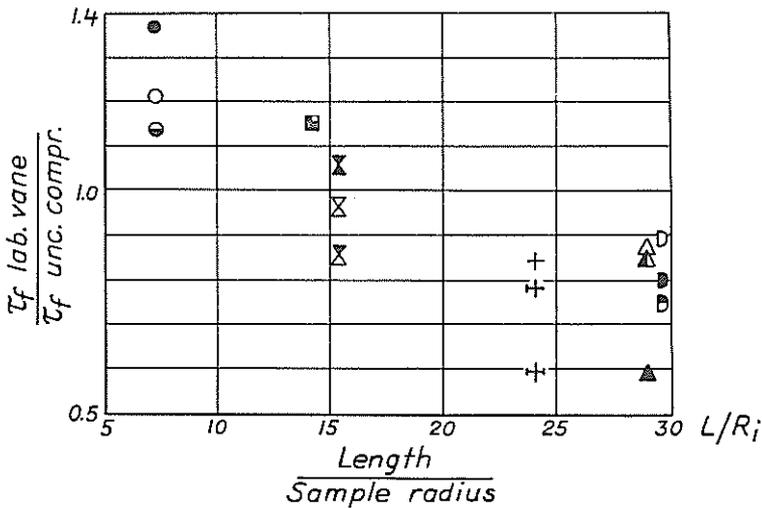


Fig. 38. Ratio of shear strengths for laboratory vane and unconfined compression tests versus depth (Ultuna) (cf. table above).

4 a 8. Deduction of Disturbed Zone from Shear Strength Ratio Laboratory Vane Test—Unconfined Compression Test

In § 3 c 3 (Fig. 22) it was stated that the shear strength values in the unconfined compression test on clay from greater depths were smaller for short samplers than for long ones. It has been indicated above that the range of disturbance is greater when analyzed by means of the unconfined compression test than by means of the fall-cone test.

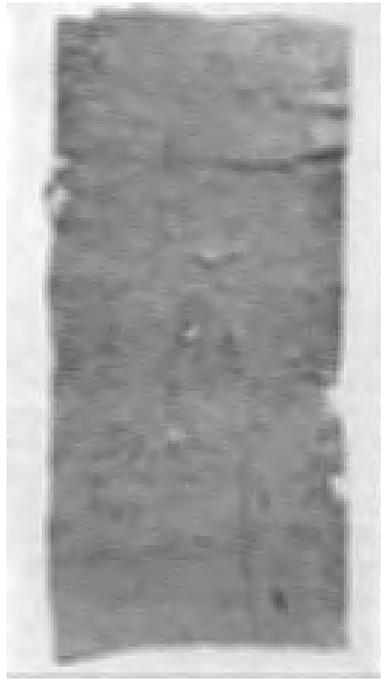


Fig. 39. Effect of freezing a slice of SGI IV-sample.

Fig. 37 shows schematically how different laboratory tests are influenced by weaknesses in the samples caused by shearing strains.

Obviously, the unconfined compression test must be more sensitive to such disturbances than the laboratory vane test, since the latter is performed in the least disturbed part of a sample and in a direction little influenced by shear resulting from sampler displacement. Therefore, in Fig. 38, the ratio of shear strengths obtained by these two different laboratory methods has been plotted against the sampler length for different depths.

It will be seen that the ratio is always great for short samplers, but it seems to reach a constant value with increasing sampler length. A high ratio means that the unconfined compression test has given low values (*e.g.* caused by shear zones) or that the laboratory vane has given high values (*e.g.* caused by loss of water). In both cases it is a sign of disturbance.

As the tests have been performed on specimens taken on the average in the middle of the samples, half the distance required to reach a stable value would indicate the probable range of disturbance. Fig. 38 indicates that the amount and even the range of disturbance increases with sampling depth. The range seems to be about 12 times the sampler radius (R) at a 10 metres depth. The great extension of disturbance indicates that local shear failures, mainly in-

fluencing the unconfined compression strength, must be one reason for the observed change in the shear strength ratio.

It is interesting to observe how close together the strength ratios for samplers SJ and NGI lie in spite of the great differences in sample quality obtained with them.

Attempts have been made to get an indication of possible weaker zones in the samples by freezing thin slices positioned on glass plates and lubricated with thin silicon oil (Fig. 39).

4 a 9. Conclusions

Both theoretical estimations and field tests indicate the following types of disturbance around a sampler pushed down in a clay soil.

Around the sampler there is a zone where all the soil is more or less disturbed. In a normal Swedish clay at 10 metres depth this zone reaches about 6-8 times the radius of the sampler below its point. As disturbance decreases rapidly with increasing radius, it is for practical purposes only important in the case of fall-cone tests or laboratory vane tests within 3 to 6 radii from the point (*cf.* Fig. 33). The extension of this zone is confirmed by the observation stated in § 3 b 2 that the surface of rupture at the lower end of the sample was cone-shaped when sampling with the short sampler SGI IV ($L/R_s \approx 6$) but was rather plane when sampling with the other samplers ($L/R_s \geq 11$). (Here R_s is the sampler radius.)

Within and outside the primary zone, and reaching as far as 12-15 radii from the point, there is a secondary zone where disturbance by shear is local. The local disturbances affect mainly the unconfined compression test. For practical purposes (routine tests) this zone of local disturbances may have to be considered as reaching as far as 8-10 radii from the point.

Near the outer parts of the secondary zone there seems to be an area where the shear strength has been reduced by an increase in water content and pore pressure. This zone may be most important under field conditions.

For soils of different permeability, sensitivity and elastic properties, the zones are different.¹ It may however be interesting to compare the above findings with the observations by CAQUOT and KERISEL (1952) that the observed disturbance below the point of piles driven in gravel reaches 10 to 12 radii below the point.

The extension of the disturbed zones increases with depth.

The theory of plasticity gives a poor picture of the occurrences but can be used as an approach which, however, must be calibrated.

If a hole is pre-bored for the sampler, there will be disturbance at the bottom of the hole. It is impossible, in practice, to keep both effective pressures and pore pressures in their natural state. Besides, the hole must be large enough to admit the sampler. Nevertheless, a hole filled with drilling mud ought, in particular, to decrease the zone of local disturbances owing to the inverted direction of the flow of soil and water.

