THE VANE BORER
An Apparatus for Determining
the Shear Strength of Clay Soils Directly
in the Ground

By
LYMAN CADLING and STEN ODENSTAD

STOCKHOLM 1950
ROYAL SWEDISH
GEOTECHNICAL INSTITUTE
PROCEEDINGS
No. 2

THE VANE BORER
An Apparatus for Determining
the Shear Strength of Clay Soils Directly
in the Ground

By
LYMAN CADLING and STEN ODENSTAD

STOCKHOLM 1950
## Contents

Preface ........................................................................................................ 5

§ 1. Introduction ......................................................................................... 7

§ 2. The Vane Borer and its Method of Application ................................. 8
   § 21. Type I. The First Experimental Apparatus .................................. 8
   § 22. Type II. A Borer for Practical Use ............................................. 11
      § 221. Lower Part ............................................................................ 11
      § 2211. Inner System ...................................................................... 11
      § 2212. Outer System ..................................................................... 13
      § 2213. Operation .......................................................................... 14
      § 222. Upper Part (Instrument) ............................................................ 14
      § 223. Method of Application ............................................................. 17

§ 3. Shape of the Surface of Rupture, Progressive Failure, and Influence
   of Various Factors ................................................................................. 17
   § 31. Shape of the Surface of Rupture ................................................... 17
      § 311. Field Tests ............................................................................ 18
      § 312. Laboratory Tests ................................................................... 18
         § 3121. Tests in Sand .................................................................... 18
         § 3122. Tests in Clay ................................................................... 20
   § 32. Progressive Failure ..................................................................... 25
   § 33. Rate of Rotation ......................................................................... 25
   § 34. Length of the Vane Shaft .............................................................. 31
   § 35. Number of Wings ....................................................................... 33
   § 36. Vane Dimensions ...................................................................... 34

§ 4. Calculation of the Modulus of Rigidity ........................................... 36
   § 41. Two-Dimensional Calculation ...................................................... 37
   § 42. Three-Dimensional Calculation ................................................... 39
   § 43. Practical Application ................................................................. 45

§ 5. Calculation of the Stress Distribution across the Surface of Rupture
   at the Moment of Rupture ................................................................. 46
The type of vane borer described in this report was invented in 1947 by Mr Lyman Cadling, Research Department Engineer of the Royal Swedish Geotechnical Institute. The experiments were performed in 1947—1949 by Mr Cadling and Mr Nils Flodin, Research Department Engineer. The design of a borer for practical use was directed by Mr Torsten Kallstenius, Head of the Mechanical Department. The mathematical treatment, §§ 4—5, was carried out by Mr Sten Odenstad, Head of the Consulting Department, who also prepared this report, together with Mr Cadling.

Stockholm, February, 1950

ROYAL SWEDISH GEOTECHNICAL INSTITUTE
§ 1. Introduction.

The shear strength of clay is usually determined in the laboratory on samples taken from different depths in the ground. In Sweden such investigations are generally carried out by means of unconfined compression tests or cone tests. Usually the shear strength thus obtained, particularly by unconfined compression test, increases only slightly with the depth under the soil surface. It is usually smaller than the shear strength calculated from stability analyses, especially in the case of deep sliding surfaces.

This discrepancy may be due partly to the disturbance of the sample caused by the sampler, and partly to changes in the sample owing to the alteration of pressure conditions during extraction. As this discrepancy is more pronounced at great depths than at small ones, the latter cause seems to be the more important (1).¹

These errors, especially that caused by the alteration of pressure conditions, are difficult to eliminate when the shear strength test is carried out on extracted samples. One way would be to re-consolidate the samples at the load that prevailed in the ground, before testing them. Unfortunately this method is rather time-wasting. Still worse, it is not quite reliable, because the sample will acquire a lower pore volume during the re-consolidation and, hence, a higher cohesion than it had in the ground. Thus, this method is not satisfactory. An other way of avoiding the errors is to determine the shear strength directly in the ground.

Such a method, in which both types of errors seem to be practically eliminated, has been developed at the Royal Swedish Geotechnical Institute, and is described in this report. The first experiments began in the summer of 1947, and some results have been published in 1948 (2) and in 1949 (3 and 4). For the sake of completeness all results are included in this report.

The shear strength test in this method is performed by driving a vane into the soil and rotating it, while the resistance to rotation is measured. The shear strength is then calculated from the maximum torsional moment thus obtained. The apparatus used for the test is called the vane borer.

Similar experiments in Sweden performed by J. Olsson were reported in 1928 (5), and a vane apparatus built by C. Forssell was demonstrated at the

¹ The figures in parentheses refer to the bibliography at the end of the report.
3rd International Congress for Applied Mechanics in Stockholm 1930. In Germany similar experiments seem to have been made, as there exists a German patent on the subject, dated 1929 (6). In these tests, especially those made in Germany, the sensitivity of the clay seems not to have been sufficiently considered. The British Army has used a small vane apparatus for assessing the bearing capacity of soft ground in connection with tank mobility (7 and 8), and also a laboratory vane apparatus (9). Furthermore, in 1948, A. W. Skempton made some tests with a vane similar to the one described in this report (10).

§ 2. The Vane Borer and its Method of Application.

§ 21. Type I. The First Experimental Apparatus.

For the first experiments a very simple vane apparatus was constructed. Essentially, it consists of parts of the Swedish piston sampler (11) and the Swedish sounding borer (12). The apparatus is shown in Fig. 1. Its lower end consists of a vane 1 made up of a steel shaft 2 on which four thin rectangular wings 3 are welded. The vane is extended upwards by means of an extension rod 4 made up of one metre sections. The rod is surrounded by a casing pipe 5 also in one metre sections.

The shaft of the vane has such a length that, when the vane is in the position shown in Fig. 1 (testing position), the wings will be rotated in that part of clay which is not disturbed by the casing pipe, as is schematically shown in Fig. 2. The length of the shaft necessary for this purpose is, as shown in § 34, about 5 d, if d is the diameter of the casing pipe. Thanks to the thinness of its wings, the vane itself does not appreciably disturb the clay to be tested, as suggested in Fig. 3.

The sections of the casing pipe are jointed by couplings 6, and each fifth coupling is fitted with a guide-plate 7 for the rod. In order to prevent penetration of soil and water into the casing, the joints are sealed with tow. The shaft of the vane is centered by means of a bushing 8 fitted to the lowest coupling. A protractor 9 is mounted on the top coupling, which is located in position by means of a set-screw 10. At the same coupling a turning handle 11 rests on a bearing. The rod is furnished with a lever 12, on which a pointer 13, for reading the protractor, is fastened. The lever is connected with the turning handle by means of two spring balances 14, so that, when the turning handle is rotated, the force is transmitted to the lever, and the rod is exposed to a torsional moment.

The borer is driven down into the ground by pressure or by ramming. Before driving the borer, the turning handle, the uppermost coupling, and the parts attached to it are removed. In order to protect the vane during driving it is lifted, so that the wings rest against the lowermost coupling.
When a soil layer to be tested is reached, the parts which were removed are reassembled, and the vane is lowered to the testing position by pushing down the extension rod. The test proper is then carried out as follows (Fig. 4). The turning handle is turned at such a speed that the rate of rotation of the lever is kept constant. This rate is checked by means of a watch and readings...
on the protractor. The forces indicated by the spring balances are noted at certain definite time intervals, and when the maximum readings are recorded, the turning is stopped. If the remoulded strength of the clay is to be measured, the turning handle is rotated much faster until the clay is completely remoulded. The number of turns required is found by interrupting the turning from time to time and running a test at the standard rate of rotation. When it is found by these tests that the decrease in strength has ceased, the remoulding is complete and the strength value last obtained represents the remoulded shear strength of the clay.

The borer is then driven down to the depth where the next test is to be performed, and the procedure is repeated.

---

**Fig. 2.** Disturbance caused by the casing pipe at the lower end of the borer, shown schematically.

**Fig. 3.** Section through the vane, schematically showing the disturbance caused by the vane.
§ 22. Type II. A Borer for Practical Use.

After some tests had been carried out with Borer Type I, and the results obtained seemed reliable, the construction of a vane borer for practical use began. Along with experiments for verifying the reliability of the vane method, the borer described below was developed. It consists of two principal parts, the lower part (which is driven into the soil), and the upper part (the instrument for measuring and recording the torsional moment).

§ 221. Lower Part.

The lower part of the borer, which is shown in Figs. 5 and 6, consists of two systems, viz., the inner system and the outer system, which can be rotated and moved vertically in relation to each other.

§ 2211. Inner System.

The lower end of the inner system consists of a vane 1 made up of four wings 1a, which are welded to a steel shaft 1b. (An ordinary set of equipment includes vanes of three sizes, see Fig. 5.) The shaft is furnished with a longitudinal channel 1c, from which a hole 1d extends radially. The channel and the hole are designed to make it possible to introduce grease for lubrication and sealing between the shaft and a protective tube 2 surrounding the shaft. Both ends of the protective tube are provided with bearings 2a for the shaft of the vane. A seat 2b for a ball bearing is fastened to the upper part of
<table>
<thead>
<tr>
<th>H</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>55</td>
</tr>
<tr>
<td>130</td>
<td>65</td>
</tr>
<tr>
<td>160</td>
<td>80</td>
</tr>
</tbody>
</table>

**Fig. 5. Vane borer, Type II. Lower part.**

**Fig. 6. Vane borer, Type II. End of the lower part and a separate vane.**
the protective tube. The vane is screwed to a coupling piece 3 provided with a grease space 3 a. This space is connected with the longitudinal channel in the shaft of the vane, and can be filled with grease through a grease fitting 3 b. When grease is pressed into this space, a certain quantity of air is compressed, thus keeping the grease under pressure even after some grease has been consumed. In the upper part of the coupling piece there is a notch 3 c for a coupling pin 4, which holds together two other pieces, the inner tube 5 and the lock piece 6. To make the grease fitting accessible, the inner tube is furnished with two holes 5 a. The lower part of the inner tube consists of a holder 5 b which grasps a coupling spring 7. The spring acts between this holder and the ball bearing seat of the protective tube. These devices constitute a dummy coupling between the vane and the lock piece. If the vane and the lock piece are pulled apart, the coupling spring is compressed, and the coupling piece releases the pin, so that the lock piece can be rotated without turning the vane. To carry the weight of the inner system, a ball bearing 8 is placed between the lower end of the coupling piece and the ball-bearing seat of the protective tube, which rests on the outer system when the vane is in the testing position. A lock pin 9 surrounded by a rubber sleeve 10 is fastened in a hole passing through the lock piece. This pin is used for locking the inner system to the outer system. The lock piece is connected with a universal joint 6 a, and an extension rod 11, made up of one-metre lengths, is screwed to this joint.

§ 2212. Outer System.

The lower end of the outer system consists of a protective cap 12, which protects the vane while the borer is being driven down. In the cap, the vane rests against a plate 13 which is supported by a rubber packing 14. These shock-absorbing parts protect the vane when the borer is driven down by ramming. If the soil is homogeneous and contains no stones, the cap is unnecessary and can be replaced by a nut (not shown in the drawing), in which the plate and the rubber packing also fit. The protective cap is screwed to a sealing piece 15, in which there is a grease space 15 a, which can be filled through a grease fitting 15 b. This sealing piece serves for packing and lubrication against the protective tube surrounding the shaft of the vane. The sealing piece is screwed to an outer pipe 16, and between these pieces a gasket 17 is placed. To the upper part of the outer pipe a lock socket 18 is screwed. This socket is furnished with notches 18 a for the lock pin of the inner system. The lock socket is located in position by means of a locking ring 19. The outer pipe is extended upwards by a casing pipe 20 in one-metre lengths. A tight coupling between the outer pipe and the lowest casing pipe, on the one hand, and the casing pipe sections, on the other, is obtained by a fixed coupling 20 a and a locking coupling 21, which is screwed against a rubber gasket 22. In order to obtain a good seal there are no threads at the contact point of the rubber gasket at the upper end of the casing pipe sections and the outer pipe.
These unthreaded surfaces are also to be used in mounting the instrument on the casing pipe. The extension rod is guided by ball bearings placed in the coupling of each fifth casing pipe section (not shown in the drawing).

§ 2213. Operation.

In Fig. 5 the inner system is shown in its upper position; the wings are in the protective cap, and the vane and the lock piece are linked together by the dummy coupling. The inner system is locked to the outer system by means of the lock pin. If the outer system is kept fast, while the inner system is lifted and rotated a little, the lock pin loosens its hold in the notches of the lock socket, and the locking between the two systems ceases. The vane and the whole inner system can then be pushed down to its lower position in which the dummy coupling is disengaged, and the vane acquires the position shown in Fig. 6 and by the dash lines in Fig. 5. Now the inner system rests on the ball bearing and can easily be rotated in the outer system.

§ 222. Upper Part (Instrument).

The upper part of the borer, i.e. the instrument for measuring and recording the torsional moment, is shown in Fig. 7 and in Fig. 8 (during a test).

The instrument works as follows. The torsional moment passes through a torsion bar, and the twist of this bar is a measure of the moment. The moment is continuously recorded on a slip of paper moved by a constant speed spring motor. The instrument is rotated by hand, and the rate of rotation is indicated by a bell operated by the spring motor and ringing at regular intervals, and by readings on a protractor.

The instrument (Fig. 7) is encased in a box 1, furnished with a window 1 a, through which the paper slip can be seen, and a door 1 b, through which the paper can be taken out. Through another window 1 c a pointer, rotating synchronously with the tollings of the bell, is seen. This pointer was designed for showing the time intervals, but the function of it is now taken over by the bell. When a new instrument is constructed this pointer will also be left out. The whole box can be opened, for instance in order to change the paper roll, by turning it up on a hinge 1 d, fastened to the base plate 1 e. To the left, inside the box, the spring motor 2 is placed. It pulls the pointer 2 a and (by means of the transmission belt 2 b) the paper slip, and it works the bell 2 c. The time intervals of the bell tollings can be changed by a regulator 2 d. This regulator was made because the rate of rotation was not definitively fixed when the instrument was constructed. A suitable rate of rotation has now been found, and consequently the regulator is no longer needed. It will also be omitted in a new instrument. The spring motor is wound by a crank (not shown in the drawing) fitted to the peg 2 e, and is started and stopped by means of the knob 2 f. The recording device 3 is placed to the right inside
Fig. 7. Vane borer, Type II. Upper part, the instrument for measuring and recording the torsional moment.
the box. A cylinder (behind the wheel 3 a) is rotated by the transmission belt from the spring motor, which pulls a paper slip 3 b from a magazine roll 3 c over a table 3 d. After having passed the table, where the moment is recorded, the paper slip is rolled up in the space 3 e. The gearings are adjusted to give the paper slip a velocity of 0.2 mm/sec. On the table a pen 4 a coupled by a lever 4 b and a tube 4 c to the lower end of a torsion bar 4 traces the moment curve on the paper slip. The upper end of the torsion bar is connected to the base plate of the box by a pin 4 d and a tube 4 e. If the box is rotated a little, while the lower end of the torsion bar is kept still, the angle of twist of the bar is recorded as a definite turn of the pen. The instrument can be calibrated by subjecting the torsion bar to varying known moments. The tube surrounding the torsion bar is mounted in ball bearings 4 f. The lower end of the torsion bar is connected to a head 4 g of square cross-section. This head fits inside a square tube 4 h which can be screwed to the upper end of the extension rod. The tube is relatively long and permits a variation of about 10 cm in the length of the extension rod with respect to the upper end of the casing pipe. The box and two handles 5 for rotating the instrument rest on a bearing on a tube 6 which can be fastened to the upper end of the casing pipe by means of wing nuts 6 a. A protractor 6 b is fastened to this tube. The protractor is read off by means of two pointers 5 a coupled to the box. One pointer (the lower in the drawing) is used for readings by the man turning the handles, and the other for check readings by the foreman.

A special gauge is employed for interpreting the curves (see § 7).
§ 223. Method of Application.

This borer is used in the same manner as the first experimental apparatus. It is driven down, with the instrument removed, by pressure or by ramming. Hard ramming has proved detrimental to some components of the lower part, and, for this reason, the borer is ordinarily driven down by pressure. In soft soil it is pressed down by hand, and ramming is used only to overcome temporary resistance. In deep borings and in stiff soils the borer is pressed down by some kind of jack anchored to the ground. A jacking device suited to the vane borer and useful both for pressing down and pulling up is under construction. The vane is safely guarded by the protective cap and the borer can therefore also be used in soils containing stones.

If, for instance, a clay layer beneath a very hard soil layer is to be tested, a special casing is used through the hard layer. This casing has also been used in very deep boreholes in clay in order to eliminate the driving resistance along a part of the borer, and thus to facilitate the driving work.

When performing a test, the vane is pushed down by hand ahead of the cap. If the vane should run against a stone during this operation, it is easily noticed. The vane is then pulled into the cap again, and the stone is passed by pushing down the whole borer, the vane being locked in the cap by the locking pin. No difficulties occur with holding the vane in the upper position, whereas difficulties might occur with the Type I borer, especially in deep boreholes.

The tests can be made independently of the weather conditions, since no records have to be made by hand when using the instrument.

Borings with the vane borer are generally preceded by soundings. The results of these soundings can be used for determining a suitable vane size, an appropriate spacing of tests, and the like.

The vane borer and a sampler can be used alternately in the same hole. In that case, however, the borer must be withdrawn after each test. To avoid this, it is normally used in a separate hole.

Special boxes are employed for the transport of the most easily damageable parts of the borer, such as the instrument and the vanes. The sturdier parts are transported in boxes together with ordinary boring equipment.

§ 3. Shape of the Surface of Rupture, Progressive Failure, and Influence of Various Factors.

§ 31. Shape of the Surface of Rupture.

For interpreting the results of vane tests, it is necessary to know the shape of the surface of rupture produced in the soil by the rotation of the vane. Some tests in the field and in the laboratory were made in order to study this subject.
§ 311. Field Tests.

Some very simple tests were run in clay soil in the field. They were made in an excavation (about 3 m deep) at the Bromma Airfield, near Stockholm (at the excavation for Hangar III. See § 33). A vane (H = 100 mm, D = 80 mm) with two wings was pushed into the clay to a depth of about 25 cm below the bottom of the excavation, and rotated until rupture was observed. It was then withdrawn, and the piece of clay in which it had been rotated was excavated. When this piece was cut at right angles to the previous direction of the shaft of the vane, a fairly distinct surface of rupture was seen. This piece of excavated clay is shown in Fig. 9. The clay seems to have ruptured along a surface of oval, almost circular cross-section.

§ 312. Laboratory Tests.

The laboratory tests were first run in sand, chiefly for developing a suitable testing technique, and then in undisturbed clay.

§ 3121. Tests in Sand.

For the tests in sand use was made of the apparatus shown in Fig. 10. It consists of an iron barrel in which a vane can be rotated. The barrel is placed on a stool, and the shaft of the vane extends below the stool. The vane can be rotated by means of a lever furnished with a bead and sight for reading the
Fig. 10. Apparatus used for investigating the surface of rupture.

angle of rotation on a scale. The barrel can be covered with a lid which is held in position by wing nuts.

The sand used for the tests had a uniform grain size of about 1 mm (standard sand, quartz).

The barrel was first filled with sand to the mid-point of the wings. The sand surface was carefully levelled, and a sheet of wetted tissue-paper with a pattern was placed on the sand, see Fig. 11. (The square frame shown on the photograph is of no importance in this connection.) The barrel was then filled with sand to a level slightly above its top, and the lid was put on and pressed against the sand by means of the wing nuts. The vane was rotated a certain number of degrees, which was read on the scale by means of the bead and sight on the lever. The lid was then removed, and the sand was taken away to a level little above the tissue-paper. The paper was dried by means of a lamp placed above the remaining sand, so as to make it possible to remove the remaining sand and thus to expose the pattern. Seven tests were made using a new sheet of tissue-paper each time. After each test the pattern was photographed. The result of these tests with angles of rotation of 1, 2, 3, 5, 10, 15, and 20 degrees are shown in Figs. 12 to 18 respectively. The circles correspond-
Fig. 11. Tissue-paper placed on the levelled sand surface.

ing to the vane diameter (= the distance between the outermost edges of two opposite wings) are indicated by arrows. The surface of rupture seems to be a circular cylinder, and its diameter equals that of the vane.

§ 3122. Tests in Clay.

For the tests in clay the same apparatus was used as for the tests in sand. The barrel, however, was cut horizontally into two cylinders.

The clay used in the tests was taken from the bottom of an excavation, about 3 m deep, at the Bromma Airfield, about 500 m north-west of the test area described in § 33. As the soil at the airfield is fairly homogeneous, the soil data given in § 33 may also be taken to be representative of the clay used for these tests (Table 1 and Plate 1).

The tests were carried out in the same manner as those in sand. The two cylinders (the lower cylinder being provided with a bottom plate and a vane)
Figs. 12—15. Surface of rupture in sand.
Figs. 16–18. Surface of rupture in sand.
were first filled with clay as undisturbed as possible by pushing them into the bottom of the excavation and digging them up. The clay at the open ends of the cylinders was then levelled. A wetted sheet of tissue-paper similar to those used in sand was placed on the clay surface of the lower cylinder, as shown in Fig. 19. The clay surface was covered with another sheet of wetted tissue-paper. The upper cylinder and the lid were put on and pressed against the lower cylinder by means of the wing nuts. The clay in the upper cylinder had been made to project a little beyond the ends of the cylinder, so that the clay was subjected to pressure when the lid was screwed down. The vane was rotated a certain number of degrees, and, after removing the lid, the cylinders could easily be separated thanks to the two sheets of paper. The upper sheet of paper stuck to the clay in the upper cylinder, and the pattern was there-
Figs. 20—22. Surface of rupture in clay.
fore exposed. Several tests were made, using new clay and new sheets of paper each time, with angles of rotation of 1.5, 3, and 5 degrees. The results are shown in Figs. 20 to 22 respectively. (The circles corresponding to the vane diameter are marked by arrows.) The pattern shown in Fig. 21 was somewhat disturbed when the upper cylinder was removed, and this accounts for its oval form. As is seen from the photographs, the surface of rupture in the clay also seems to be a circular cylinder surrounding the vane.

From the field and laboratory tests it may be concluded that the surface of rupture produced when a vane is rotated closely coincides with the circular cylinder circumscribed round the vane. The oval shape obtained in the field tests with a two-winged vane, may be due to the fact that the pressure in the clay (depth 25 cm) in which the tests were made was so low as to allow the clay to separate from the vane. (Note the crack in the piece of clay shown in Fig. 9.)

§ 32. Progressive Failure.

In shear test devices it is attempted to apply the stresses so that the stress distribution should be as uniform as possible, in order to avoid progressive failure of the sample. In a vane test progressive failure might be expected to start in front of the edge of each wing and to spread gradually across the whole surface of rupture.

An idea of the process of rupture can be formed by studying the deformations at different angles of rotation of the vane, see Figs. 12 to 18 and 20 to 22. Generally, the deformation in front of each wing seems to be somewhat larger than behind it. The contrary, i.e. a deformation that is larger behind a wing, can also be observed, as, for instance, in Fig. 22 (upper and right-hand wing). Usually, however, the deformation seems to be comparatively uniform across the whole surface of rupture. Hence it may be concluded that the progressive character of failure seems to be slight and does not appreciably affect the test results.

§ 33. Rate of Rotation.

In shear tests the rate of application of stress or strain influences the result. Shear tests are stress-controlled or strain-controlled. A vane test is made by rotating the upper end of the extension rod at a constant rate. On account of the twisting of the rod the rate of rotation of the vane is much smaller than that of the upper end of the rod during the first stage of the test. However, the two rates are fairly equal during the last and most important stage of the test, and they are exactly equal at the peak point. As a result, the vane test is not exactly a strain-controlled test with constant increase in deformation, but it is closely related to such a test.

In order to investigate the influence of the rate of strain increase, tests have been carried out at different rates of rotation of the upper end of the extension...
Fig. 23. Maximum torsional moments obtained at different rates of rotation. Test site at the Bromma Airfield.
rod. The tests have been performed in the field by using different rates of rotation in different boreholes. The investigations have been made at two sites, viz., at the Bromma Airfield, near Stockholm, and at the Lidan River in southern Sweden. In both these places borings had previously been made, so that soil data were available.

Some results of the earlier borings at Bromma are shown in Plate 1, and some soil data are given in Table 1. The results of the soundings are presented in
Table 1. Soil data from the borehole B at the Bromma Airfield.

<table>
<thead>
<tr>
<th>Sample from el. m</th>
<th>Classification</th>
<th>Unit weight t/m³</th>
<th>Poresity %</th>
<th>Water content %</th>
<th>Liquid limit %</th>
<th>Plastic limit %</th>
<th>Sensitivity (cone test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3</td>
<td>Muddy clay</td>
<td>1.46</td>
<td>69</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>1.8</td>
<td>Clay</td>
<td>1.56</td>
<td>60</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>0.8</td>
<td>Clay with layers of fine sand</td>
<td>1.56</td>
<td>66</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>-0.7</td>
<td>Clay</td>
<td>1.52</td>
<td>69</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>-1.7</td>
<td>Clay with layers of fine sand</td>
<td>1.62</td>
<td>62</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>-2.7</td>
<td>Clay</td>
<td>1.57</td>
<td>66</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>-3.7</td>
<td></td>
<td>1.48</td>
<td>71</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>-4.7</td>
<td></td>
<td>1.64</td>
<td>61</td>
<td>71¹</td>
<td>69¹</td>
<td>31¹</td>
<td>12¹</td>
</tr>
<tr>
<td>-5.7</td>
<td></td>
<td>1.69</td>
<td>64</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>-6.7</td>
<td></td>
<td>1.62</td>
<td>62</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

¹ Approximate. The tests run on a sample from another borehole.

accordance with the standards used by the Institute. See, for instance, (11). (The figures to the left of a borehole refer to the load in kg and those to the right to the number of half-turns used for driving down the sounding device.) Tests were run in seven boreholes, Nos. 1, 2, 3, 4, 5, 6, and 10, the rate of rotation being respectively 0.50, 0.25, 1.00, 0.19, 0.40, 0.75, and 0.10 deg/sec. A vane test was generally carried out at every metre from 2 to 10 metres below the soil surface. A Type I borer, with a vane having two wings, was used. The size of the vane was: H = 200 mm, D = 80 mm. The results of the tests are shown in Figs. 23 and 24. The maximum torsional moments, which are proportional to the shear strength, are shown as functions of the angular velocity. The scattering of the observations, especially in the deep tests, is great, but a tendency towards a decrease in moment with decreasing velocity is evident. In Fig. 24 the average values of all the tests are also shown. In spite of the scattering at the individual depths, this curve clearly shows a decrease in maximum torsional moment with decreasing rate of rotation.

Some results of the earlier borings at the Lidan River are shown in Plate 2 and Table 2. The clay below elevation 55 is very sensitive and can be referred to as a “quick clay” (kvicklera), while the clay at lesser depths is not so sensitive. Tests were run in three boreholes, Nos. 5, 6, and 7. The lower part of the vane borer was of Type II and the instrument of Type I. The size of the vane was: H = 134 mm, D = 64 mm. Vane tests were carried out in the less sensitive clay (depths 4.0–5.5 m) and in the quick clay (depths 11.0–13.0 m). The rate of rotation was adjusted so as to produce a rate of loading of about 5 t/m²min and 0.5 t/m²min respectively in the boreholes Nos. 5 and 6. The results are shown in Fig. 25. The results of the tests in the clay which was not very
sensitive (upper part of the figure) are similar to those obtained at Bromma, i.e. the shear strength decreases as the rate of loading decreases. In the quick clay (lower part of the figure), this tendency is not to be observed. This may be due to the influence of the great sensitivity of this soil. In the borehole No. 7, tests were made at a constant load, which consisted of hanging pails filled with water and coupled over guide rollers to the lever. The stress applied in this way was somewhat smaller than the strength at the rate of loading of 0.5 t/m².min. The stress was applied quickly, and was then kept constant until the lever ceased moving, see Fig. 26. Evidently, this stress can be regarded as a minimum value of the strength at a zero rate of loading, and it is plotted in this way in Fig. 25. Afterwards the load was removed, and ordinary tests were made at a rate of loading of 0.5 t/m².min. The values observed in these tests are somewhat greater than those obtained at the same rate of loading without a previous constant load test, see Fig. 25. This may be a result of consolidation of the clay during these tests.
The following conclusions may be drawn from the results of the tests at Bromma and the Lidan River.

Within the range investigated (0.1—1.0 deg/sec) the strength decreases with the rate of rotation of the upper end of the extension rod. At smaller rates (< 0.1 deg/sec) the strength does not seem to decrease appreciably; rather it seems to increase as a result of consolidation of the clay. Anyhow, this is true at very small rates.

The test results agree with the influence of the rate of loading in ordinary laboratory shear tests. They also agree with tests made with a laboratory vane apparatus in England (9).

Now the rate of rotation should correspond to the most unfavourable case, i.e. that rate at which the smallest shear strength is obtained. A rate of rotation of 0.1 deg/sec seems to be a practical lower limit for turning by hand without any gearing. As has been mentioned above, it also roughly seems to correspond to the rate at which the smallest shear strength is obtained. For this reason, it has been adopted as standard. At this rate of rotation, a vane test normally takes from 2 to 15 min, according to the strength of the soil and the depth of testing. This time is comparable to the time of loading in laboratory tests. The same rate of rotation is standard for the laboratory vane apparatus used in England (9).

In the tests shown in Figs. 23 and 24 the maximum torsional moment at the rate of 0.1 deg/sec only slightly exceeds the moment obtained by extending the curves so that the rate is equal to zero. The difference seems to be less than 5
### Table 2. Soil data from the test site at the Lidan River.

<table>
<thead>
<tr>
<th>Bore-hole No. from cl. m</th>
<th>Sample Unit</th>
<th>Classification</th>
<th>Unit weight t/m³</th>
<th>Porosity %</th>
<th>Sensitivity (cone test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>61.3</td>
<td></td>
<td>Silty clay with layers of fine sand</td>
<td>1.93</td>
<td>44</td>
<td>8</td>
</tr>
<tr>
<td>59.0</td>
<td></td>
<td>Clay</td>
<td>1.51</td>
<td>69</td>
<td>14</td>
</tr>
<tr>
<td>57.3</td>
<td></td>
<td>Clay</td>
<td>1.55</td>
<td>67</td>
<td>24</td>
</tr>
<tr>
<td>55.3</td>
<td></td>
<td>Clay with layers of fine sand</td>
<td>1.64</td>
<td>61</td>
<td>5</td>
</tr>
<tr>
<td>53.3</td>
<td></td>
<td>Clay</td>
<td>1.60</td>
<td>64</td>
<td>90</td>
</tr>
<tr>
<td>51.3</td>
<td></td>
<td>Clay</td>
<td>1.62</td>
<td>62</td>
<td>&gt;400</td>
</tr>
<tr>
<td>49.3</td>
<td></td>
<td>Clay</td>
<td>1.56</td>
<td>66</td>
<td>&gt;540</td>
</tr>
<tr>
<td>47.3</td>
<td></td>
<td>Clay</td>
<td>1.60</td>
<td>64</td>
<td>&gt;412</td>
</tr>
<tr>
<td>45.3</td>
<td></td>
<td>Clay</td>
<td>1.65</td>
<td>61</td>
<td>163</td>
</tr>
<tr>
<td>43.3</td>
<td></td>
<td>Clay with layers of fine sand</td>
<td>1.74</td>
<td>55</td>
<td>87</td>
</tr>
<tr>
<td>61.6</td>
<td></td>
<td>Clayey fine sand</td>
<td>1.98</td>
<td>41</td>
<td>30</td>
</tr>
<tr>
<td>59.6</td>
<td></td>
<td>Clay with layers of fine sand</td>
<td>1.60</td>
<td>64</td>
<td>15</td>
</tr>
<tr>
<td>57.6</td>
<td></td>
<td>Clay</td>
<td>1.58</td>
<td>65</td>
<td>26</td>
</tr>
<tr>
<td>55.6</td>
<td></td>
<td>Clay with layers of fine sand</td>
<td>1.62</td>
<td>62</td>
<td>29</td>
</tr>
<tr>
<td>53.6</td>
<td></td>
<td>Clay</td>
<td>1.58</td>
<td>65</td>
<td>133</td>
</tr>
<tr>
<td>51.6</td>
<td></td>
<td>Clay</td>
<td>1.62</td>
<td>63</td>
<td>65</td>
</tr>
<tr>
<td>49.6</td>
<td></td>
<td>Clay</td>
<td>1.56</td>
<td>67</td>
<td>10</td>
</tr>
<tr>
<td>47.6</td>
<td></td>
<td>Clay</td>
<td>1.67</td>
<td>59</td>
<td>&gt;540</td>
</tr>
<tr>
<td>45.6</td>
<td></td>
<td>Clay</td>
<td>1.60</td>
<td>64</td>
<td>313</td>
</tr>
<tr>
<td>43.6</td>
<td></td>
<td>Clay</td>
<td>1.62</td>
<td>62</td>
<td>255</td>
</tr>
<tr>
<td>41.6</td>
<td></td>
<td>Clay</td>
<td>1.67</td>
<td>59</td>
<td>&gt;378</td>
</tr>
<tr>
<td>39.6</td>
<td></td>
<td>Clay with layers of fine sand</td>
<td>1.74</td>
<td>55</td>
<td>192</td>
</tr>
</tbody>
</table>

Per cent. Similar tests with the laboratory vane apparatus (9) show differences of the same order. For this reason, we seem to be justified in using the rate adopted, and the errors involved in the case do not seem to be of any practical importance.

### § 34. Length of the Vane Shaft.

When a borer is driven into clay, it disturbs the clay ahead of and around itself. The size of this zone of more or less disturbed clay must bear a definite proportion to the size of the borer. The casing pipe of the vane borer produces a zone of disturbance indicated by the shaded area in Fig. 2, and the vane itself may cause a disturbance shown in Fig. 3.