¹ For instance, in a varved soil containing very soft layers between stiffer ones, local disturbances may occur in the soft layers still further away from the point than said here.

4 b. Disturbance by Punching Operation

4 b 1. Influence of Stresses within Plasticized Zone

When punching out samples in the ground, some disturbance will occur in the clay even if the cylinder had practically zero thickness and no friction against the soil. As shown in Fig. 32, the stresses below a sampler pushed down into a soil decrease rapidly with the distance from the piston. If a sample is punched out, these stresses must be equalized. The average stress will be larger inside the cylinder than at the edge. The sample will therefore have a tendency to expand vertically downwards. Now, the vertical stress (σ_r in Fig. 32) cannot increase at the edge without plastic flow (*i.e.* as far as punching is carried out within the plasticized zone). This means a disturbance of the sample immediately before it enters the sampler cylinder. This, however, can be neglected in ordinary soils.

The existence of the zone with high stresses is very obvious when sampling with the Steel foil sampler. It is quite easy with this tool to take continuous cores to great depths, but if sampling is started at a depth below 10 metres, the foils will break owing to excess pressure against the inside wall. When sampling with piston samplers, such stresses sometimes cause the formation of plugs which prevent the entrance of soil. The tendency to form plugs is especially marked in expansive soils.

4 b 2. Influence of Friction on "Safe Length of Sample"

At any moment of the punching operation, friction between soil and sampling cylinder must be overcome to allow the sample to enter the cylinder. Therefore a certain difference in axial pressure σ_d must exist between the lower end of the cylinder and the stationary piston. If, as before, S_t is the sensitivity of the soil, τ_f the shear strength, L the punched length and R_t the radius of the sample, we obtain

$$\frac{\sigma_d}{\tau_f} = \frac{2 K_f}{S_t} \cdot \frac{L}{R_t} \dots\dots\dots (6)$$

where K_f is a factor.

We now use the following symbols:

- σ_s = Axial soil pressure at sampling depth
- σ_{re} = Axial overpressure at edge caused by pushing down sampler before punching
- σ_p = Soil pressure against piston (this value cannot be lower than about -0.7 kg/cm² for a tight fitting piston and ± 0 kg/cm² for one which is not tight)

We must also allow for the fact that the axial pressure in the sampler adjusts itself to $\approx \sigma_{re}$ without appreciable disturbance.

The requirement for obtaining 100 per cent sample recovery is then (*cf.* Fig. 40, Case I)

$$\sigma_s + \sigma_{re} - \sigma_d = \sigma_p \dots\dots\dots (7)$$

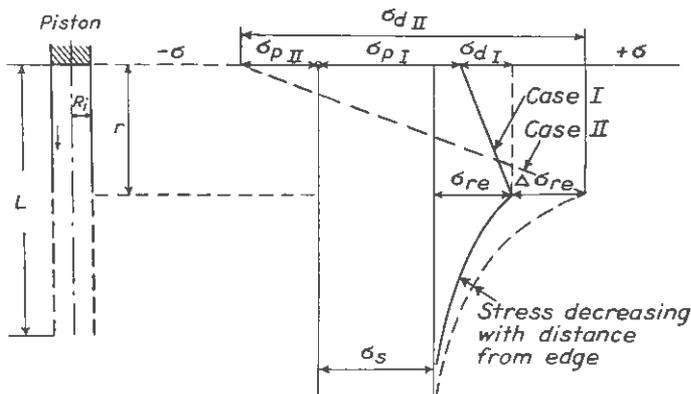


Fig. 40. Influence of friction on the vertical pressure in the axial direction of the sampler for different cases of gain factors (in principle).

If the minimum values for σ_p are insufficient to overcome σ_d , an extra axial overpressure $\Delta\sigma_{re}$ will be created through displacement of soil outside the edge axially away (cf. Fig. 40, Case II). The entering soil will then be disturbed and the sample will be too short. When $\sigma_{re} + \Delta\sigma_{re}$ reach the value σ_{max} (cf. § 4 a 2) soil can no longer enter the sampler and a plug is formed which follows the punching travel.

Eq. (7) may be used to calculate the length of sample which can be taken safely with 100 per cent recovery. Allowing for an untight piston we can transform Eq. (7) into

$$\frac{\sigma_s}{\tau_f} + \frac{\sigma_{re}}{\tau_f} - \frac{\sigma_d}{\tau_f} > 0 \quad \dots\dots\dots (8)$$

$\frac{\sigma_{re}}{\tau_f}$ can be obtained approximately from Eq. (3) and $\frac{\sigma_d}{\tau_f}$ was given in Eq. (6). For clays the remaining part $\frac{\sigma_s}{\tau_f}$ can be obtained by studying their increase in shear strength with depth. For Norwegian conditions it has been said that there is a connection between this ratio and the plasticity index (BJERRUM and ROSENQVIST, 1956, Fig. 5).

The result of a calculation on "safe" length of sample is shown below.

Plasticity index	Calculated "safe" length of sample as ratio L/R_i (Eq. 8)			
	$S_t = 1$	$S_t = 5$	$S_t = 10$	$S_t = 100$
5	8	18	>50	>500
10	7	15	40	
20	6	14	30	

The values in the table seem to correspond reasonably well with HVORSLEV's statement (1949, p. 109) that the "safe" length of sample is about 20 times the sample radius for a stiff clay and 40 for a soft clay.

For some Swedish clays the ratio of shear strength versus effective overburden pressure seems to be directly proportional to the liquid limit (HANSBO, 1957, p. 19 and 20).

For the samplers used at Ultuna the sampling length was in all cases much smaller than the safe length, and therefore the above considerations only lead us to the conclusion that the SGI samplers might safely have been longer.

One must, however, bear in mind that for less sensitive soils, and for samplers displaying great inside friction, the sampling length must be much more restricted if great disturbance is to be avoided. This will be especially the case for cohesionless soils.