It is believed that the disturbance caused by the vane is very small owing to the thinness of the wings, so that it does not appreciably affect the results.

The disturbance caused by the casing pipe, on the other hand, may affect the results to a great extent if the shaft of the vane is too short. Some tests have been made in order to investigate this circumstance. The disturbed zone in a
sensitive clay is probably greater than in an ordinary clay, and, for this reason, the tests were made in a quick clay.

In the test area at the Lidan River (Plate 2; soil data in Table 2), tests were run in the boreholes Nos. 1 to 4. The lower part of the borer was of Type II, without protective cap, and the instrument was of Type I. The size of the vane was: \( H = 134 \text{ mm} \), \( D = 64 \text{ mm} \). The length of the vane shaft that could be advanced ahead of the casing was adjusted by placing spacer sleeves around the protective tube inside the borer. The length was \( 4.17 \text{ d}, 1.67 \text{ d}, 3.17 \text{ d}, \) and \( 0.67 \text{ d} \) (\( d \) being the diameter of the casing pipe) in the boreholes Nos. 1 to 4 respectively. The tests were run at a rate of rotation adjusted so as to give a rate of loading of about \( 0.5 \text{ t/m}^2\text{min} \), i.e. approximately the rate corresponding to the standard rate of rotation \( 0.1 \text{ deg/sec} \) when used in a test at a depth of 10 m. The tests were performed at depths between 10 and 13 m, with a vertical spacing of 0.5 m.

The test results expressed in terms of shear strength are shown in Fig. 27. The shear strength increases as the length of the vane shaft becomes greater. The difference between the results corresponding to the shortest and the longest shaft is rather great; the lowest values being approximately 80 per cent of the highest. The shear strength (average in each borehole, i.e. average for each
length of the vane shaft) is shown as a function of the shaft length in Fig. 28. The average strength value at a shaft length of 3.17 d is probably somewhat too small and the value obtained at 4.17 d is somewhat too great, as a result of the exceptionally low value at the depth of 13.0 m and the high value at the depth of 11.5 m in Fig. 27. The curve in Fig. 28 has been drawn accordingly. The tests should of course be supplemented by tests with a still longer shaft, but this was impossible to do with the apparatus used. However, the decreasing influence of the disturbance is clearly seen, and it seems that it can be disregarded at a shaft length of about 5 d. In an ordinary clay, not nearly so sensitive as the quick clay, the zone of disturbance is probably still smaller. For this reason, the tests have been considered sufficient, and the length of the vane shaft has been made 5 d. In view of the use of the protective cap, the distance 5 d is measured from the upper end of the wings to an imaginary cylinder fitted to the lower end of the borer and having a volume equal to that of the cap.

§ 35. Number of Wings.

The number of wings of the vane may affect the maximum torsional moment to some extent. If the vane is equipped with a small number of wings, the stress distribution on the surface of rupture may be not as uniform as in the case of a vane having a great number of wings. A non-uniform stress distribution would
Shearing strength

0 0.5 1 1.5 t/m²

Vane with:
2 wings, 4 wings

Depth

Borehole no:
4, 10, 11

Fig. 29. Vane test results. Vanes having two and four wings.

favour progressive failure causing the maximum torsional moment to be smaller. On the other hand, a great number of wings would increase the disturbance of the clay, and thus also diminish the maximum torsional moment. Consequently, a certain definite number of wings would produce the best results.

Only a few tests have been made to investigate this matter. They were made on the test site at Bromma (Plate 1; soil data in Table 1). In the borehole No. 11 three tests were run at the depths of 2.0, 3.0, and 4.0 m, using a vane with four wings. The borer was the same as that used on this site for investigating the influence of the rate of rotation (§ 33). The only difference was the number of wings (two in the earlier tests). The standard rate of rotation of 0.1 deg/sec was used, just as in the earlier tests in the boreholes Nos. 4 and 10.

The results of the tests with two and four wings are compared in Fig. 29. The values obtained with four wings are somewhat greater than those obtained with two wings. In spite of the very small number of tests and the relatively great difference between the results in the boreholes Nos. 4 and 10, probably depending on the heterogeneity of the soil, four wings seem better than two.

As a vane with four wings is stronger and also more suitable for practical use from other points of view, four wings were adopted as standard.

The error introduced by using four wings instead of the ideal number, which probably differs from the adopted number, is not likely to be of any practical importance.

§ 36. Vane Dimensions.

At the moment of rupture the stress distribution in the clay at the cylindrical surface of rupture is fairly well known (§§ 32 and 5), but the stress distribution at the end surfaces of the cylinder is uncertain. In this report the stress distribution at the end surfaces is assumed to be uniform. This assumption involves,
that an error is introduced, which brings the result on the safe side but which should, nevertheless, be kept as small as possible. This can be done by making the vane height (H) large in proportion to the diameter (D).

If the real stress distribution at the end surfaces is assumed to be triangular, the error (the difference between the moments corresponding to a uniform and a triangular stress distribution) can be estimated. It amounts to the following percentages of the total moment (§ 6):

<table>
<thead>
<tr>
<th>H/D</th>
<th>Error Per cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.3</td>
</tr>
<tr>
<td>2</td>
<td>3.6</td>
</tr>
<tr>
<td>3</td>
<td>2.5</td>
</tr>
</tbody>
</table>

If the torsional system of a borer is designed to withstand a certain maximum torsional moment, the diameter of the vane shaft is fixed. Consequently, if the vane height is made larger, the vane diameter must be made accordingly smaller, in order not to overstress the shaft. However, the vane diameter shall not be made so small that the surface of rupture is formed in the disturbed zone caused by the shaft. An upper limit for the vane height is thus obtained.

At the test site at Bromma (Plate 1; soil data in Table 1) some tests have
been made with vanes having different heights, other conditions being equal. Earlier tests (§ 33) made in the boreholes Nos. 4 and 10 with a 200 mm high vane were supplemented by tests using a 100 mm high vane in the boreholes Nos. 8, 12, and 13 and with a 300 mm high vane in the boreholes Nos. 7 and 9. Use was made of a Type I borer and the standard rate of rotation of 0.1 deg/sec.

The results are shown in Fig. 30. The vane used in the borehole No. 8 was damaged. Therefore the results are incorrect, and have been omitted. The difference between the 300 mm vane curve and the 200 mm curve is approximately equal to the difference between the 200 mm vane curve and the 100 mm curve. This shows that the influence of these vane dimensions does not appreciably affect the results. This circumstance is demonstrated still more clearly by Fig. 31, which represents the average shear strength for each vane (calculated in accordance with § 6).

All dimensions of the vanes used in the tests seem to be acceptable, and a $\frac{H}{D}$-ratio equal to 2 has been adopted as standard.


In this section the relation between the angle of rotation of the vane and the torsional moment is calculated on the basis of the theory of elasticity. The clay is assumed to be an isotropic, elastic body obeying Hooke's law and extend-
Fig. 32. Shearing stresses acting on the element under consideration.

ing to infinity in all directions. The result is applied to the straight parts of the vane test curves (§ 7), so as to determine the modulus of rigidity of the clay in its "elastic" state.

§ 41. Two-Dimensional Calculation.

The vane is replaced by a rigid cylinder with the same radius $r_0$ as the vane and extending, in the axial direction, throughout the whole clay layer. The clay is assumed to adhere to the surface of this cylinder. Because of the symmetry of rotation, the shear stress is uniformly distributed across the cylindrical surface. This assumption also agrees with the tests in § 32.

Because of the symmetry of rotation, the small volume element (Fig. 32) at the distance $r$ from the centre of rotation is subjected only to the shearing stresses $\tau$ and $\tau + dr$. Hence we obtain the equation of equilibrium

$$\tau = \frac{r_0^2}{r^2} \tau_0$$

in which $\tau_0$ = the shearing stress at the surface of the cylinder.

Substituting the shearing strain $\gamma$ from the formula

$$\tau = G \gamma$$

in which $G$ = the modulus of rigidity of the clay, we obtain

$$\gamma = \frac{r_0^2}{r^2} \gamma_0$$

in which $\gamma_0$ = the shearing strain at the surface of the cylinder.
During deformation each point of the clay moves, as a result of the symmetry of rotation, a short distance on a circle whose centre coincides with the centre of rotation. The motion (Fig. 33) can therefore be considered as a rotation by an angle $\omega$ around the centre of rotation, in which

$$\omega = \omega(r)$$

If the point $r + dr$ moves the distance $(r + dr) \omega$ on its circle, no shear occurs in the element $r$. In reality, however, the point $r + dr$ moves the distance $(r + dr) (\omega + d\omega)$. Consequently, the shearing strain at the point $r$ is

$$\gamma = \frac{(r + dr) \omega - (r + dr)(\omega + d\omega)}{dr} = -\frac{(r + dr)d\omega}{dr} = -r \frac{d\omega}{dr}$$

Substituting

$$\gamma = \frac{\gamma_0^2}{r^2} \gamma_0$$

we obtain

$$\frac{d\omega}{dr} = -\frac{\gamma_0^2}{r^3} \gamma_0$$

$$\omega = \frac{1}{2} \frac{\gamma_0^2}{r^3} \gamma_0 + C$$
The constant $C$ is determined from

$$\omega = 0 \text{ if } r = \infty$$

$$\therefore C = 0$$

$$\omega = \frac{1}{2} \frac{r^2 \gamma_0}{r^2}$$

The angle of rotation of the cylinder is therefore

$$\omega_0 = \frac{1}{2} \gamma_0$$

which is transformed by substitution of $\tau_0$ into

$$G = \frac{\tau_0}{2 \omega_0}$$

§ 42. Three-Dimensional Calculation.

The vane is replaced by a rigid sphere, and the clay is assumed to adhere to the surface of this sphere.

As a result of the symmetry of rotation, the sphere is subjected only to horizontal shearing stresses, and the intensity of these stresses is constant on every parallel.

We use a spherical coordinate system with its origin at the centre of the sphere. A point $A$ in the clay (Fig. 34) is determined by the coordinates $r$, $\varphi$, and $\psi$, where

$\tau =$ the distance from the origin,

$\varphi =$ the angle with respect to the vertical diameter,

$\psi =$ the angle with respect to an arbitrary direction in the equatorial plane.

Consider a small volume element (shown in Fig. 34) with the sides $d\tau$, $rd\varphi$, and $r \sin \varphi d\psi$. As a result of the symmetry of rotation, the element is subjected only to shearing stresses, and only to those shown in the drawing and to the corresponding shearing stresses in the opposite surfaces. The following resulting shearing forces are obtained in the surfaces of the element:

<table>
<thead>
<tr>
<th>Surface</th>
<th>$r$</th>
<th>$T_{\varphi \tau} = \tau_0 r^2 \sin \varphi , d\varphi , d\psi$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\varphi$</td>
<td>$T_{\varphi \varphi} = \tau_0 r \sin \varphi , dr , d\psi$</td>
</tr>
<tr>
<td>$\psi$</td>
<td>$T_{\psi \psi} = \tau_0 r , dr , d\varphi$ and $T_{\psi \varphi} = \tau_0 r , dr , d\varphi$</td>
<td></td>
</tr>
<tr>
<td>$r + d\tau$</td>
<td>$T_{\varphi \tau} + \frac{\partial T_{\varphi \tau}}{\partial \tau} , dr$</td>
<td></td>
</tr>
<tr>
<td>$\varphi + d\varphi$</td>
<td>$T_{\psi \psi} + \frac{\partial T_{\psi \psi}}{\partial \varphi} , d\varphi$</td>
<td></td>
</tr>
<tr>
<td>$\psi + d\psi$</td>
<td>$T_{\tau \psi}$ and $T_{\varphi \psi}$</td>
<td></td>
</tr>
</tbody>
</table>
The equations of equilibrium are obtained by projections in the directions $r$, $\varphi$, and $\psi$ traced through the centre \( \left( r + \frac{1}{2} dr, \varphi + \frac{1}{2} d \varphi, \psi + \frac{1}{2} d \psi \right) \) of the volume element.

Fig. 35 shows the projection of the volume element on that plane through the centre whose perpendicular lies in the $\varphi$-direction, and Fig. 36 shows the corresponding projection on the $r$-plane. From Fig. 35 it is seen that the equation of equilibrium in the $r$-direction leads to the identity $0 = 0$. The same identity is obtained from the equation of equilibrium in the $\varphi$-direction, see Fig. 36. The equations of equilibrium are thus reduced to only one, namely the equation of equilibrium in the $\psi$-direction.

From Fig. 36 we obtain

\[
\delta = \frac{1}{2} \left( r + \frac{d r}{2} \right) \cos \varphi d \varphi d \psi \frac{1}{\left( r + \frac{d r}{2} \right) d \varphi} = \frac{1}{2} \cos \varphi d \psi
\]
Consequently, the equation of equilibrium in the \( \varphi \)-direction is

\[
\frac{\partial T_{\varphi \varphi}^{\varphi \varphi}}{\partial r} dr + \frac{\partial T_{\varphi \varphi}^{\varphi \varphi}}{\partial \varphi} d \varphi + T_{\varphi \varphi} \sin \varphi d \varphi + T_{\varphi \varphi} \cos \varphi d \varphi = 0
\]

Substituting the expressions for \( T \), we find

\[
\frac{\partial \tau_{\varphi \varphi}}{\partial r} r^2 \sin \varphi d \varphi d \varphi d \varphi + \tau_{\varphi \varphi} 2 \tau \sin \varphi d \varphi d \varphi d \varphi + \\
+ \frac{\partial \tau_{\varphi \varphi}}{\partial \varphi} r \sin \varphi d \varphi d \varphi d \varphi + \tau_{\varphi \varphi} \cos \varphi d \varphi d \varphi d \varphi + \\
+ \tau_{\varphi \varphi} r \sin \varphi d \varphi d \varphi d \varphi + \tau_{\varphi \varphi} \cos \varphi d \varphi d \varphi d \varphi = 0
\]

\[
r \frac{\partial \tau_{\varphi \varphi}}{\partial r} \sin \varphi + 3 \tau_{\varphi \varphi} \sin \varphi + \frac{\partial \tau_{\varphi \varphi}}{\partial \varphi} \sin \varphi + 2 \tau_{\varphi \varphi} \cos \varphi = 0 \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldotted{
Thus the point \( A \) moves the distance \( r\omega \) on the parallel. If the point \((r + dr, \varphi, \psi)\) moves the distance \((r + dr)\omega\) on its parallel, no shear is produced in the plane perpendicular to the \( \varphi \)-direction. Therefore the shearing strain in this plane is

\[
\gamma_{\varphi} = \frac{(r + dr)\left(\omega + \frac{\partial \omega}{\partial r} dr\right) - r\omega}{dr} = r \frac{\partial \omega}{\partial r} \quad \ldots \ldots \ldots \ldots (2)
\]

Further, if the point \((r, \varphi + d\varphi, \psi)\) moves the distance \( r \sin (\varphi + d\varphi) \frac{\omega}{\sin \varphi} = r \omega + r \omega \frac{\cos \varphi}{\sin \varphi} d\varphi\) on its parallel, no shear occurs in the plane perpendicular to the \( r \)-direction. Thus, the shearing strain in this plane is

\[
\gamma_{r} = \frac{r\left(\omega + \frac{\partial \omega}{\partial \varphi} d\varphi\right) - r\omega - r\omega \frac{\cos \varphi}{\sin \varphi} d\varphi}{r d\varphi} = \frac{\partial \omega}{\partial \varphi} = \frac{\omega}{\sin \varphi} \quad \ldots (3)
\]

Differentiating Eqs. (2) and (3), we find

\[
\begin{align*}
\frac{\partial \gamma_{\varphi}}{\partial \varphi} & = r \frac{\partial^{2} \omega}{\partial r \partial \varphi} \\
-r \frac{\partial \gamma_{r}}{\partial r} & = -r \frac{\partial^{2} \omega}{\partial r \partial \varphi} + r \frac{\partial \omega}{\partial r} \frac{\cos \varphi}{\sin \varphi}
\end{align*}
\]

Adding and substituting Eq. (2), we find

\[
\frac{\partial \gamma_{\varphi}}{\partial \varphi} - \gamma_{\varphi} \frac{\cos \varphi}{\sin \varphi} - r \frac{\partial \gamma_{r}}{\partial r} = 0 \quad \ldots \ldots \ldots \ldots (4)
\]

Substituting

\[
\gamma_{\varphi} = \frac{\tau_{\varphi}}{G} \quad \gamma_{r} = \frac{\tau_{r}}{G}
\]

in which \( G \) = the modulus of rigidity of the clay, we obtain the compatibility equation

\[
\frac{\partial \tau_{\varphi}}{\partial \varphi} - \tau_{\varphi} \frac{\cos \varphi}{\sin \varphi} - r \frac{\partial \tau_{r}}{\partial r} = 0 \quad \ldots \ldots \ldots \ldots (5)
\]

Eqs. (1) and (5) determine the stress distribution in the clay. The boundary conditions close to the rotating sphere are \( \tau_{r} = \tau = 0 \). If a trial is made with

\[
\tau_{r} = 0
\]
throughout the whole clay volume, Eq. (1) becomes
\[ r \frac{\partial \tau_{\varphi}}{\partial r} + 3 \tau_{\varphi} = 0 \]
\[ \frac{\partial \tau_{\varphi}}{\tau_{\varphi}} = -3 \frac{\partial r}{r} \]
\[ \ln \tau_{\varphi} = -\ln r^3 + f_1(\varphi) = \ln \frac{f(\varphi)}{r^3} \]
\[ \tau_{\varphi} = \frac{f(\varphi)}{r^3} \]

Substituting in Eq. (5), we find
\[ \frac{f(\varphi)}{r^3} - \frac{f(\varphi) \cos \varphi}{r^3 \sin \varphi} = 0 \]
\[ \frac{d f}{f} = \frac{\cos \varphi}{\sin \varphi} d \varphi \]
\[ \ln f = \ln \sin \varphi + C_1 = \ln C \sin \varphi \]
\[ f(\varphi) = C \sin \varphi \]
in which \( C \) is a constant.

We thus obtain the solution
\[ \left\{ \begin{array}{l}
\tau_{\varphi} = \frac{C \sin \varphi}{r^3} \\
\tau_r = 0 
\end{array} \right. \]
which represents the distribution of the shearing stress over the surface of the rotating sphere.

The constant \( C \) is determined by the magnitude of the moment \( M \) which acts on the rotating sphere. If the radius of the sphere is \( R \), we obtain
\[ M = \int_0^{\pi} \frac{C \sin \varphi}{R^3} 2 \pi (R \sin \varphi)^3 R d \varphi = 2 \pi C \int_0^{\pi} \sin^3 \varphi d \varphi = \frac{8}{3} \pi C \]
\[ C = \frac{3 M}{8 \pi} \]
and hence
\[ \tau_{\varphi} = \frac{3 M \sin \varphi}{8 \pi r^3} \]

(6)
Substituting in Eq. (2), we obtain

\[
\frac{1}{G} \frac{3M \sin \varphi}{8 \pi r^3} = r \frac{\partial \omega}{\partial r}
\]

\[
\omega = -\frac{1}{G} \frac{M \sin \varphi}{8 \pi r^3}
\]

Therefore, the angle of rotation of the sphere is

\[
\omega_n = -\frac{1}{G} \frac{M}{8 \pi R^3}
\]

This implies that the above solution for the rigid sphere is exact according to the theory of elasticity. From the angle of rotation of the sphere and the moment we obtain the modulus of rigidity of the clay by means of the formula (disregarding the minus sign)

\[
G = \frac{M}{8 \pi R^3 \omega_n}
\] ............................... (7)

When applying this theory to the real vane of standard dimensions \((H = 2D)\), the radius of the sphere should be chosen somewhere between half the height of the vane \((H/2 = D)\) and half its diameter \((D/2)\). Now we choose the radius so that the average shearing stress at the surface of the sphere equals that recorded by the vane borer and calculated according to the formula \((\S \ 6)\)

\[
s = \frac{6}{7} \frac{M}{\pi D^3}
\]

We obtain

\[
s = \frac{6}{7} \frac{M}{\pi D^3} = \tau_{av} = \frac{1}{A_o} \int_A \tau_\varphi \ dA =
\]

\[
= \frac{1}{4 \pi R^2} \int_0^\pi \frac{3M \sin \varphi}{8 \pi R^3} 2 \pi R \sin \varphi \ R \ d\varphi =
\]

\[
= \frac{3M}{16 \pi R^2} \int_0^\pi \sin^2 \varphi \ d\varphi = \frac{3M}{32 R^3}
\]

\[
R = \frac{1}{4} \sqrt{\frac{3}{7\pi}} D = 0.70 \ D
\]
The shearing stress at the equator of the sphere is then
\[ \tau = \frac{3M}{8\pi \frac{7\pi}{64} D^3} = \frac{4}{\pi} s = 1.28 \, s \]

It is further assumed that the angle of rotation of the chosen sphere \( \omega_R \) equals that of the vane. Thus, the modulus of rigidity is
\[ G = \frac{\frac{M}{8\pi \frac{7\pi}{64} D^5 \omega_R}} {\omega_R} \text{ or} \]
\[ G = \frac{s}{2.25 \, \omega_R} \]

If we assume instead that the shearing stress \( s \) prevails at the equator of the sphere, we obtain from Eqs. (6) and (7)
\[ G = \frac{s}{3 \, \omega_R} \]
which should be a lower limit of \( G \).

In the two-dimensional calculation (§ 41) we obtained the following expression for \( G \)
\[ G = \frac{\tau_0}{2 \omega_0} \]
which should be an upper limit of \( G \).

Thus, the value of \( G \) obtained from Eq. (8) lies between the two limits, as expected.

§ 43. Practical Application.

The formula, Eq. (8), when applied to some vane tests described in § 8, gives the following average values of \( G \):
\[
\begin{array}{ccc}
0.5 \text{ kg/cm}^2 & \text{at Bocksjön} & (§ \, 8:11) \\
1 \rightarrow & \text{Hagalund} & (§ \, 85) \\
3 \rightarrow & \text{Bromma} & (§ \, 82) \\
15 \rightarrow & \text{The Lidan River} & (§ \, 83)
\end{array}
\]

The result obtained at Hagalund (\( G = 1 \text{ kg/cm}^2 \)) is remarkable, as \( G \) calculated from the loading tests on the same site mentioned in § 85 (1) is about 5 kg/cm². The discrepancy between the \( G \)-values may indicate that the vane causes some disturbance of the clay in spite of the thinness of its wings, or that the stress distribution prior to rupture is not uniform. The latter cause, however, does not seem likely, as tests with two and four wings (§ 35) have given similar values of \( G \). (Dynamic tests on samples from Hagalund also
deserve attention, as they show values of $G$ of 3 to 12 kg/cm$^2$.) Another explanation of the discrepancy may be that the clay in the horizontal direction is softer than in the vertical direction.

A large angle of rotation of the vane ($\omega_R$) before rupture implies a large deformation of the clay before rupture. Then a large deformation before rupture is also likely if the soil in question is loaded by an embankment, by excavation, etc. In the vane tests described in § 8, the value of $\omega_R$ at rupture was generally 2 to 5 degrees. Considerable deviations from these values may occur, as has been shown by the vane tests in morainic clay at Norrtälje (not described in this report), in which rupture did not occur until $\omega_R$ reached 14 to 15 degrees. The values of $\omega_R$ obtained from tests in saturated silty clay, at Mo i Rana in Norway (not described in this report), were also quite large.

§ 5. Calculation of the Stress Distribution Across the Surface of Rupture at the Moment of Rupture.

The surface of rupture produced during the rotation of a vane was expected to be of circular cross-section, as this seemed to be the only way in which the deformation could occur. The correctness of this assumption is shown, with satisfying accuracy, by the test described in § 31.

In the present section we shall calculate the stress distribution across the circular surface of rupture at the moment of rupture. The calculations are made for clay only. (A corresponding analysis for a non-cohesive material is easily carried out by using Kötter's equation.)

The clay is considered as a two-phase system consisting of a solid phase, the grain skeleton having a true cohesion $c$ and an internal friction $\phi$, and a fluid phase, the pore water. The process is assumed to take place without flow of pore water, and thus without volume change of the elements under consideration, at the surface of rupture. Further, the height of the vane is assumed to extend to infinity.

The calculation is based on a paper by N. Carrillo (13), in which he determines the stress distribution across the surface of rupture in clay. As use is made of an equation in Carrillo's paper an account is first given of the paper, in order to make it possible to follow the course of the calculations without resorting to Carrillo's paper.

Consider the stresses in a small volume element of clay (Fig. 37), in which $ds$ is an element of the surface of rupture, and $0$ its centre of curvature. Equilibrium of the element requires

$$\begin{align*}
\frac{\partial n'}{\partial r} - \frac{1}{r} \frac{\partial t'}{\partial \alpha} + \frac{n' - m'}{r} - \gamma \cos \alpha &= 0 \\
\frac{1}{r} \frac{\partial m'}{\partial \alpha} - \frac{\partial t'}{\partial r} - \frac{2t'}{r} + \gamma \sin \alpha &= 0
\end{align*}$$

46
in which \( m', n', \) and \( t' \) are the total stresses (including the effects of both phases).

If \( u \) is the pore water pressure, we obtain the following stresses \( m, n, \) and \( t \) in the solid phase
\[
\begin{align*}
    m &= m' - u \\
n &= n' - u \\
t &= t'
\end{align*}
\]
Substituting these expressions in the equations of equilibrium, we obtain, for the solid phase,
\[
\begin{align*}
    \frac{\partial n}{\partial r} + \frac{\partial u}{\partial r} - \frac{1}{r} \frac{\partial t}{\partial \alpha} + \frac{1}{r} \frac{m}{r} - \gamma \cos \alpha &= 0 \\
    \frac{1}{r} \frac{\partial m}{\partial \alpha} + \frac{1}{r} \frac{\partial u}{\partial \alpha} - \frac{\partial t}{\partial r} - \frac{2t}{r} + \gamma \sin \alpha &= 0
\end{align*}
\]
In rupture, according to Coulomb's law, Mohr's circle is tangent to the critical envelope (Fig. 38), and, as can be seen directly from the figure,
\[
\begin{align*}
    n &= (t - c) \cot \Phi \\
m &= n + 2t \tan \Phi
\end{align*}
\]
Differentiating these equations, we obtain

\[
\frac{\partial n}{\partial \tau} = \frac{\partial t}{\partial \tau} \cot \Phi
\]

\[
\frac{\partial n}{\partial \alpha} = \frac{\partial t}{\partial \alpha} \cot \Phi
\]

\[
\frac{\partial m}{\partial \alpha} = \frac{\partial t}{\partial \alpha} (\cot \Phi + 2 \tan \Phi)
\]

Introducing these values into the equations of equilibrium of the solid phase, we find

\[
\begin{align*}
\frac{\partial t}{\partial \tau} \cot \Phi + \frac{\partial u}{\partial \tau} - \frac{1}{r} \frac{\partial t}{\partial \alpha} - \frac{2t \tan \Phi}{r} - \gamma \cos \alpha &= 0 \\
\frac{1}{r} \frac{\partial t}{\partial \alpha} (\cot \Phi + 2 \tan \Phi) + \frac{1}{r} \frac{\partial u}{\partial \alpha} + \frac{\partial t}{\partial \tau} - \frac{2t}{r} + \gamma \sin \alpha &= 0
\end{align*}
\]

Eliminating \( \frac{\partial t}{\partial \tau} \), we finally obtain the required equation

\[
\frac{\partial t}{\partial \alpha} = 2t \tan \Phi - \gamma \tau \sin \Phi \sin (\alpha - \phi) - \frac{\partial u}{\partial \alpha} \sin \Phi \cos \Phi - \tau \frac{\partial u}{\partial \tau} \sin^{2} \Phi
\]

which, if \( u = 0 \), becomes identical with Kötter's equation.

For a vertical vane, \( \gamma \) can be disregarded. If the vane is not vertical, \( \gamma \) can also be disregarded in consequence of its slight effect in comparison with the forces produced by the vane. Thus, Eqs. (1) and (2) are transformed into

\[
\begin{align*}
\frac{\partial t}{\partial \tau} \cot \Phi + \frac{\partial u}{\partial \tau} - \frac{1}{r} \frac{\partial t}{\partial \alpha} - \frac{2t \tan \Phi}{r} &= 0 \\
\frac{\partial t}{\partial \alpha} &= 2t \tan \Phi - \frac{\partial u}{\partial \alpha} \sin \Phi \cos \Phi - \tau \frac{\partial u}{\partial \tau} \sin^{2} \Phi
\end{align*}
\]

Thus far we have followed Carrillo's paper.
Now the solid phase is assumed to behave like an elastic material following a modified Hooke's law. Consider a small cube of the solid phase (Fig. 39), which is subjected to the principal stresses $p_1$, $0$, and $p_3$ on condition that the unit elongation $\varepsilon_2 = 0$. If

\[ E_c = \text{the modulus of compression} \]
\[ E_s = \text{the modulus of swelling} \]
\[ \mu = \text{Poisson's ratio (equal for compression and swelling)} \]

the unit elongations are

\[
\begin{align*}
\varepsilon_1 &= \frac{p_1}{E_c} + \frac{\mu}{E_s} p_3 \\
\varepsilon_2 &= -\mu \left( \frac{p_1}{E_c} - \frac{p_3}{E_s} \right) = 0 \\
\varepsilon_3 &= -\frac{\mu}{E_c} p_1 - \frac{p_3}{E_s}
\end{align*}
\]

Adding, we obtain the relative volume change of the small cube

\[ \varepsilon_1 + \varepsilon_2 + \varepsilon_3 = (1 - \mu) \left( \frac{p_1}{E_c} - \frac{p_3}{E_s} \right) = 0 \]

From this reasoning it follows that, during a plane deformation, without any volume change, the middle principal stress is zero. This has also been found by A. W. Skempton (14).

We now revert to Fig. 38, and let $p$ be the horizontal pressure in the solid phase prior to a vane test. At the moment of rupture, assuming no volume change and a plane deformation, a Mohr's circle is developed, in which the principal stresses $\sigma_1$ and $\sigma_3$ satisfy the equation

\[
\frac{\sigma_1 - p}{E_c} = \frac{p - \sigma_3}{E_s} = 0 \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (3)
\]
Fig. 40. Variation of pore water pressure across the surface of rupture.

From this we conclude that the same Mohr circle holds good across the whole surface of rupture, so that \( t \) is also constant across this surface. Consequently, Eq. (2 a) is transformed into

\[
0 = 2 t - \frac{\partial u}{\partial \alpha} \cos^2 \phi - r \frac{\partial u}{\partial r} \sin \phi \cos \phi \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (4)
\]

Now consider Eq. (1 a). We substitute

\[
\frac{\partial t}{\partial r} = 0
\]

This assumption seems likely. (Assuming, for instance, a state of equilibrium in the clay close to and outside the surface of rupture, with sliding in concentric circles, the above assumption is exact.) Eq. (1 a) is then transformed into

\[
\frac{\partial u}{\partial r} - \frac{2 t \tan \phi}{r} = 0
\]

Substituting into Eq. (4), we obtain

\[
0 = 2 t - \frac{\partial u}{\partial \alpha} \cos^2 \phi - 2 t \sin^2 \phi
\]

\[
\frac{\partial u}{\partial \alpha} = 2 t
\]

\[
u = 2 t \alpha + \nu_0
\]
The variation in pore water pressure is shown in Fig. 40. In order to eliminate the influence of pore water flow caused by the pressure variations, a vane test should not be carried out too slowly. Compare the tests run after the test at a constant load, shown in Fig. 27.

§ 6. Calculation of the Shear Strength.

In accordance with the results described above, the shear strength is calculated on the basis of the following assumptions:

The surface of rupture is a circular cylinder surrounding the vane. The diameter \((D)\) and the height \((H)\) of this cylinder are equal to those of the vane.

The stress distribution at the maximum torsional moment \((M_{\text{max}})\) is uniform across the whole surface of the cylinder, including its end surfaces.

The friction in the borer is neglected.

The torsional moment exerted by the clay upon the shaft of the vane is disregarded. (This applies to a Type I borer. In a Type II borer, the shaft runs in grease in the protective tube.)

The moment required to mobilize the shear strength \((s)\) of the clay is:

\[
M_{\text{max}} = s \left( \pi DH \frac{D}{2} + 2 \frac{\pi D^2}{4} \frac{2}{3} \frac{D}{2} \right)
\]

and, if \(H = 2D\)

\[
s = \frac{6}{7} \frac{M_{\text{max}}}{\pi D^3} = \frac{M_{\text{max}}}{C}
\]

where \(C\) is a constant.

The dimensions and the values of \(C\) for the three standard vanes are given in Table 3.

In addition, this table contains a column for \(s_{\text{max}}, \) i.e. the greatest shear strength that can be measured with each vane. These values correspond to a torsional moment of 600 kg-cm, for which the torsional system of the borer is designed.

Table 3. Standard vane sizes, constants, and maximum measurable strengths.

<table>
<thead>
<tr>
<th>Vane</th>
<th>C</th>
<th>(s_{\text{max}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>D cm</td>
<td>H cm</td>
<td>cm³</td>
</tr>
<tr>
<td>8.0</td>
<td>16.0</td>
<td>1876</td>
</tr>
<tr>
<td>6.5</td>
<td>13.0</td>
<td>1006</td>
</tr>
<tr>
<td>5.5</td>
<td>11.0</td>
<td>610</td>
</tr>
</tbody>
</table>
With the instrument of Type II, the torsional moment is obtained on the basis of a calibration of the torsion bar.