4 b 3. *Inside Shear through Friction*

Inside friction may damage the sample even after it has entered the sampling cylinder. The frictional forces act axially on the periphery of the sample. The force which has to overcome friction is distributed over the cross-section. Thus axial shear stresses arise in the sample in the sampling cylinder. Owing to the unavoidable deformations of the circumferential parts of the sample (which are evident when observing the bent strata of a sample taken with great inside friction) the pressure against the piston can never be evenly distributed.

As friction acts axially away from the piston, it is evident that the piston can never prevent such deformation of the sample if inside friction is great. At the periphery of the piston the axial contact pressure will often reach its lowest possible value, and consequently the contact pressure at the center will be correspondingly higher than the average value. Especially at the beginning of a punching operation, when side pressure is great and sample length is small, distortion and sample disturbance will be considerable if the angle of friction is great. Too low inside friction, on the other hand, may cause loss of samples.

Outside friction has a similar effect to that described in § 4 b 2 and should not be neglected, especially as low outside friction involves no disadvantages in practice.

4 b 4. *Piston Travel*

Piston travel axially downwards must cause plastic flow below the sampler edge. If the piston moves at the beginning of a punching stroke, the disturbance below the piston has already reached the maximum value and thus no extra disturbance is created. At a later stage of the stroke, however, considerable disturbance may arise in the sample.

A piston travelling axially upwards at the beginning of a punching stroke may be to some advantage since it decreases axial stresses. The travel may go so far as to mobilize the shear stresses in an opposite direction to those present in

the zone plasticized by sampler displacement (*cf.* Eq. 4). The permitted travel upwards is, however, not constant and the positive effect is probably small (*cf.* § 4 a 1). Therefore it seems best to fix the piston.

During the first half part of the punch, a piston travel of ± 1 mm, or still a little more during routine investigations, does not seem to affect sample quality in practice.

4 b 5. *Inside Clearance*

Inside clearance can be harmful. The difference between axial stresses (σ_z) and radial stresses (σ_r) is already at a maximum in the plasticized zone during the first part of the punching travel. If the radial stresses are decreased by a clearance, an added plastic flow arises until the clearance is filled and equilibrium is restored. This flow causes disturbance both in the part of the sample which already has entered and in the soil just entering below the edge. This flow may, on the other hand, reduce disturbance caused by displacement of soil from the cylinder wall. For certain dimensions of cylinder walls this positive effect seems to outweigh the above mentioned negative effect.

If inside friction is great, it may cause great disturbance, which can be reduced by suitable inside clearance. There ought to be an ideal amount of clearance.

The right amount of clearance will depend on the type of sampler tube, the soil type and sampling depth. If it is too large, extra disturbance will follow through excess flow of soil. From a practical point of view, a disadvantage with too great a clearance is the danger of losing samples.

In principle it seems better to reduce inside friction by other means than great clearance (laquer—lubrication—foils). On the other hand, practical experience has shown that clearances of 0.5-1.0 per cent of the sample radius are advantageous for Swedish clays. This is in agreement with Hvorslev's recommendations (HVORSLEV, 1949, p. 108).

Inside clearance should not be less than half the thickness of the lower end of the cutting edge. A minimum value is therefore 0.1 mm. It is our opinion that inside clearance should not begin too near the edge.

4 b 6. *Edge Sharpness*

If we indicate the shape of the lowest part of the edge by a radius R_c (Fig. 41) and this is small compared with the radius R_i of the sample, we can regard the sampler cylinder as folded out in a plane. The end effect of the edge can then be regarded as the disturbance around a rod, and Eq. (2) can be applied (the cylindrical case). From § 4 a the radius of the disturbed zone can be obtained. Theoretically ϱ_2/R_c would vary depending on depth. A value of

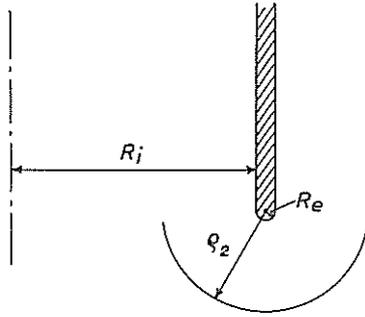


Fig. 41. Influence of sampler wall.

$Q_2/R_e \approx 20$ might be accepted as a design criterion for good samplers. For practical purposes, an edge cannot be made much thinner than 0.25 mm ($= 2R_e$). Thus, one must, in practice, reckon with a disturbed zone of about 2.5 mm thickness. This means greater average disturbance for smaller sampler diameters. When using thin edges, this disturbance will not reach the central parts of the samples.

4 b 7. Edge Angle—Theoretical Considerations

An increase in thickness of the sampling cylinder wall will affect sample quality if the disturbance caused by the corresponding displacement of soil reaches beyond the edge.

As regards thin walls, Fig. 42 illustrates the plausible condition for avoiding wall disturbances. If the increase in thickness is Δ_s and in length Δ_r , we get

$$\text{tg } \alpha = \frac{\Delta_s}{\Delta_r} < \frac{R_e}{\rho} \dots\dots\dots (9)$$

Here α is the edge angle. According to § 4 b 6 Q/R_e ought to be about 20 in the actual clay used and then α would be $\sim 3^\circ$. This gives the criterion that, for good samplers, wall thickness may increase with 1 mm for each 20 mm length.

In some cases it is not necessary to be so strict. If, say 5 per cent, sample disturbance caused by the edge is permitted, the edge angle may be 1.5 times greater than the above value. For depths smaller than 10 metres the angle may also be increased (while the opposite is valid for larger depths).

HVORSLEV (1949, p. 127), dealing with open samplers, has found that the ratio of sample recovery was influenced by the edge angle and recommends that this angle should not exceed 10° . This value is, according to our experience,

Plausible conditions to avoid wall disturbances

$$\frac{\Delta s}{\Delta r_s} = \operatorname{tg} \alpha < \frac{R_e}{\rho_2}$$

where

s = wall thickness at distance r_s from edge

α = edge angle

ρ_2 = radius of plastic zone from edge radius R_e

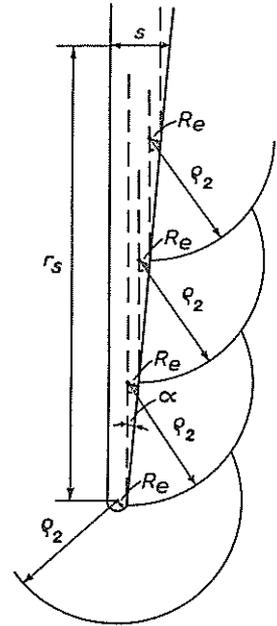


Fig. 42. Influence of edge angle, in principle.

a little high. With the Steel foil sampler we have found that a decrease of edge angle from 7° to about 2° has greatly facilitated sampling.