With the instrument of Type I, the torsional moment is calculated from the readings of the spring balances. When loaded, the spring balances extend, causing the moment arm to vary with the load. A correction for this variation is easily made. With the notations given in Fig. 41, the torsional moment is:

\[ M = (P_1 + P_2) A \cos \alpha \]
The factor \( \cos \alpha \), which varies with the load only, can be determined experimentally for different loads.

By using the results of the tests with vanes of different heights (§ 36), it is possible to distinguish the moments exerted by the clay on the envelope surface from the moment exerted on the end surfaces and the vane shaft, including the friction in the borer.

The difference between the moment obtained by the 300 mm vane and that obtained by the 200 mm vane equals the moment exerted on an envelope surface 100 mm in height. This is also the case as regards the difference between the moments obtained by the 200 mm vane and that obtained by the 100 mm vane. The average of these differences is shown in Fig. 42. From these values the shear strength has been calculated, and in Fig. 43 the result is compared with the average strength values obtained by means of the different vanes. It is seen from the drawing that the difference is small, and this shows that the assumption of a uniform stress distribution across the end surfaces is perfectly permissible.

The moment \( M_e \) exerted by the clay on the end surfaces and the vane shaft, including the friction in the borer, can be estimated. If \( M_1, M_2, \) and \( M_3 \) are the total maximum moments obtained with vanes 100, 200, and 300 mm in height, then
\[ M_0 = 2M_1 - M_2 \]

or \[ M_0 = \frac{3M_1 - M_3}{2} \]

or \[ M_0 = 2\left(\frac{3}{2}M_2 - M_3\right) = 3M_2 - 2M_3 \]

\[ M_e \] has been calculated in accordance with these three possibilities, and the average values thus found are shown in Fig. 42. In spite of the great scattering, a curve has also been drawn. For comparison, an imaginary moment exerted by fully mobilized shearing resistance on the end surfaces, is also shown (dash lines). The \[ M_e \] curve is situated to the left of the imaginary moment curve, thus showing that the real moment exerted by the clay on the end surfaces is smaller than the moment assumed in the calculation, although the moments exerted by the clay on the shaft and by the friction in the apparatus are also included in the \[ M_e \] curve. Consequently, the assumption of a uniform stress distribution across the end surfaces seems to result in strength values on the safe side.

The shear strength calculated in the simple manner described in this section is not likely to involve any errors of practical importance. As seen in § 8, the strength values check fairly well without applying a calibration factor as used by Skempton (10).

§ 7. Interpretation of Test Results in Practice.

The general shape of a moment curve obtained in a vane test is shown in Fig. 44. The curve rises with the angle of rotation, first rectilinearly, then gradually passing into a curved shape, and finally reaching a maximum value \( M_{\text{max}} \), after which it falls. If the rotation is continued, the clay is remoulded, and the curve asymptotically approaches a minimum value \( M_{\text{remoulded}} \).

\[ \text{Angle of twist} \]

\[ \text{Angle of rotation of vane} \]

\[ \text{Angle of rotation of instrument (Time)} \]

\[ M_{\text{max}} \]

\[ M_{\text{remoulded}} \]

Fig. 44. General shape of a curve obtained from a vane test.
The angle of twist of the torsion system of the borer can be determined experimentally for different numbers of extension rod sections. Thus, we can trace a curve representing the angle of twist as a function of the torsional moment, see Fig. 44. The horizontal distance between this curve and the test curve represents the angle of rotation of the vane, which can be measured in this way.

This angle bears a definite relation to the angle of shearing strain in the clay (§ 4), and though it can be measured only approximately, it may be useful, e.g. for determining the elastic properties of the soil.

For interpreting the test curves, use is made of a special gauge shown in Fig. 45. The gauge is furnished with four vertical scales on a transparent plate. The left-hand scale shows the torsional moment, and the others indicate the shear strength for the three standard vanes. If a standard vane has been used, the paper slip with the test curves can be pulled through the gauge, and the shear strength can be read off directly. If a special vane, i.e. not a standard vane, has been used, the moment is read off, and the shear strength is obtained by dividing the moment by the vane constant. The figures referring to the interpreted curve in Fig. 45 express: 0.20 = shear strength in kg/cm², 0.020 = remoulded shear strength in kg/cm², 10 = sensitivity, 2:3.0 = number of the test (borehole: depth).

If the graph is also to be interpreted with respect to the angle of rotation of the vane, the strength gauge is placed on a plate, to which a ruler is fastened (Fig. 46). The ruler is adjustable, and its slope corresponds to the slope of the angle-of-twist curve varying with the number of extension rod sections. The paper slip can be pulled through the strength gauge and below the ruler, (see Fig. 46), so as to trace the actual angle-of-twist curve. Then the angle of rotation of the vane can be measured with a horizontal scale placed between the two
shear strength scales on the right-hand side of the strength gauge. The angle of rotation of the vane on the test graph shown below the ruler has been measured at the peak value of the moment and found to be 6°. (The figures shown on the angle scale are incorrect.)

§ 8. Comparison between Shear Strength Values Obtained by Vane Tests, by Calculations from Slides, and by Laboratory Investigations of Extracted Samples.

§ 81. Sampler Used, Laboratory Investigations, and Stability Computations.

Shear strength values obtained by vane tests, by calculations from slides, and by laboratory investigations of extracted samples are compared in what follows.

All samples, with only a few exceptions pointed out below, were taken by a piston sampler (11) with a liner and a stationary piston. Its area ratio (defined as the ratio of the volume of displaced soil to the volume of the sample) is 90 per cent, and the cutting edge angle is 30°. It might appear, perhaps, that the area ratio is very high and that the cutting edge angle is very obtuse. Nevertheless, as will be shown later on (§ 86), by comparing the results of tests on samples taken by this sampler with the results of tests on samples taken by a very thin-walled sampler, the former sampler seems to work fairly well.
Fig. 47. Vane test results obtained at Bromma, together with laboratory test results and the shear strength calculated from slides.

The laboratory shear strength investigations were generally made as unconfined compression tests and cone tests.

The unconfined compression tests were run at a constant rate of stress increase varying from 0.0005 to 0.013 kg/cm² min. The use of different rates is due to the circumstance that the tests were carried out through a period of many years, during which the standard rate used in the laboratory was increased. The increase in the rate does not seem to affect the tests results appreciably, as was shown by tests.

The cone tests were made according to the method used in Sweden (11, 12).

The stability computations for determining the shear strength from slides were made in accordance with the circular arc method with $\phi = 0$. The critical circle was not determined for each slide, but several circles were tried, and the greatest shear stress thus found cannot be appreciably smaller than the stress in the critical circle. For the different circles we calculated a factor of safety with respect to shear strength ($F_s$). This factor was equal to the quotient of the average shear strength ($s_{av}$), as determined by vane tests, and the requisite shear strength ($s_{re}$), as obtained from stability computations. The calculation of $s_{av}$ was carried out without regard to the higher shear strength in dry crusts. It is assumed that a higher shear strength in the dry crust balances the effect of tension cracks, so that the shear strength of the underlying soft soil is equal
Fig. 48. Plan of the slide area at the Lidan River.

to that of the dry crust. The computations were further made for low water in the rivers and canals affecting the slides (except where the real water level at the time of the slide is known).

§ 82. Tests No. I at Bromma.

At the test site at Bromma, where some of the tests described above were carried out, borings had previously been made (Plate 1; soil data in Table 1). At the foundation for a hangar (No. III in Plate 1) a few slides occurred, showing that the shear strength had been reached. It was found to average 0.9 t/m² in the upper clay layer.
The results of the vane tests, averages from 100, 200, and 300 mm high vanes (§ 36), are shown in Fig. 47, together with the laboratory test results for the borehole B and the strength calculated from the slides. Only two vane tests for measuring the remoulded strength of the clay were run, and the results of these tests are also shown in Fig. 47.

As is seen from Fig. 47, the factor of safety is about 1.0 according to the vane test results, while it is about 0.7 according to the compression test results and about 0.5 according to the cone test.

§ 83. Tests No. I at the Lidan River.

At the Lidan River a large slide occurred in 1946 (15). The western bank of the river failed, causing about half a million m$^3$ of soil to move towards the river.

A plan of the slide area is shown in Fig. 48. The section of borings marked out in the plan is shown in Plate 3, and some soil data obtained from the boreholes Nos. 1 and 2 are given in Table 4.

As has been found from the borings, the soil, with the exception of the uppermost sand layer, consist of clay, the lower stratum being very sensitive (quick clay). Vane tests were run in three boreholes, Nos. 1, 2, and 13. The vane strength values in these boreholes are approximately equal and vary in a similar manner with the depth. The average result has been used for the stability analysis, and is shown in Plate 3 at 180 m on the scale of length. The original soil profile at the river-bank is traced very approximately because of the lack of information. It is not known how the shear strength varied near the original slope, but two conceivable borderline cases are shown in Plate 3, viz. horizontal equal strength lines, and equal strength lines parallel to the slope. The stability computations have been made for both cases (the $F_s$ and $s_{av}$ values in Plate 3 refer to the horizontal equal strength lines).

As is seen from Plate 3, the factor of safety of the original slope seems to have been something between 0.77 and 1.34, according to the vane tests.

The corresponding factors obtained from the unconfined compression test and the cone test seem to be about 0.4 and 0.6 respectively, showing these strength values to be much too small.

§ 84. Tests at Väsby.

At Väsby, near Stockholm, the Institute is running various field tests. Extensive soil exploration has been carried out in this place, including vane tests. At the laboratory, among other tests, unconfined compression tests and cone tests have been made. Shear strength values obtained from these tests are compared in Fig. 49 (borehole No. 1) and Fig. 50 (borehole No. 2). Some soil data are given in Table 5. The boreholes for the vane tests were located at the distance of one metre from those used for extracting the samples for the laboratory investigations.
Table 4. Soil data from the site of the slide at the Lidan River.

<table>
<thead>
<tr>
<th>Bore-hole No.</th>
<th>Sample from el. m</th>
<th>Classification</th>
<th>Unit weight t/m³</th>
<th>Porosity %</th>
<th>Water content %</th>
<th>Liquid limit %</th>
<th>Plastic limit %</th>
<th>Sensitivity (cone test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>63.0</td>
<td>Fine sand</td>
<td>1.93</td>
<td>44</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>62.0</td>
<td>Fine sand with layers of clay</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>61.0</td>
<td>Clay with layers of fine sand</td>
<td>1.81</td>
<td>51</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>81</td>
</tr>
<tr>
<td>60.0</td>
<td>Clay</td>
<td>1.02</td>
<td>62</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>61</td>
</tr>
<tr>
<td>59.0</td>
<td>Fine sand</td>
<td>1.62</td>
<td>63</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>41</td>
</tr>
<tr>
<td>58.0</td>
<td></td>
<td>1.60</td>
<td>64</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>47</td>
</tr>
<tr>
<td>57.0</td>
<td></td>
<td>1.61</td>
<td>65</td>
<td>--</td>
<td>--</td>
<td>70</td>
<td>23</td>
<td>39</td>
</tr>
<tr>
<td>56.0</td>
<td></td>
<td>1.56</td>
<td>66</td>
<td>65</td>
<td>58</td>
<td>70</td>
<td>23</td>
<td>39</td>
</tr>
<tr>
<td>55.0</td>
<td></td>
<td>1.55</td>
<td>67</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>25</td>
</tr>
<tr>
<td>54.0</td>
<td></td>
<td>1.64</td>
<td>61</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>43</td>
</tr>
<tr>
<td>53.0</td>
<td></td>
<td>1.62</td>
<td>62</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>35</td>
</tr>
<tr>
<td>52.0</td>
<td></td>
<td>1.62</td>
<td>62</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>25</td>
</tr>
<tr>
<td>51.0</td>
<td></td>
<td>1.61</td>
<td>63</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>92</td>
</tr>
<tr>
<td>50.0</td>
<td></td>
<td>1.64</td>
<td>64</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>174</td>
</tr>
<tr>
<td>49.0</td>
<td></td>
<td>1.60</td>
<td>64</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>&gt;540</td>
</tr>
<tr>
<td>48.0</td>
<td></td>
<td>1.64</td>
<td>61</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>8</td>
</tr>
<tr>
<td>47.0</td>
<td></td>
<td>1.62</td>
<td>62</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>&gt;430</td>
</tr>
<tr>
<td>46.0</td>
<td></td>
<td>1.59</td>
<td>64</td>
<td>65</td>
<td>58</td>
<td>25</td>
<td>--</td>
<td>&gt;330</td>
</tr>
<tr>
<td>45.0</td>
<td></td>
<td>1.50</td>
<td>70</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>&gt;100</td>
</tr>
<tr>
<td>44.0</td>
<td></td>
<td>1.64</td>
<td>61</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>&gt;490</td>
</tr>
<tr>
<td>43.0</td>
<td></td>
<td>1.60</td>
<td>58</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>&gt;480</td>
</tr>
<tr>
<td>42.0</td>
<td></td>
<td>1.67</td>
<td>59</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>273</td>
</tr>
<tr>
<td>41.0</td>
<td>Clay with layers of fine sand</td>
<td>1.72</td>
<td>65</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>123</td>
</tr>
<tr>
<td>57.0</td>
<td>Fine sand</td>
<td>1.98</td>
<td>41</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>55.5</td>
<td>Fine sand with layers of clay</td>
<td>2.04</td>
<td>37</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>80</td>
</tr>
<tr>
<td>55.0</td>
<td>Clay with layers of fine sand</td>
<td>1.58</td>
<td>65</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>28</td>
</tr>
<tr>
<td>54.0</td>
<td></td>
<td>1.63</td>
<td>62</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>53.0</td>
<td>Clay</td>
<td>1.61</td>
<td>63</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>34</td>
</tr>
<tr>
<td>52.0</td>
<td></td>
<td>1.64</td>
<td>61</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>28</td>
</tr>
<tr>
<td>51.0</td>
<td></td>
<td>1.58</td>
<td>65</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>33</td>
</tr>
<tr>
<td>50.0</td>
<td></td>
<td>1.68</td>
<td>59</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>7</td>
</tr>
<tr>
<td>49.0</td>
<td></td>
<td>1.62</td>
<td>62</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>220</td>
</tr>
<tr>
<td>48.0</td>
<td>Clay with layers of fine sand</td>
<td>1.87</td>
<td>47</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>16</td>
</tr>
<tr>
<td>47.0</td>
<td>Clay</td>
<td>1.68</td>
<td>62</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>&gt;294</td>
</tr>
<tr>
<td>46.0</td>
<td></td>
<td>1.62</td>
<td>62</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>&gt;412</td>
</tr>
<tr>
<td>45.0</td>
<td></td>
<td>1.61</td>
<td>63</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>&gt;190</td>
</tr>
<tr>
<td>44.0</td>
<td></td>
<td>1.66</td>
<td>60</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>&gt;336</td>
</tr>
<tr>
<td>43.0</td>
<td></td>
<td>1.67</td>
<td>59</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>&gt;546</td>
</tr>
<tr>
<td>42.0</td>
<td></td>
<td>1.67</td>
<td>59</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>380</td>
</tr>
<tr>
<td>41.0</td>
<td></td>
<td>1.64</td>
<td>61</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>&gt;440</td>
</tr>
<tr>
<td>40.0</td>
<td></td>
<td>1.68</td>
<td>59</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>&gt;108</td>
</tr>
<tr>
<td>39.0</td>
<td></td>
<td>1.65</td>
<td>61</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>170</td>
</tr>
<tr>
<td>38.0</td>
<td></td>
<td>1.68</td>
<td>59</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>73</td>
</tr>
<tr>
<td>37.0</td>
<td>Clay with layers of fine sand</td>
<td>1.70</td>
<td>58</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>67</td>
</tr>
<tr>
<td>36.0</td>
<td></td>
<td>1.78</td>
<td>53</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>66</td>
</tr>
<tr>
<td>35.0</td>
<td></td>
<td>1.76</td>
<td>54</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>103</td>
</tr>
</tbody>
</table>
§ 85. Tests at Hagalund.

At Hagalund, near Stockholm, loading tests on clay were carried out in 1944 by S. Odenstad (1). The loading tests were made at the bottom of nine pits, 1.1 m deep. Four samples for laboratory investigations were extracted from the clay in each pit. The samples were taken 1.15—1.50 m below the soil surface, i.e. from the same clay as that affected by the loading tests. The shear strength of the clay was determined by laboratory tests (unconfined compression tests and cone tests) and by calculation from the loading test results.

Two vane tests, at 1.2 and 1.5 m below the soil surface, were run in each of the ten boreholes situated as shown on the plan in Fig. 51. All results are compared in this diagram which also gives some average soil data. The laboratory test results are shown for each loading test, and are plotted from the top to the bottom in the same sequence as that in which the samples were extracted. The vane results are shown between the loading test results in a manner corresponding to the situation of these borings on the plan. At the bottom of the figure the average shear strength values are also shown according to the different test methods.
Fig. 50. Vane test results obtained from the borehole No. 2 at Väsby, together with laboratory test results.

As is seen from Fig. 51, the vane results are closely in agreement with the loading test results, while the unconfined test results are a little too small, and the cone test results too great; the factors of safety being 1.00, 0.85, and 1.30 respectively.