In the case of the edge angle, as computed by Eq. (9), there are certain boundary conditions. One of these is that the cylindrical stress distribution is continuously converted to spherical stress distribution as the wall thickness increases. Consequently, wall thickness may increase more than linearly at increasing distances from the edge. This means that the external profile should be concave.

Another boundary condition exists when the edge angle is great but the wall thickness does not exceed a certain value (s_{max} in Fig. 43). In this case the disturbance is less than that indicated solely by the edge angle, and this is especially true when s_{max} is small and α is large. This condition corresponds partly with Hvorslev's concept "area ratio" and probably affected the results from Ultuna considerably in the case of sampler SJ but only slightly as regards sampler NGI. (For complicated edges one must calculate with the α -value and the limiting wall thickness S_0 which gives the greatest disturbance. Normally the conditions close to the edge predominate.)

When using inside clearance, part of the material displaced by the edge may escape inwards. Thus inside clearance means a reduction of edge angle influence.

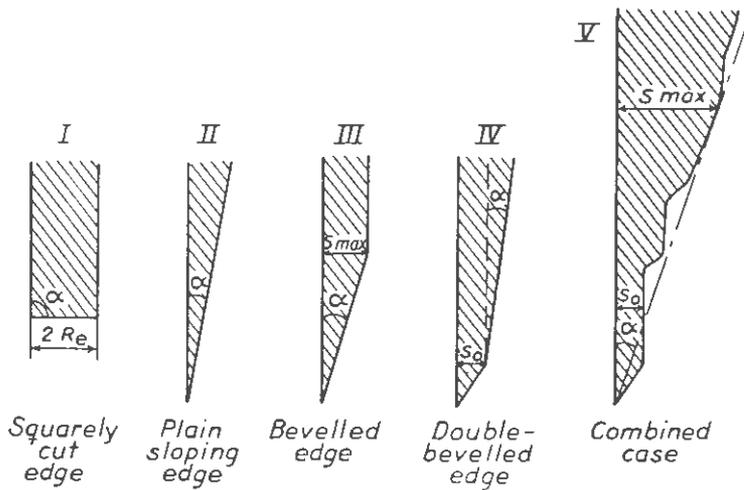


Fig. 43. Types of edges.

4 b 8. Edge Angle in Practice

The test results from *Enköping*, described in Proc. No. 8, have, as mentioned before, been re-studied and a comparison has been made between unconfined compression test strengths and edge angles. Fig. 44 shows that there is an obvious relationship which is most evident when we note the different versions of sampler SGI IV. At that time samplers SGI V and VI were provided with a moderate inside clearance. This seems to have been advantageous. Sampler GH had an edge angle of 45° and a wall thickness of 6.25 mm. This sampler has been influenced by the wall thickness boundary condition (see § 4 b 7) and would fit the picture better if one reckoned with a smaller "apparent" edge angle.

The connection between edge angle and shear strength is especially remarkable when it is considered that all other possible disturbing influences are included. The dimensions of the samplers as well as the sampling techniques were different. The edge angle is evidently a most important factor.

In a manner similar to that described above, the unconfined compression tests from *Ultuna* have been related to the edge angle (Fig. 45). It should be noted that the samplers were not the same in both investigations. Sampler SJ, which has an edge very like that of sampler GH used at *Enköping*, suits the picture well if the same "apparent" edge angle is used as fitted the *Enköping* results best.

It will be seen that the shear strength obtained from samples taken with samplers Gk and NGI, which were provided with inside clearance, have increased more than the others when the sampling depth was increased from

Sampler type	GH	IV _w	IV	IV _a	V	VI	F	T
	Gothenburg Harbour	Shutter "Wager"	Without shutter	Automatic shutter	Type IV lengthened	Pneumatic	Foil sampler	Thin-walled
Edge angle, degrees..	(45)*	30	26.5	13	15	7	7.7	9
τ_f in per cent of field vane tests	67.2	60.2	70.9	85.8	86.9	98.5	92.3	85.8

* Largest thickness of the edge determines the disturbance.

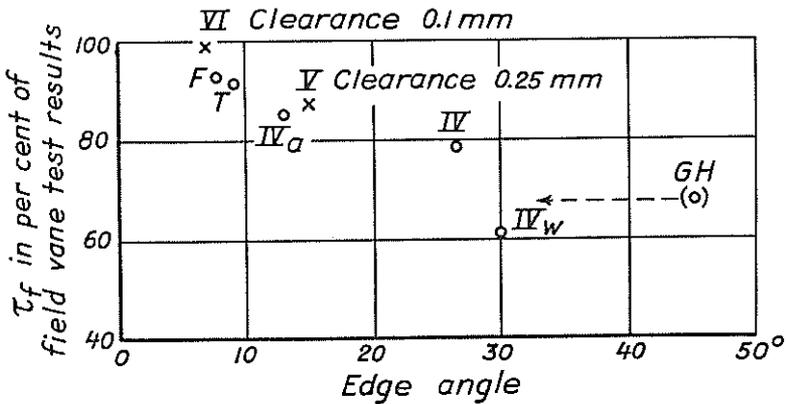


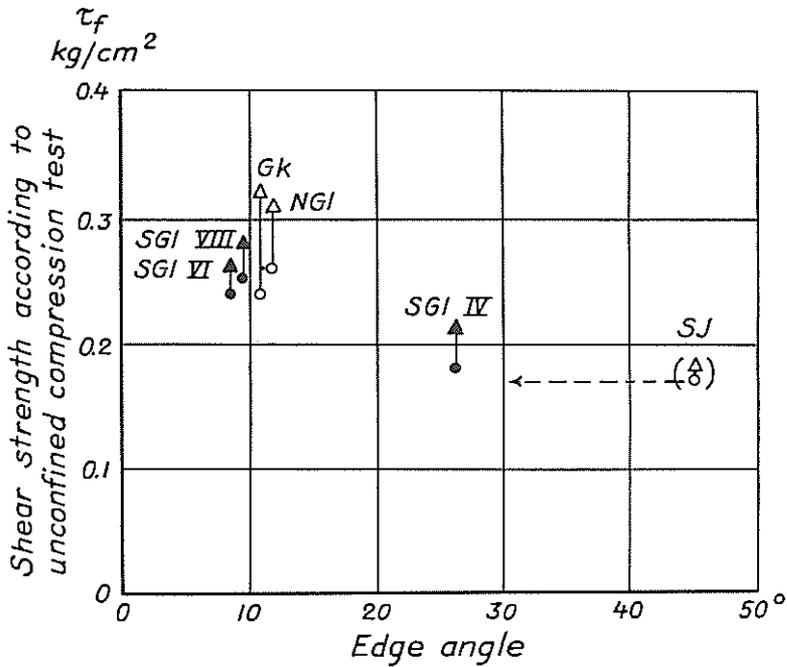
Fig. 44. Relative shear strength versus edge angle from tests at Enköping (cf. table above).

5-10 metres to 10-15 metres. This indicates that inside clearance has had a good effect, probably optimal at 15 metres. This seems logical when comparing Fig. 15 and Fig. 46. The latter figure has been assembled in such a way that samples taken with the same sampler and from the same depth, but which had pressed differently against their cylinders, were compared on the basis of shear strength. Fig. 46 indicates that the highest strength was obtained when the samples had a small contact pressure against the cylinders.

If this contact pressure is great, the disturbing influence of friction must also be great. If the pressure is nil, this may have been caused by tensile stresses during withdrawal (the unfavourable influence most probably caused by tensile stresses can be observed in Figs. 35 and 36). Loosely fitting samples are also more easily damaged during shipment. Such damage has been investigated by the

Sampler type	SJ	SGI IV	SGI VI	Gk	NGI	SGI VIII
Edge angle	(45)*	26.5	8.8	10.5	(12)*	9.7
τ_f 5-10 m depth	0.17	0.18	0.24	0.24	0.26	0.25
τ_f 10-15 m depth	0.18	0.21	0.26	0.32	0.31	0.28
Relative length L/R _i	29.1	7.4	14.2	24.2	29.2	15.3

* Largest thickness of the edge determines the disturbance.



- short sampler, 5 - 10 m depth
- long " 5 - 10 m "
- ▲ short " 10 - 15 m "
- △ long " 10 - 15 m "

Fig. 45. Shear strength versus edge angle from tests at Ultuna (cf. table above).

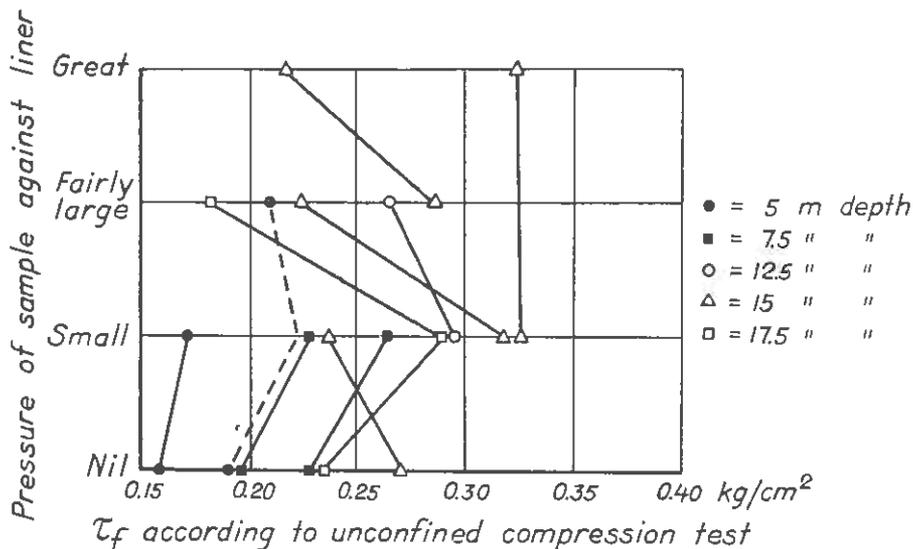


Fig. 46. Shear strength versus radial pressure against liner (Ultuna).

Swedish State Railways (ALTE, 1955) and was found to be serious in the case of ordinary railway transport and sensitive clay samples. (As regards our investigation, shipment was, as already mentioned, therefore made with great care.)

After having obtained an interim report of the above results from Ultuna, the *Swedish State Railways* decided to check the described influence of edge angle. Sampler SJ was provided with two exchangeable edges (HELLMAN, 1958). One of them had the same data as before, but the other had an edge angle of only 7° (i.e., of the same order as sampler SGI VI). They found that the shear strength as obtained with the cone test was about 20 per cent higher in the case of the samples taken with the sharper edge. If this result is compared with the cone tests from Ultuna (Fig. 23), we find that this change of edge alone would bring sampler SJ almost in parity with the best samplers tested here. This seems to be a most convincing proof of the importance of the edge angle.

5. Conclusions from Ultuna Tests

The investigations and analyses mentioned in the foregoing have enabled the following conclusions to be reached. These are considered to be directly valid for reasonably homogeneous post-glacial Swedish clays.

1. *The sampler ought to take a long sample.* A length of 20 times the sample radius is desirable (cf. § 4 a) to ensure a sample free from initial disturbance caused by pushing the sampler down (or by making a bore hole in advance).