§ 86. Tests at Agnesberg.

For calibration of a sounding apparatus, samples had previously been extracted at Agnesberg, on the Göta River, in southern Sweden, and submitted to direct shear tests, unconfined compression tests, and cone tests.

Vane tests were now made, and some new samples were also extracted from new boreholes sunk close to the earlier boreholes. The new samples were submitted to consolidated-undrained direct shear tests and consolidated-undrained triaxial tests under a pressure equal to the overburden pressure in the soil, as determined from the unit weights and the hydrostatic uplift. The results of the earlier tests and the new tests are shown in Fig. 52. Some soil data are given in Table 6.
Table 5. Soil data from Väsb"y.

<table>
<thead>
<tr>
<th>Borehole No.</th>
<th>Sample from depth m</th>
<th>Classification</th>
<th>Unit weight t/m³</th>
<th>Porosity %</th>
<th>Water content %</th>
<th>Liquid limit %</th>
<th>Plastic limit %</th>
<th>Sensitivity (vane test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0 Muddy clay</td>
<td></td>
<td>1.37</td>
<td>112</td>
<td>132</td>
<td>44</td>
<td>42</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td></td>
<td>1.31</td>
<td>131</td>
<td>126</td>
<td>42</td>
<td>42</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td></td>
<td>1.39</td>
<td>112</td>
<td>12</td>
<td>42</td>
<td>42</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>Clay</td>
<td>1.40</td>
<td>72</td>
<td>97</td>
<td>42</td>
<td>42</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td></td>
<td>1.45</td>
<td>71</td>
<td>93</td>
<td>105</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.0</td>
<td></td>
<td>1.45</td>
<td>71</td>
<td>96</td>
<td>30</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7.0</td>
<td></td>
<td>1.45</td>
<td>71</td>
<td>96</td>
<td>30</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8.0</td>
<td></td>
<td>1.48</td>
<td>68</td>
<td>83</td>
<td>15</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9.0</td>
<td></td>
<td>1.52</td>
<td>67</td>
<td>77</td>
<td>15</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10.0</td>
<td></td>
<td>1.54</td>
<td>66</td>
<td>80</td>
<td>20</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11.0</td>
<td></td>
<td>1.55</td>
<td>72</td>
<td>92</td>
<td>25</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12.0</td>
<td></td>
<td>1.51</td>
<td>68</td>
<td>87</td>
<td>25</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

1 Approximate. The tests run on samples from another borehole.

As is seen from Fig. 52, the strength values obtained from the direct shear test and the compression test are very low, especially at great depths. In order to find out whether this is due to a disturbance of the clay caused by the sampler, new samples were extracted by two other samplers.

The sampler used for the earlier borings had an area ratio of 90 per cent and a cutting edge angle of 30°. The first new samples were taken by a similar sampler provided with a sharp cutting edge (its lower part, 7 mm, had an angle of 15° and the upper part, 7°). The other new samples were taken by a very thin-walled piston sampler, area ratio 13.8 per cent and cutting edge angle 7.5°.

Unconfined compression tests and cone tests were run on these samples. The results of these tests, together with the results of the corresponding earlier tests
and the vane tests, are shown in Figs. 53 and 54. It is seen from these figures that the new results differ very little from those obtained before. This shows that the sampler disturbance is not the most important cause of the great difference between the unconfined compression tests and the direct shear tests on the one hand, and the vane tests on the other.
Table 6. Soil data from Agnesberg.

<table>
<thead>
<tr>
<th>Sample from depth m</th>
<th>Classification</th>
<th>Unit weight t/m³</th>
<th>Porosity %</th>
<th>Sensitivity (cone test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>Clay</td>
<td>1.57</td>
<td>65</td>
<td>2</td>
</tr>
<tr>
<td>2.5</td>
<td></td>
<td>1.55</td>
<td>67</td>
<td>11</td>
</tr>
<tr>
<td>3.5</td>
<td></td>
<td>1.56</td>
<td>66</td>
<td>13</td>
</tr>
<tr>
<td>4.5</td>
<td></td>
<td>1.52</td>
<td>69</td>
<td>12</td>
</tr>
<tr>
<td>5.6</td>
<td></td>
<td>1.52</td>
<td>69</td>
<td>15</td>
</tr>
<tr>
<td>6.5</td>
<td></td>
<td>1.58</td>
<td>65</td>
<td>10</td>
</tr>
<tr>
<td>7.5</td>
<td></td>
<td>1.58</td>
<td>65</td>
<td>10</td>
</tr>
<tr>
<td>8.5</td>
<td></td>
<td>1.60</td>
<td>64</td>
<td>14</td>
</tr>
<tr>
<td>9.5</td>
<td></td>
<td>1.55</td>
<td>67</td>
<td>22</td>
</tr>
<tr>
<td>10.5</td>
<td></td>
<td>1.55</td>
<td>67</td>
<td>22</td>
</tr>
<tr>
<td>11.5</td>
<td>Clay with shells</td>
<td>1.68</td>
<td>60</td>
<td>57</td>
</tr>
<tr>
<td>12.5</td>
<td>Clay</td>
<td>1.70</td>
<td>58</td>
<td>43</td>
</tr>
<tr>
<td>13.5</td>
<td>Clay with shells</td>
<td>1.62</td>
<td>62</td>
<td>39</td>
</tr>
<tr>
<td>14.5</td>
<td>Clay</td>
<td>1.54</td>
<td>67</td>
<td>67</td>
</tr>
<tr>
<td>15.5</td>
<td></td>
<td>1.51</td>
<td>69</td>
<td>112</td>
</tr>
<tr>
<td>16.5</td>
<td></td>
<td>1.47</td>
<td>72</td>
<td>113</td>
</tr>
<tr>
<td>17.5</td>
<td></td>
<td>1.51</td>
<td>69</td>
<td>130</td>
</tr>
<tr>
<td>18.5</td>
<td></td>
<td>1.53</td>
<td>68</td>
<td>75</td>
</tr>
<tr>
<td>19.5</td>
<td></td>
<td>1.64</td>
<td>67</td>
<td>105</td>
</tr>
<tr>
<td>20.5</td>
<td></td>
<td>1.58</td>
<td>68</td>
<td>123</td>
</tr>
<tr>
<td>21.5</td>
<td></td>
<td>1.55</td>
<td>67</td>
<td>167</td>
</tr>
<tr>
<td>22.5</td>
<td></td>
<td>1.55</td>
<td>67</td>
<td>167</td>
</tr>
<tr>
<td>23.5</td>
<td></td>
<td>1.53</td>
<td>68</td>
<td>-</td>
</tr>
</tbody>
</table>

§ 87. Tests at the Säve River.

At the Säve River, in southern Sweden, a slide occurred in 1945. Borings and a stability analysis were made by C. Caldenius (16). The soil consists chiefly of clay, and its shear strength was determined by cone tests on extracted samples.

Vane tests were run in two boreholes beside the Caldenius boreholes Nos. 1 and 2, as shown in the plan, Fig. 55. The section of the borings marked out in the plan is shown in Plate 4. This plate is a copy of a section in the Caldenius monograph, to which the vane results have been added. For the stability computation, the Caldenius values of \( s_{rc} \) were used for the two circles shown in Plate 4. The values of \( s_{sv} \) are computed on the basis of the equal strength lines shown in Plate 4. The lowest factor of safety obtained from the vane tests is 0.86. According to Caldenius, the corresponding factor with respect to the cone tests is 0.88.
In 1948 a part of a boulder fill at the Bromma Airfield sank into the clay soil, causing the soil to rise in front of the fill. A plan of the area is shown in Fig. 56.

Vane tests were run in the borehole No. 3, which is situated in a section of borings investigated prior to the failure and shown in Fig. 56 and in Plate 5. Some soil data from the earlier borings are given in Table 7.

As is seen from the borings, the soil seems to be relatively homogeneous. For this reason, it was considered proper to base the stability computation on the vane results in the borehole No. 3, in spite of the distance (about 20 m) between this borehole and the fill. The lowest factor of safety obtained from the stability computation for the three circles shown in Plate 5 is 1.33. This value is uncertain owing to uncertainty of the unit weight of the fill (assumed to be 1.8 t/m$^3$).
Table 7. Soil data from borings prior to the fill failure at the Bromma Airfield.

<table>
<thead>
<tr>
<th>Borehole No.</th>
<th>Sample from el. m</th>
<th>Classification</th>
<th>Unit weight t/m³</th>
<th>Porosity %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2.7</td>
<td>Muddy clay</td>
<td>1.80</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td>1.7</td>
<td></td>
<td>1.88</td>
<td>77</td>
</tr>
<tr>
<td></td>
<td>0.7</td>
<td>Clay</td>
<td>1.40</td>
<td>74</td>
</tr>
<tr>
<td></td>
<td>-0.3</td>
<td>Clay with layers of fine sand</td>
<td>1.44</td>
<td>73</td>
</tr>
<tr>
<td></td>
<td>-1.3</td>
<td></td>
<td>1.48</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td>-2.8</td>
<td></td>
<td>1.50</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>-4.3</td>
<td></td>
<td>1.59</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>-6.3</td>
<td>Clay</td>
<td>1.56</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>2.3</td>
<td>Clayey muddy soil</td>
<td>1.69</td>
<td>89</td>
</tr>
<tr>
<td></td>
<td>1.3</td>
<td>Clayey peat</td>
<td>1.60</td>
<td>91</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>Muddy clay</td>
<td>1.32</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td>-0.7</td>
<td>Clay</td>
<td>1.41</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>-1.7</td>
<td></td>
<td>1.53</td>
<td>68</td>
</tr>
<tr>
<td></td>
<td>-2.7</td>
<td>Clay with layers of fine sand</td>
<td>1.45</td>
<td>73</td>
</tr>
<tr>
<td></td>
<td>-4.7</td>
<td>Clay</td>
<td>1.50</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>-6.7</td>
<td></td>
<td>1.50</td>
<td>70</td>
</tr>
</tbody>
</table>

By comparing the vane results with those obtained from the unconfined compression tests and the cone tests in the borehole No. 2, it is found that stability computations based on these laboratory results would give factors of safety of about 0.9 and 1.1 respectively.

§ 89. Tests No. II at the Lidan River.

On the test site at the Lidan River shown in Plate 2 (soil data in Table 2), samples had been extracted from the boreholes A and D and tested with respect to shear strength by unconfined compression tests and cone tests.

Table 8. Soil data from the borehole No. 3 at Angsö.

<table>
<thead>
<tr>
<th>Sample from el. m</th>
<th>Classification</th>
<th>Unit weight t/m³</th>
<th>Porosity %</th>
<th>Water content %</th>
<th>Liquid limit %</th>
<th>Plastic limit %</th>
<th>Sensitivity (cone test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.70</td>
<td>Clay</td>
<td>1.39</td>
<td>—</td>
<td>—</td>
<td>99</td>
<td>31</td>
<td>91</td>
</tr>
<tr>
<td>1.70</td>
<td></td>
<td>1.44</td>
<td>78</td>
<td>104</td>
<td>101</td>
<td>31</td>
<td>97</td>
</tr>
<tr>
<td>0.70</td>
<td></td>
<td>1.50</td>
<td>107</td>
<td>75</td>
<td>34</td>
<td>31</td>
<td>97</td>
</tr>
<tr>
<td>-0.30</td>
<td></td>
<td>1.44</td>
<td>73</td>
<td>103</td>
<td>99</td>
<td>25</td>
<td>31</td>
</tr>
<tr>
<td>-1.30</td>
<td></td>
<td>1.46</td>
<td>72</td>
<td>92</td>
<td>80</td>
<td>27</td>
<td>8</td>
</tr>
<tr>
<td>-2.30</td>
<td></td>
<td>1.49</td>
<td>70</td>
<td>91</td>
<td>87</td>
<td>29</td>
<td>7</td>
</tr>
</tbody>
</table>

67
Table 9. Soil data from the boreholes Nos. 2 and 3 at Bocksjön.

<table>
<thead>
<tr>
<th>Borehole No.</th>
<th>Sample from el. m</th>
<th>Classification</th>
<th>Unit weight t/m²</th>
<th>Water content %</th>
<th>Liquid limit %</th>
<th>Plastic limit %</th>
<th>Sensitivity (cone test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>8.8</td>
<td>Clay</td>
<td>1.60</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>7.5</td>
<td>Muddy clay</td>
<td>1.33</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>6.8</td>
<td>Clay</td>
<td>1.62</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>5.7</td>
<td>Clayey mud</td>
<td>1.18</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>3</td>
<td>3.7</td>
<td></td>
<td>1.28</td>
<td>110–146</td>
<td>113–168</td>
<td>37–55</td>
<td>4–5</td>
</tr>
<tr>
<td></td>
<td>2.7</td>
<td></td>
<td>1.41</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>1</td>
<td>1.7</td>
<td></td>
<td>1.36</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

1 Approximate. From borings in section 247 + 80.
In Fig. 57 these results are compared with the vane results obtained in the tests described in § 33, using a rate of rotation corresponding to a rate of loading of 0.5 t/m²/min, i.e. that rate which corresponded best to the standard rate of rotation. The vane results are similar to those obtained in the slide area (Tests No. 1) on the opposite bank of the river. The great scattering of the laboratory test results may be due to the sensitivity of the clay, which is in part extremely high, as shown by the soil data.

§ 8: 10. Tests at Angsö.

In 1946 the height of a dyke at Angsö at Lake Mälaren, partly built in 1943, was increased from about 0.5 m to about 1.5 m by adding soil masses. During this work, part of the dyke failed, so that a canal inside the dyke was pressed
together. However, the dyke and the canal were restored afterwards. A plan of
the dyke and the canal is shown in Fig. 58.

In 1948 borings were made in two sections, 232 + 20 and 232 + 60. The re­
results of these borings are shown in Plates 6 and 7 and in Table 8.

According to the vane test results, the shear strength of the clay in the upper
soil layer inside (to the left of) the dyke is higher than outside. For the most
part, this difference is probably due to the lowering of the ground-water table
inside the dyke during the period from 1946 to 1948. The stability computations
are based on the vane results obtained outside the dyke, as these results are most
likely to represent the strength of the clay in the surface of rupture at the
time of failure. The lowest factor of safety for the circles investigated is 0.85
and 1.04 in sections 232 + 20 and 232 + 60 respectively.

No samples were extracted outside the dyke, but as far as can be judged by
comparing the results obtained from the borehole No. 3, a stability computation
based on laboratory test results from representative samples would give a si­
milar result.

70
§ 8: 11. Tests at Bocksjön.

In 1948 a part of a dyke alongside a small river, at Bocksjön about 15 km north-east of Västerås, failed, causing soil masses to fill up a canal inside the dyke.

On the site shown in Fig. 59 borings were made in a section 246 + 30. Their results are shown in Plate 8 and in Table 9.

As is seen from Plate 8, the stability computations made on the basis of the vane test results show the lowest factor of safety for the circles investigated to be 1.10.

As the laboratory test results closely agree with the vane results, a stability computation based on the former results would give a similar factor of safety.
§ 8:12. Tests at Skattmansö.

At Skattmansö, about 40 km north-east of Västerås, four small slides occurred in the western bank of a canal shown in Fig. 60. The slide at section 11 + 25 occurred in 1944, and the other slides, in 1948, just after the canal had been cleared out by a machine working on the western bank.

Borings were made in one section through each slide and one beside it. The results are shown in Plates 9 to 12 and in Table 10.

In the first slide, see Plate 9, the strength values are higher in the section through the slide than in the other section. This was probably not the case.
prior to the slide. The soft soil layer in the borehole No. 2 is likely to have existed in the slide area too, but is not shown by the borings in the shifted soil in the hole No. 1. For this reason, the stability computation was based on the average vane values obtained from the borehole No. 2. In the canal, two rows of piles had been driven, see Plate 9. When the slide occurred, the piles on the left side of the canal broke. The stabilizing effect of these piles is probably very small, and is disregarded in the stability computation. The lowest factor of safety obtained is 1.05.

Fig. 58. Plan of the slide area at the Ängsö dyke.

Fig. 59. Plan of the slide area at the Bocksjön dyke.
Fig. 60. Plan of the canal at Skattmansö showing the slide areas.
Table 10. Soil data from the slide areas at Skattmansö.