- The necessary length of sample is associated with the method of testing. Thus, the unconfined compression test requires, to get away from initial disturbances, a greater length of sample than the cone test (Figs. 35 and 36).
2. *The sampler ought to have a sharp edge and a small edge angle* (preferably less than 5°; Figs. 44 and 45). The angle should be increased with increasing distance from the edge (§ 4 b 7). Hvorslev's concept "area ratio" need not to be regarded as an absolute criterion if only the edge angle is small.
 3. *The sampler ought to have a moderate inside clearance.* The clearance reduces the wall friction and probably counteracts to a certain extent the disturbance from displacement of soil caused by the edge and the sampler wall during the punching operation. If the clearance and the edge angle are moderate, the above positive effects outweigh the disturbance caused by deformation when the sample tends to fill the clearance.
 4. *In principle, it is advantageous to use a large diameter,* as inside friction and edge sharpness then have decreased influence. However, sampler Gk has shown that in clay a diameter of 42 mm is usable for practical purposes. Smaller diameters seem inadvisable.
 5. *It is preferable to have a rigidly fixed piston,* but small piston travel (of the size ± 1 mm or even a little more) at the beginning of a punch has no obvious effect on sample disturbance (Ultuna test results and § 4 b 4).
 6. *Punching speed need not be especially high* for piston samplers. The different punching speeds of the different samplers do not seem visibly to have affected the results obtained at Enköping and Ultuna (§ 3 and Figs. 44 and 45).
 7. *Disturbance from sampling increases with sampling depth.* Thus, a sampler for great depths should be longer and have sharper edge than one for shallow sampling (*cf.* Fig. 22, long samplers versus short samplers).
 8. *In clay, long samplers do not require a special shutter device.* In most cases our samples were separated at the edge even when shutters were provided. A shutter may, however, permit very small inside friction and is very useful in cohesionless soil or for short samplers. An obvious disturbance is created at the lower end of a sample when it is torn off, but this disturbance is normally of restricted range. If sample quality must be high all the way down to the edge, arrangements for sample cutting or vacuum breaking may be useful. Normally they seem to be an unnecessary complication.
 9. *Composite samplers are quicker* in use and more universal than simple ones (§ 3).
 10. Long-term experience has shown that waxing of the ends of the samples provides better tightness than simple rubber covers. For the Ultuna tests no marked difference in water content could be observed in the two types of sealing (Fig. 24). As *waxing in the field* is time-consuming and troublesome it *does not seem to be necessary if rubber covers are used.* For long-term storage in the laboratory waxing is advisable. It can then be done better and cheaper in the laboratory.

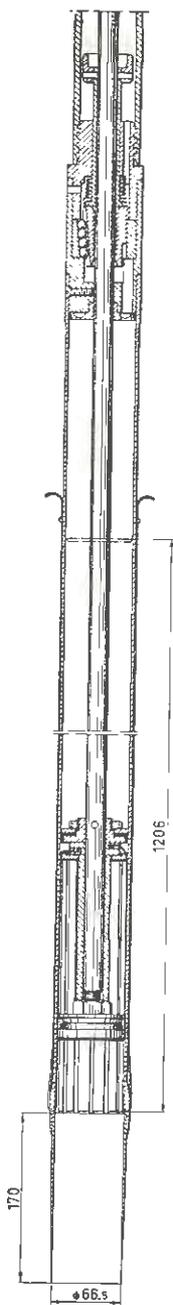


Fig. 47. Research sampler SGI IX.

11. The results described above are in agreement with other (less extensive) investigations carried out by the Swedish Geotechnical Institute on many other sites in Central Sweden. They can therefore be regarded as representative for Swedish post-glacial clays. In glacial clays, in which layers of silt and sand occur frequently, the aspects are a little different (as shear strength in certain layers may even increase through disturbances and friction has increased influence), but most of the findings will certainly hold true also for such clay.

6. Tests with Research Sampler SGI IX

In the tests described above no direct attempt was made to determine sample disturbance numerically, even though indirect evidence can be taken from results shown in Figs. 38, 44, and 45.

Instead we designed an extreme sampler (SGI IX) where the conclusions drawn in § 5 were utilized. It was hoped that comparisons between the ordinary samplers and this research sampler would give an idea as to the possible gain in sample quality (and the increase in sampling costs) when going to the extreme practical limit. The sampler would also provide proof of the validity of the conclusions drawn from the Ultuna tests.

The following considerations mainly influenced the design of the sampler and its handling:

1. The sampler should be made sufficiently long to permit specimens to be taken out of the samples free from the initially disturbed zone. Besides, this zone should, if possible, be reduced by remoulding the clay with a posthole auger down to sampling depth.
2. The disturbance from displacement of soil during the punching operation should be eliminated as far as possible by making the cutting edge as thin and as sharp as machining allows. Even the wall thickness should be kept as small as possible.
3. The disturbance from inside friction should be reduced by using a proper clearance in the edges and by steel foils fastened to the piston in a similar way as in the Steel foil sampler.

The resulting sampler SGI IX is shown in Fig. 47. Fig. 48 shows some of the cutting edges tested. One long edge without inside clearance, one long with inside clearance and one short

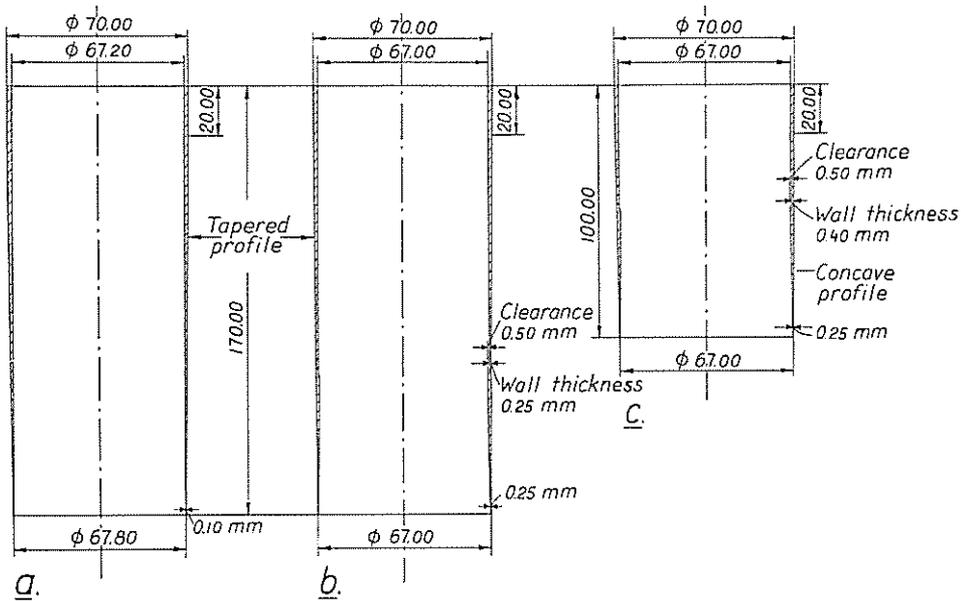


Fig. 48. Edges tested for sampler SGI IX.

- a. Long edge, no clearance.
- b. Long edge, inside clearance.
- c. Short edge, inside clearance.

with inside clearance were tested. The short edge had the same sharpness and edge angle as the long ones. Shortness had been achieved by making the outer profile concave (cf. § 4 b 7).

6 a. Preliminary Tests at Skå Edeby

At Skå Edeby, about 20 km west of Stockholm, the Institute is running a large test to study the consolidation process under field conditions. A comparison between ordinary samplers and sampler SGI IX was considered especially desirable here. The comparison comprised strength tests and even consolidation tests.

The investigations at Skå Edeby were performed in the same way as at Ultuna.

In the autumn 1957 sampler SGI IX was compared with SGI VIII. SGI IX was provided with a long edge without clearance. Sampler SGI VIII was pushed down in a normal way while, for SGI IX, holes were prepared by remoulding the clay by means of a $\phi 125$ mm posthole auger. Sampling depth was 3 metres. The results are given below.

Test results from Skå Edeby, Autumn 1957

Type of laboratory test	Shear strength, kg/cm ²							
	SGI VIII				SGI IX			
	Individual		Average		Individual		Average	
Fall-Cone	0.089	0.096	0.100	0.095	0.102	0.135	0.104	0.114
Unconf. Compr.	0.068	0.125	0.092	0.095	0.133	0.180	0.124	0.129
Lab. Vane	0.085	0.093	0.089	¹ 0.089	0.096	0.091	0.092	² 0.093
" "					0.087	0.116	0.101	³ 0.101

¹ Test depth 2.9 metres

² " " 3.1 "

³ " " 2.8 "

The clay at Skå Edeby was soft post-glacial with some content of sulphides. The sensitivity varied between 5 and 10. The natural water content was about 70 per cent, which is near the liquid limit. As can be seen from the laboratory vane tests, the soil had decreasing strength with depth. The difference in sample quality is, however, obvious. Thus it is round 20 per cent higher for SGI IX for the fall-cone test, 35 per cent for the unconfined compression test and about 10 per cent for the laboratory vane test (if compared at the same depth).

If we extrapolate the edge angle curve in Figs. 44 and 45, we find that the difference in edge angle between the two samplers (1° and 9.7°) has probably caused a difference of about 10 per cent in the unconfined compression test results.

With the aid of Fig. 38 we can get an impression of the influence of sampler length. The shear strength ratio (*i.e.*, the ratio between the strengths obtained with the laboratory vane test and the unconfined compression test, *cf.* § 4 a) at Skå Edeby is 0.94 for SGI VIII and 0.75 for SGI IX. This could mean that the unconfined compression strength (which depends most on sampler length) should have increased 1.25 times for the increased length.

Thus, an analysis of the first results from Skå Edeby indicates that the differences between samplers SGI VIII and IX in edge angle and sampler length (inclusive the effect of pre-boring) may fully explain the great increase in strength for SGI IX samples.

The stress-strain curves for the unconfined compression test showed the same great difference in sample quality, whilst the laboratory vane curves showed no clear difference.

The consolidation test gave values to some extent much in favour of sampler SGI IX. We found, however, different curves in two different types of consolidation test (which has been found to be due to occasional friction in the consolidation cell). The results can thus not serve as a basis for final conclusions and are not included here.

In the spring of 1958, a new test series was performed at Skå Edeby. This time sampling depth was 4 metres and samplers SGI IV, VIII and IX were compared. Sampler SGI VIII was now used alternatively without and with

remoulding of the soil to sampling depth. Sampler SGI IX was provided with edges, which had inside clearance and were alternatively long or short. For the sake of comparison a long edge without inside clearance was also used. The test results for sampler SGI IX with the different edges are shown below.

Test results from Skå Edeby, Spring 1958. Sampler SGI IX

Type of laboratory test	Shear strength, kg/cm ²								
	Long edge, no clearance		Long edge and clearance		Short edge and clearance				
	Individual	Average	Individual	Average	Individual	Average			
Fall-Cone	0.089	0.102	0.095	0.120	0.100	0.110	0.100	0.108	0.104
Unconf. Compr.	0.085	0.090	0.087	0.104	0.108	0.106	0.108	0.107	0.104
Lab. Vane, 3.9 m. depth ..	0.072	0.070	0.071	0.078	0.080	0.079	0.075	0.089	0.082
Lab. Vane, 4.2 m depth ..	0.067	0.062	0.064	0.066	0.060	0.063	0.067	0.071	0.069

There is no obvious difference in the results between the two types of edge with inside clearance. The long edge without clearance has given decidedly poorer sample quality. This indicates the influence of inside friction in the edge below the foils.

The test results from samplers SGI IV and VIII (the latter with and without remoulding) are given below.

Test results from Skå Edeby, Spring 1958. Samplers SGI IV and VIII

Type of laboratory test	Shear strength, kg/cm ²								
	SGI IV		SGI VIII		SGI VIII remoulding				
	Individual	Average	Individual	Average	Individual	Average			
Fall-Cone	0.098	0.083	0.090	0.089	0.096	0.091	0.104	0.095	0.100
Unconf. Compr.	0.059	0.054	0.056	0.072	0.088	0.080	0.086	0.078	0.082
Lab. Vane	0.074	0.068	0.071	0.069	0.076	0.073	0.071	0.080	0.075

The remoulding before pushing seems to have been advantageous for SGI VIII.