<table>
<thead>
<tr>
<th>Borehole No.</th>
<th>Sample from el. m</th>
<th>Classification</th>
<th>Unit weight t/m³</th>
<th>Porosity %</th>
<th>Water content %</th>
<th>Liquid limit %</th>
<th>Plastic limit %</th>
<th>Sensitivity (cone test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.1</td>
<td>Clay</td>
<td>1.60</td>
<td>52</td>
<td>35</td>
<td>58</td>
<td>24</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>6.1</td>
<td></td>
<td>1.78</td>
<td>56</td>
<td>54</td>
<td>56</td>
<td>25</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>5.1</td>
<td></td>
<td>1.60</td>
<td>64</td>
<td>61</td>
<td>60</td>
<td>26</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>4.1</td>
<td></td>
<td>1.65</td>
<td>61</td>
<td>58</td>
<td>55</td>
<td>24</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>3.1</td>
<td></td>
<td>1.60</td>
<td>64</td>
<td>75</td>
<td>64</td>
<td>28</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>7.9</td>
<td>Muddy clay</td>
<td>1.31</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>5.7</td>
<td>Muddy peat</td>
<td>1.10</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>4</td>
<td>4.7</td>
<td>Muddy clay</td>
<td>1.83</td>
<td>—</td>
<td>141</td>
<td>155</td>
<td>57</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>3.7</td>
<td>Clay</td>
<td>1.40</td>
<td>76</td>
<td>101</td>
<td>98</td>
<td>39</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>2.7</td>
<td></td>
<td>1.50</td>
<td>70</td>
<td>87</td>
<td>64</td>
<td>25</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>1.7</td>
<td></td>
<td>1.50</td>
<td>70</td>
<td>79</td>
<td>63</td>
<td>27</td>
<td>11</td>
</tr>
<tr>
<td>6</td>
<td>7.0</td>
<td>Clay</td>
<td>1.37</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>7</td>
<td>6.4</td>
<td>Muddy peat</td>
<td>1.05</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>6.0</td>
<td>Muddy peat</td>
<td>1.01</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>Clayey mud</td>
<td>1.18</td>
<td>—</td>
<td>221</td>
<td>263</td>
<td>116</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>Muddy clay</td>
<td>1.38</td>
<td>—</td>
<td>115</td>
<td>127</td>
<td>49</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>Clay</td>
<td>1.46</td>
<td>72</td>
<td>73</td>
<td>69</td>
<td>24</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td></td>
<td>1.45</td>
<td>73</td>
<td>90</td>
<td>73</td>
<td>28</td>
<td>10</td>
</tr>
<tr>
<td>11</td>
<td>7.0</td>
<td>Clay</td>
<td>1.46</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>5.5</td>
<td>Clayey mud</td>
<td>1.16</td>
<td>—</td>
<td>221</td>
<td>217</td>
<td>67</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>Muddy clay</td>
<td>1.25</td>
<td>—</td>
<td>141</td>
<td>167</td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>12</td>
<td>4.0</td>
<td></td>
<td>1.22</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td>Clay</td>
<td>1.48</td>
<td>71</td>
<td>110</td>
<td>76</td>
<td>29</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td></td>
<td>1.41</td>
<td>75</td>
<td>104</td>
<td>79</td>
<td>28</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td></td>
<td>1.46</td>
<td>72</td>
<td>88</td>
<td>63</td>
<td>23</td>
<td>12</td>
</tr>
</tbody>
</table>

In the slide at section 15 + 35 (Plate 10) the smallest factor of safety was 1.12. The value of $s_{uv}$ was determined by comparing the results of the vane tests in the boreholes Nos. 4, 5, and 8. The latter borehole was sunk in the canal at section 16 + 00. No borings were made in the canal at section 15 + 35, but, as is seen from the boreholes Nos. 8 and 13 (Plates 11 and 12), the shear strength in the canal is generally lower than beside it. As can be seen from the borehole No. 4, a stability computation based on the unconfined compression test would result in a factor of safety which is somewhat smaller than that based on the vane test results, say 1.0. The corresponding factor based on the cone test results seems to be about 1.1.
The smallest factor of safety resulting from the slide stability computations at section 16 + 00 (Plate 11) was 1.6. The corresponding factors based on the results of the unconfined compression test and the cone test would be of the same order, say 1.8 and 1.1 respectively, as can be seen from the results obtained in the borehole No. 7.

In the slide at section 22 + 50 the smallest factor of safety resulting from the stability computations was 1.8, as shown in Plate 12. The corresponding factors based on the compression test results and the cone test results are about 0.85 and 1.4 respectively.
For a hotel building at Gothenburg, soil investigations had been carried out by the Geotechnical Section of the Swedish State Railroad Board. Samples had been extracted to a great depth (65 m) by means of a piston sampler similar to that used by the Institute. The samples had been tested with respect to shear strength by cone tests.

Vane tests were run in two boreholes. The tests were first run in each borehole to a depth of about 30 m. This was the greatest depth to which it was possible to drive the borer in the ordinary way by a jack. Later on, in one borehole (No. 1) the skin friction on the upper 30 m of the borer was eliminated by means of a casing, and the tests were continued to a depth of 50 m.

The results of the vane tests are shown in Figs. 61 and 62, together with the cone test results. Some soil data are given in Table 11. As is seen from Fig. 61, the cone test values increase with the depth to about 30 m, but from this depth on they are approximately constant to 50 m (in reality to 65 m, but this depth is not shown in the figure). The vane test values, on the other hand, increase uniformly with the depth throughout the tested depth.

<table>
<thead>
<tr>
<th>Bore-hole No.</th>
<th>Sample from depth m</th>
<th>Classification</th>
<th>Unit weight t/m³</th>
<th>Porosity %</th>
<th>Sensitivity (cone test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>Sandy clay (fill)</td>
<td>1.70</td>
<td>51</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>4.0</td>
<td>Clay</td>
<td>1.59</td>
<td>65</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>6.0</td>
<td>»</td>
<td>1.60</td>
<td>65</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>8.0</td>
<td>»</td>
<td>1.53</td>
<td>67</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>10.0</td>
<td>»</td>
<td>1.55</td>
<td>66</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>12.0</td>
<td>Sandy clay</td>
<td>1.64</td>
<td>64</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>14.0</td>
<td>Clay</td>
<td>1.62</td>
<td>64</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>16.0</td>
<td>»</td>
<td>1.57</td>
<td>64</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>18.0</td>
<td>»</td>
<td>1.59</td>
<td>65</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>20.0</td>
<td>»</td>
<td>1.63</td>
<td>65</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>22.0</td>
<td>»</td>
<td>1.64</td>
<td>62</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>24.0</td>
<td>»</td>
<td>1.60</td>
<td>62</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>26.0</td>
<td>»</td>
<td>1.62</td>
<td>64</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>28.0</td>
<td>»</td>
<td>1.62</td>
<td>63</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>30.0</td>
<td>»</td>
<td>1.59</td>
<td>64</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>32.0</td>
<td>»</td>
<td>1.57</td>
<td>64</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>34.0</td>
<td>»</td>
<td>1.60</td>
<td>65</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>36.0</td>
<td>»</td>
<td>1.62</td>
<td>65</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>38.0</td>
<td>»</td>
<td>1.62</td>
<td>64</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>40.0</td>
<td>»</td>
<td>1.65</td>
<td>64</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>42.0</td>
<td>»</td>
<td>1.60</td>
<td>63</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>44.0</td>
<td>»</td>
<td>1.63</td>
<td>65</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>46.0</td>
<td>»</td>
<td>1.63</td>
<td>63</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>48.0</td>
<td>»</td>
<td>1.63</td>
<td>64</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>50.0</td>
<td>»</td>
<td>1.64</td>
<td>64</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td>Sandy clay (fill)</td>
<td>1.72</td>
<td>48</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>4.0</td>
<td>Clay</td>
<td>1.54</td>
<td>69</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>6.0</td>
<td>»</td>
<td>1.59</td>
<td>66</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>8.0</td>
<td>»</td>
<td>1.55</td>
<td>65</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>10.0</td>
<td>»</td>
<td>1.55</td>
<td>67</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>12.0</td>
<td>»</td>
<td>1.62</td>
<td>62</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>14.0</td>
<td>»</td>
<td>1.55</td>
<td>64</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>16.0</td>
<td>»</td>
<td>1.56</td>
<td>66</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>18.0</td>
<td>»</td>
<td>1.57</td>
<td>64</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>20.0</td>
<td>»</td>
<td>1.57</td>
<td>66</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>22.0</td>
<td>»</td>
<td>1.59</td>
<td>64</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>24.0</td>
<td>»</td>
<td>1.59</td>
<td>65</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>26.0</td>
<td>»</td>
<td>1.62</td>
<td>62</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>28.0</td>
<td>»</td>
<td>1.62</td>
<td>62</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>30.0</td>
<td>»</td>
<td>1.60</td>
<td>65</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>32.0</td>
<td>»</td>
<td>1.59</td>
<td>65</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>34.0</td>
<td>»</td>
<td>1.58</td>
<td>65</td>
<td>9</td>
<td></td>
</tr>
</tbody>
</table>

At Munkedal, about 100 km north of Gothenburg, a slide occurred in 1940 on the western bank of the Örekil River (Fig. 63). A very low factor of safety (about 0.5, according to unconfined compression test results) for this river-bank was found by borings carried out after the slide. In 1947 cracks occurred in a road running parallel to the river in the vicinity of the slide area of 1940. To improve the stability, the road was lowered 2 m.

In 1949 vane tests were run in two boreholes in a section through the river bank, see Fig. 63. Samples were also extracted from boreholes beside them, and were tested in the laboratory. The results of these investigations are shown in Plate 13 and in Table 12.
The smallest factor of safety of the slope prior to excavation was computed at 1.0 on the basis of the equal strength lines traced on Plate 13 with the guidance of the vane results. (The clay extends below elevation -20, according to the neighbouring borings of 1940.)

A corresponding stability computation based on the unconfined compression test results would give a factor of safety of about 0.3, i.e. the same value as that obtained on the basis of the borings of 1940. The corresponding factor based on the cone test results seems to be about 0.9.

§ 8: 15. Tests at Hålan.

At Hålan, about 10 km south of Munkedal, soil investigations had been carried out for the main road from Uddevalla to Strömsstad. Owing to the great sensitivity of the clay, it had been difficult to obtain undisturbed samples.

Vane tests were run in one borehole. The results of these tests and the labo-
Table 12. Soil data from borings at Munkedal.

<table>
<thead>
<tr>
<th>Borehole No.</th>
<th>Sample from cl. m</th>
<th>Classification</th>
<th>Unit weight t/m³</th>
<th>Porosity %</th>
<th>Water content %</th>
<th>Liquid limit %</th>
<th>Plastic limit %</th>
<th>Sensitivity (cone test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.6</td>
<td>Clay</td>
<td></td>
<td>1.05</td>
<td>61</td>
<td>48</td>
<td>—</td>
<td>—</td>
<td>6</td>
</tr>
<tr>
<td>13.5</td>
<td></td>
<td></td>
<td>1.71</td>
<td>57</td>
<td>48</td>
<td>—</td>
<td>—</td>
<td>10</td>
</tr>
<tr>
<td>12.6</td>
<td></td>
<td></td>
<td>1.71</td>
<td>57</td>
<td>51</td>
<td>54</td>
<td>25</td>
<td>14</td>
</tr>
<tr>
<td>11.6</td>
<td></td>
<td></td>
<td>1.70</td>
<td>58</td>
<td>32</td>
<td>—</td>
<td>—</td>
<td>10</td>
</tr>
<tr>
<td>10.6</td>
<td></td>
<td></td>
<td>1.64</td>
<td>61</td>
<td>59</td>
<td>—</td>
<td>—</td>
<td>83</td>
</tr>
<tr>
<td>9.6</td>
<td>Clay and fine sand</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>8.6</td>
<td>Clay with layers of fine sand</td>
<td>1.97</td>
<td>41</td>
<td>33</td>
<td>—</td>
<td>—</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>7.6</td>
<td>Clay</td>
<td></td>
<td>1.96</td>
<td>57</td>
<td>46</td>
<td>46</td>
<td>18</td>
<td>5</td>
</tr>
<tr>
<td>6.5</td>
<td></td>
<td></td>
<td>1.71</td>
<td>57</td>
<td>46</td>
<td>—</td>
<td>—</td>
<td>9</td>
</tr>
<tr>
<td>5.6</td>
<td></td>
<td></td>
<td>1.69</td>
<td>58</td>
<td>52</td>
<td>—</td>
<td>—</td>
<td>9</td>
</tr>
<tr>
<td>4.6</td>
<td></td>
<td></td>
<td>1.68</td>
<td>59</td>
<td>56</td>
<td>—</td>
<td>—</td>
<td>83</td>
</tr>
<tr>
<td>3.6</td>
<td></td>
<td></td>
<td>1.61</td>
<td>68</td>
<td>60</td>
<td>—</td>
<td>—</td>
<td>35</td>
</tr>
<tr>
<td>2.6</td>
<td></td>
<td></td>
<td>1.63</td>
<td>62</td>
<td>59</td>
<td>60</td>
<td>25</td>
<td>28</td>
</tr>
<tr>
<td>1.0</td>
<td></td>
<td></td>
<td>1.67</td>
<td>59</td>
<td>57</td>
<td>—</td>
<td>—</td>
<td>32</td>
</tr>
<tr>
<td>0.6</td>
<td></td>
<td></td>
<td>1.76</td>
<td>54</td>
<td>45</td>
<td>—</td>
<td>—</td>
<td>38</td>
</tr>
<tr>
<td>-0.4</td>
<td></td>
<td></td>
<td>1.65</td>
<td>61</td>
<td>55</td>
<td>—</td>
<td>—</td>
<td>36</td>
</tr>
<tr>
<td>-1.4</td>
<td>Clay with layers of fine sand</td>
<td>1.80</td>
<td>52</td>
<td>34</td>
<td>—</td>
<td>—</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>-2.4</td>
<td>Clay</td>
<td></td>
<td>1.71</td>
<td>57</td>
<td>45</td>
<td>43</td>
<td>20</td>
<td>35</td>
</tr>
<tr>
<td>-3.4</td>
<td></td>
<td></td>
<td>1.81</td>
<td>51</td>
<td>46</td>
<td>—</td>
<td>—</td>
<td>37</td>
</tr>
<tr>
<td>-4.4</td>
<td></td>
<td></td>
<td>1.78</td>
<td>53</td>
<td>40</td>
<td>—</td>
<td>—</td>
<td>41</td>
</tr>
<tr>
<td>9.2</td>
<td>Clay</td>
<td></td>
<td>1.87</td>
<td>47</td>
<td>31</td>
<td>—</td>
<td>—</td>
<td>2</td>
</tr>
<tr>
<td>8.2</td>
<td></td>
<td></td>
<td>1.83</td>
<td>50</td>
<td>38</td>
<td>—</td>
<td>—</td>
<td>4</td>
</tr>
<tr>
<td>7.2</td>
<td></td>
<td></td>
<td>1.73</td>
<td>56</td>
<td>49</td>
<td>61</td>
<td>26</td>
<td>6</td>
</tr>
<tr>
<td>6.2</td>
<td></td>
<td></td>
<td>1.70</td>
<td>58</td>
<td>55</td>
<td>—</td>
<td>—</td>
<td>29</td>
</tr>
<tr>
<td>5.2</td>
<td></td>
<td></td>
<td>1.66</td>
<td>60</td>
<td>51</td>
<td>—</td>
<td>—</td>
<td>3</td>
</tr>
<tr>
<td>4.2</td>
<td></td>
<td></td>
<td>1.65</td>
<td>60</td>
<td>54</td>
<td>—</td>
<td>—</td>
<td>5</td>
</tr>
<tr>
<td>3.2</td>
<td></td>
<td></td>
<td>1.65</td>
<td>60</td>
<td>54</td>
<td>—</td>
<td>—</td>
<td>16</td>
</tr>
<tr>
<td>2.2</td>
<td></td>
<td></td>
<td>1.62</td>
<td>62</td>
<td>55</td>
<td>—</td>
<td>—</td>
<td>11</td>
</tr>
</tbody>
</table>

Table 13. Soil data from borings at Hålan.

<table>
<thead>
<tr>
<th>Sample from depth m</th>
<th>Classification</th>
<th>Unit weight t/m³</th>
<th>Porosity %</th>
<th>Sensitivity (vane test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>Silty clay</td>
<td>1.94</td>
<td>43</td>
<td>15</td>
</tr>
<tr>
<td>4.0</td>
<td>Clay</td>
<td>1.99</td>
<td>46</td>
<td>13</td>
</tr>
<tr>
<td>6.0</td>
<td></td>
<td>1.85</td>
<td>49</td>
<td>18</td>
</tr>
<tr>
<td>8.0</td>
<td></td>
<td>1.76</td>
<td>54</td>
<td>31</td>
</tr>
<tr>
<td>10.0</td>
<td></td>
<td>1.77</td>
<td>54</td>
<td>53</td>
</tr>
<tr>
<td>12.0</td>
<td></td>
<td>1.76</td>
<td>54</td>
<td>37</td>
</tr>
</tbody>
</table>
latory tests are shown in Fig. 64 and Table 13. With the instrument used, the very low remoulded strength of the clay can only be determined very approximately. The sensitivity determined by the cone test, for instance, is probably much higher.


At Hogdal, at the main road Strömstad-Svinesund in southern Sweden, vane tests were run and samples were extracted for laboratory investigations.

The samples were tested with respect to shear strength by unconfined compression tests and cone tests. The results of these tests are shown in Fig. 65, together with the vane test results. Some soil data are given in Table 14. The sensitivity of the clay obtained from cone tests and vane tests is about 10. This is a common value for Swedish clays.

§ 8: 17. Conclusions from the Comparative Tests.