Sampler SGI IV shows results in the same relation to SGI VIII as was found at Ultuna (Fig. 23).

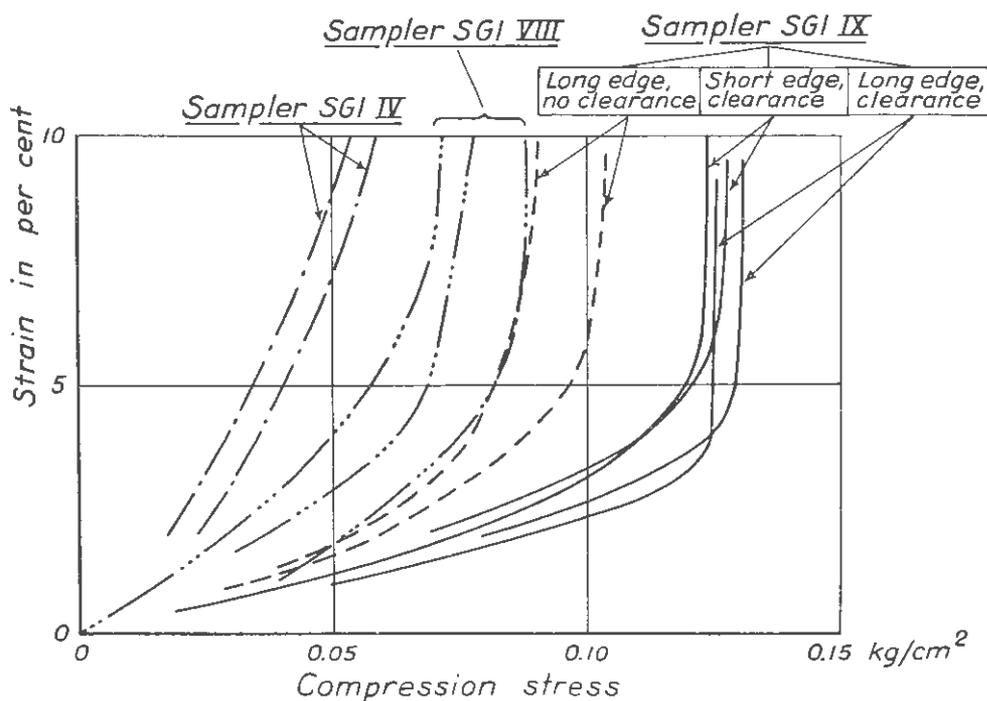


Fig. 49. Stress-strain curves, Skå Edeby 1958 (unconfined compression test).

The field vane was also used and gave an average strength of 0.90 kg/cm² at a depth of 4 metres. This value lies in similar relation to the shear strengths obtained in the laboratory tests for samples taken with samplers SGI IV and VIII as was obtained at Ultuna (cf. Fig. 23). It is therefore probable that sampler SGI IX would have been better than even the other samplers tested at Ultuna. The stress-strain curves showed the same tendencies as the shear strengths (Fig. 49).

The consolidation curves (void ratio—log. normal stress) indicated the same quality scale if judged by the slope immediately above the pre-consolidation stress. The SGI IV samples had clearly smaller slopes. The different types of samples from SGI VIII and IX showed less differences than the scatter in the test. The average curve for all SGI IX-samples was a trifle steeper than that for the SGI VIII samples, but the difference is of no practical importance.

6 b. Conclusions after Skå Edeby Tests

It seems obvious that, within the range of routine samplers, sample quality can be improved over that of present routine samplers.

It seems possible that test values obtained in soils of moderate sensitivity with a certain sampler of good quality can be corrected by means of applied coefficients, although these are different for each type of laboratory test. In a well-known soil, it seems reasonable to use a sampler similar in quality to the better types tested at Ultuna. It is however recommended to improve them as suggested in § 5.

For a sampler like the SGI IV in Skå Edeby clay, the coefficients to be applied would, for 10 metres depth, be about 1.6 for the unconfined compression test, 1.35 for the fall-cone test and about 1.2 for the laboratory vane test (*cf.* Fig. 23 and § 6 a). Coefficients above ≈ 1.25 are inconveniently high. By lengthening of the sampler and providing it with sharper edge one ought to come near coefficients of the order of 1.1-1.2.

In less known soils and for research purposes, a use of coefficients for the correction of test values will be risky and the best possible sample quality is highly desirable.

The proper choice of a research class sampler also seems to permit some regard to practical considerations as disturbance may arise also during shipment and testing. As sampling costs increase rapidly when demands on sample quality go over a certain limit, a small sample disturbance would appear permissible even for qualified purposes.

Such extremely small edge angles as used for sampler SGI IX make, of course, the edges both expensive and fragile. An edge with an angle lying between 2 and 3 degrees ought to be sufficient. On the other hand, an edge angle of 5 degrees gives ample strength for routine purposes and should therefore not be exceeded.

Remoulding or pre-boring may help to give better sample quality but is rather expensive for use in most Swedish clays. It is for our conditions better and cheaper to get away from the initially disturbed zone by using ample sample length. In cohesionless soils preboring may be advantageous.

The investigations with sampler SGI IX are not complete. Results from great depths, more consolidation tests and a detailed study of the influences of inside friction and clearance are still lacking. These tests will take a long time. Therefore, a preliminary evaluation has been considered justified.

The tests with sampler SGI IX have indicated that the shear strength of soils can be much higher than the shear strength values obtained with to-day's routine methods for sampling and testing. As current methods to calculate, *e.g.* stability, are based on these lower shear strength values, one will, when using better samplers, have either to recheck the calculation methods or to introduce greater factors of safety. The great advantage of improved sampling will however lie in the smaller scatter of test results. This reduction in scatter means that stability can be determined with greater accuracy than before.

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<i>Meddelanden</i>		
No. 1.	Kortfattat kompendium i geoteknik 1946 (utgånet)	1946 out of print
2.	Redogörelse för Statens geotekniska instituts verksamhet under åren 1944—1948	1949 8:—
3.	»Bra borrat — bättre byggt». Meddelande utgivet till institutets deltagande i utställningen »Bygg bättre», Nordisk Byggnadsdag V 1950	—