A summary of the results of the tests described in § 8 concerning the stability computations is given in Table 15.

The factor of safety according to the vane test is close to unity, the maximum variations being +16 and -15 per cent and the average variation, +3 per cent (exclusive of the unknown value in the tests No I at the Lidan River).
Table 14. Soil data from borings at Hogdal.

<table>
<thead>
<tr>
<th>Sample from depth m</th>
<th>Classification</th>
<th>Unit weight t/m³</th>
<th>Porosity %</th>
<th>Water content %</th>
<th>Liquid limit %</th>
<th>Plastic limit %</th>
<th>Sensitivity (cone test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>Sandy clay</td>
<td>2.92</td>
<td>38</td>
<td>23</td>
<td>—</td>
<td>—</td>
<td>9</td>
</tr>
<tr>
<td>4.0</td>
<td>Clay</td>
<td>1.88</td>
<td>47</td>
<td>30</td>
<td>—</td>
<td>—</td>
<td>8</td>
</tr>
<tr>
<td>5.0</td>
<td>Clay</td>
<td>1.78</td>
<td>53</td>
<td>42</td>
<td>42</td>
<td>20</td>
<td>13</td>
</tr>
<tr>
<td>6.0</td>
<td>Clay</td>
<td>1.59</td>
<td>64</td>
<td>57</td>
<td>—</td>
<td>—</td>
<td>20</td>
</tr>
<tr>
<td>7.0</td>
<td>Clay</td>
<td>1.73</td>
<td>56</td>
<td>46</td>
<td>—</td>
<td>—</td>
<td>5</td>
</tr>
<tr>
<td>8.0</td>
<td>Clay</td>
<td>1.65</td>
<td>61</td>
<td>53</td>
<td>—</td>
<td>—</td>
<td>3</td>
</tr>
<tr>
<td>9.0</td>
<td>Clay</td>
<td>1.65</td>
<td>61</td>
<td>57</td>
<td>—</td>
<td>—</td>
<td>6</td>
</tr>
<tr>
<td>10.0</td>
<td>Clay</td>
<td>1.67</td>
<td>59</td>
<td>54</td>
<td>58</td>
<td>23</td>
<td>13</td>
</tr>
<tr>
<td>11.0</td>
<td>Clay</td>
<td>1.58</td>
<td>65</td>
<td>68</td>
<td>—</td>
<td>—</td>
<td>7</td>
</tr>
<tr>
<td>12.0</td>
<td>Clay</td>
<td>1.55</td>
<td>67</td>
<td>69</td>
<td>—</td>
<td>—</td>
<td>7</td>
</tr>
<tr>
<td>13.0</td>
<td>Clay</td>
<td>1.57</td>
<td>66</td>
<td>66</td>
<td>—</td>
<td>—</td>
<td>7</td>
</tr>
<tr>
<td>14.0</td>
<td>Clay</td>
<td>1.63</td>
<td>68</td>
<td>71</td>
<td>—</td>
<td>—</td>
<td>9</td>
</tr>
<tr>
<td>15.0</td>
<td>Clay</td>
<td>1.55</td>
<td>67</td>
<td>76</td>
<td>76</td>
<td>27</td>
<td>6</td>
</tr>
<tr>
<td>16.0</td>
<td>Clay</td>
<td>1.53</td>
<td>68</td>
<td>72</td>
<td>—</td>
<td>—</td>
<td>8</td>
</tr>
<tr>
<td>17.0</td>
<td>Clay</td>
<td>1.59</td>
<td>64</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>9</td>
</tr>
<tr>
<td>18.0</td>
<td>Clay</td>
<td>1.57</td>
<td>66</td>
<td>62</td>
<td>—</td>
<td>—</td>
<td>12</td>
</tr>
<tr>
<td>19.0</td>
<td>Clay</td>
<td>1.59</td>
<td>64</td>
<td>62</td>
<td>—</td>
<td>—</td>
<td>11</td>
</tr>
<tr>
<td>20.0</td>
<td>Clay</td>
<td>1.66</td>
<td>60</td>
<td>53</td>
<td>57</td>
<td>26</td>
<td>7</td>
</tr>
</tbody>
</table>

The factors of safety obtained from the unconfined compression tests in shallow slides and in clay of low sensitivity also seem to check fairly well, but in deep slides and in clay of high sensitivity they seem to be too small.

The factor of safety determined by cone tests generally seems to check fairly well. However, in deep slides in sensitive clay it seems to be too small, and in shallow slides it often seems to be too great.

The quotient of vane test results \(s_{vane}\) and the unconfined compression test results \(s_{u,c,r}\) is shown in Fig. 66 for a great number of tests (including tests at other sites than those shown in Table 15) carried out at different depths and in clays of different sensitivity. The values are grouped around the dash line starting from unity at zero depth and extending to about 3 at a depth of 20 m. Consequently, vane test results and unconfined compression test results generally are approximately equal at small depths, while at great depths the vane strength increases more rapidly than the compression strength.

The corresponding relation between vane test results \(s_{vane}\) and cone test results \(s_{cone}\) is shown in Fig. 67. The values are grouped around the dash line starting from about 0.9 at zero depth and extending to about 1.3 at a depth of 20 m. Consequently, vane test results and cone test results are generally in fairly close agreement. However, at small depths, cone results often are somewhat greater, and, at great depths, smaller, than vane results.
Fig. 66. Diagram showing the relation between vane test results ($s_{\text{vane}}$) and unconfined compression test results ($s_{u,c}$) at different depths.

Fig. 67. Diagram showing the relation between shear strengths determined by vane tests ($s_{\text{vane}}$) and by cone tests ($s_{\text{cone}}$) at different depths.
Table 15. Results of stability computations for eleven slides and one loading test.

<table>
<thead>
<tr>
<th>Test place</th>
<th>Factor of safety</th>
<th>Depth of critical circle (approx.)</th>
<th>Sensitivity from vane tests (average)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vane tests</td>
<td>Compr. tests (approx.) Cone tests (approx.)</td>
<td></td>
</tr>
<tr>
<td>Bromma I</td>
<td>1.0</td>
<td>0.7</td>
<td>0.9</td>
</tr>
<tr>
<td>The Lidan River I</td>
<td>0.77—1.34</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Hagalund</td>
<td>1.00</td>
<td>0.65</td>
<td>1.80</td>
</tr>
<tr>
<td>The Säve River</td>
<td>0.80</td>
<td>—</td>
<td>0.88</td>
</tr>
<tr>
<td>Bromma II</td>
<td>1.03</td>
<td>0.9</td>
<td>1.1</td>
</tr>
<tr>
<td>Ångsö</td>
<td>0.85</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Bocksjön</td>
<td>1.04</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Skottsmanö 11 + 25</td>
<td>1.10</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>1.05</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>1.12</td>
<td>1.0</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>1.06</td>
<td>1.0</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>1.19</td>
<td>0.85</td>
<td>1.4</td>
</tr>
<tr>
<td>Munkedal</td>
<td>1.07</td>
<td>0.5</td>
<td>0.9</td>
</tr>
<tr>
<td>Average (exclusive of test No. I at the Lidan River)</td>
<td>1.03</td>
<td>1 From the tests No. II at the Lidan River.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 From cone tests.</td>
<td></td>
</tr>
</tbody>
</table>

The following conclusions can be drawn from the tests described in this paper. The shear strength determined by vane tests equals the real strength of the clay as calculated from slides.

The shear strength determined by unconfined compression tests at small depths equals the real strength of the clay as calculated from slides, while, at great depths and in clay of high sensitivity, it is too small.

The shear strength determined by cone tests generally equals the real strength of the clay as calculated from slides; however, at small depths it often is somewhat too great, and at great depths it is too small.

From the above statements we also conclude that the more sensitive the clay, and the greater the depth (pressure) from which they are taken, the more difficult it seems to obtain undisturbed samples.


In soil investigations of stability problems it is possible to determine the shear strength of clay soils solely on the basis of vane tests. Of course, samples always have to be taken for classification tests, unit weight tests, etc., but generally a few samples are sufficient for this purpose.
Some data as to the time required for boring with the vane borer are given in Fig. 68. These values were obtained in borings with two helpers and with a vertical spacing of 1.0 m between the tests. The average shear strength of the clay varied from about 1 t/m² at small depths to about 4 t/m² at a depth of 20 m.

At small depths the requisite number of working hours approximately equals that needed for sampling under similar conditions by means of the Swedish piston sampler (11). At great depths, however, the number of hours required for the vane borer is less than that needed for the sampler, because the sampler has to be withdrawn between sampling operations, while the vane borer, after a test has been run, is driven down directly to the next depth at which a test is to be made.

Consequently, the cost of vane tests is equal to, or smaller than, the cost of taking samples. Furthermore, in vane tests, the shear strength values are obtained directly in the field. This saves cost and time for a corresponding laboratory investigation of samples.

Fig. 68. Time required for borings with a vane borer.
As the vane results can be used for rough stability calculations directly in the field, the program for a site investigation can easily be adjusted to meet the special needs of each site. Therefore, the program can often be limited on the basis of a few tests only. On the other hand, this would not be possible if only samples were taken without waiting for the laboratory results.

The most expensive part of soil investigations, the sampling operation and the laboratory investigations, can thus be reduced to a minimum.

It is easy to realize the advantages of using shear strength values which generally increase with depth more than laboratory strength values. Deep sliding surfaces are often a determining factor in stability analyses, for instance in the design of loading berms for highways.

§ 10. Summary.

Laboratory shear strength tests on clay samples extracted from boreholes often give too small strength values as compared with values obtained in stability analyses, especially when samples are taken from great depths. This may largely be due to changes in the pressure conditions during the extraction of samples.

A method for determining the shear strength of clay soils directly in the ground is described. The strength test is made by driving a vane into the soil and rotating it, while measuring the resistance to rotation. The shear strength is calculated from the torsional moment thus obtained.

Tests for determination of an appropriate rate of rotation and a suitable shape of the vane are described. The stress and strain conditions in the soil around a vane are subjected to mathematical treatment based on the results of some laboratory tests. A definite relation is found between the angle of rotation of the vane and the angle of shearing strain in the clay. This relation makes it possible to estimate the elastic properties of the soil.

Vane tests made on several sites are described, and the strength values obtained from these tests are compared with laboratory strength values relating to extracted samples and with the shear strength calculated from slides. The vane strength values are closely in agreement with the shear strength values calculated from eleven slides and one loading test, while unconfined compression test results, especially those concerning deep slides and clays of high sensitivity, are too small, and cone test results are often somewhat too great in shallow slides and too small in deep slides. Generally, vane test results and compression test results seem to agree approximately at small depths, while the former exceed the latter at great depths. Vane test results and cone test results are generally in fairly close agreement. However, cone results are often somewhat greater than vane results at small depths and smaller at great depths.

The more sensitive the clay, and the greater the depth (pressure) from which they are taken, the more difficult it seems to obtain undisturbed samples.

Finally, some data on the requisite time for boring with the vane borer are given, and some economical aspects are discussed.
Bibliography

2. CARLSON, LYMAN, Determination in situ of the shear strength of undisturbed clay by means of a rotating auger. ibid. pp. 265—270.
6. Deutsche Forschungsgesellschaft für Bodenmechanik (Degebo), Festigkeitsprüfer für die Schubfestigkeit des Baugrundes. German patent Nr 508 711 (1929).
7. SMITH, A. H. V., Some preliminary trials with the Army Operational Research Group vane apparatus. 1945. (Army Operational Research Group Memorandum Nr 540.)
8. The measurement of the shear strength of soils in the field. 1947. (ibid Report Nr 352.)
TEST SITE AT THE RIVER LIDAN

- Sounding
- Sampling
- Vane test
SECTION THROUGH THE SLIDE AREA AT THE RIVER LIDAN

Shearing strength from:
- Dashed line: Unconfined compression test
- Dotted line: Cone test
- Solid line: Vane test

Elevation

m

60
50
40
30
20
0

0 5 10 15
0 5 10 15 20
0 5 10 15 20
0 5 10 15 20

60
50
40
30
20
0
Average shearing strength from vane tests in boreholes no 1, 2, and 13

Soil surface before the slide (approximative)
Soil surface after the slide

Water level at the slide (approximative)
SECTION THROUGH THE SLIDE AREA AT THE RIVER SÄVE

Soil surface before the slide

Average shearing strength from vane tests
Shearing strength from:

- Cone test
- Vane test
- R, remoulded state

Legend for soil group symbols:

- Clay < 0.002 mm
- Silt 0.002 - 0.02
- Fine sand 0.02 - 0.2
- Sand 0.2 - 2
- Gravel 2 - 20
- Shells

II $F_s = 0.86$

I $F_s = 0.92$

THE RIVER SÄVE

m

Elevation

-10

-5

0

5

10

15

m

30

40

50 m

5 6 t/m²

s

$S_{re} = 2.02$ $S_{av} = 1.86$

$S_{re} = 2.54$ $S_{av} = 2.18$
SECTION THROUGH THE SUNKEN FILL AT BROMMA AIRFIELD

Original fill surface

Boulder fill (\( \gamma \approx 1.8 \text{ t/m}^3 \))

Natural ground level

Shearing strength from:
- Unconfined compression test
- Cone test
- Vane test
- Remoulded state
III \( F_S = 1.17 \)
I \( F_S = 1.03 \)
II \( F_S = 1.05 \)

\[ S_{av} = 0.68 \]
\[ S_{av} = 0.67 \]
\[ S_{av} = 0.76 \]

Elevation

\( S_{t/m^2} \)

\( 0.66 \)
\( 0.70 \)
\( 0.70 \)
\( 0.67 \)
\( 0.70 \)
\( 0.80 \)
\( 0.90 \)
\( 1.00 \)

\( 100 \)
\( 25 \)
\( 50 \)
\( 75 \)

\( 0 \)
\( -5 \)
\( -10 \)

0 10 20

80 m
SECTION 232+20 THROUGH THE DYKE AT ÄNGSÖ

before the slide

Rebuilt dyke

Shearing strength from:

- Vane test
- R - II, remoulded state

Average shearing strength from vane test
SECTION 232+60 THROUGH THE DYKE AT ÄNGSÖ

Shearing strength from:

- Unconfined compression test
- Cone test
- Vane test
- “R”, remoulded state
SECTION 246+30 THROUGH THE WESTERN DYKE AT BOCKSJÖN
Shearing strength from:

- Unconfined compression test
- Cone test
- Vane test
- Remoulded state

Soil surface at the rebuilding of the dyke

Soil surface before the slide

Average shearing strength from vane test

\[ s_{re} = 0.680 \quad s_{qv} = 0.780 \]

\[ s_{re} = 0.730 \quad s_{qv} = 0.804 \]

\[ s_{re} = 0.738 \quad s_{qv} = 0.843 \]
Shearing strength from:

- Unconfined compression test
- Cone test
- Vane test

Section 11 + 75

Elevation

Unconfined compression test
Cone test
Vane test

Piles 6' at L.W. ≤ 1.5 m
SECTIONS THROUGH THE

Section 15 + 35

Soil surface before the slide

I  $F_s = 1.34$

II  $F_s = 1.12$

III  $F_s = 1.13$

Shearing strength from:

- Unconfined compression test
- Cone test
- Vane test

R = Remoulded state

$\theta = 7.65$ H.W.

L.W. + 5.50

$s_{re} = 0.595$  $s_{av} = 0.8$

$s_{re} = 0.714$  $s_{av} = 0.8$

$s_{re} = 0.706$  $s_{av} = 0.8$
CANAL AT SKATTMANSÖ

Legend for soil group symbols

| Clay     | Mud              | Muddy peat |

Shearing strength from:

- Unconfined compression test
- Cone test
- Vane test
- Remoulded state

Section 15 + 50
Section 16+00

F_s = 1.18
F_s = 1.06
F_s = 1.09

Soil surface before the slide

Shearing strength from:
- Unconfined compression test
- Cone test
- Vane test

Remoulded state

+5.52 L.W. - 7.65 H.W.
Legend for soil group symbols

- Clay
- Mud
- Muddy peat

Shearing strength from:

- Unconfined compression test
- Cone test
- Vane test
- R, remoulded state

Section 16 + 25
Legend for soil group symbols

- |||| Clay
- || Mud
- || Muddy peat

Section 22 + 00

Elevation

±0 m 10 m

±0 m 10 m
Shearing strength from:

- Unconfined compression test
- Cone test
- Vane test

R --- "" --- "", remoulded state

Section 22 + 50

Soil surface before the slide

F_s = 1.21
F_s = 1.16
F_s = 1.28

\[ \gamma = 1.2 \]
Crack
Excavated soil

Original soil surface

Average shearing strength from vane test
I $F_s = 1.11$  
II $F_s = 1.07$  
III $F_s = 1.13$

SECTION THROUGH THE RIVER BANK
AT MUNKEDAL

Shearing strength from:

- Unconfined compression test
- Cone test
- Vane test
- $\text{remoulded state}$

$\pm 0.97$ Water Level 30/10-47

$s_{re} = 3.05$  $s_{av} = 3.42$

$s_{re} = 3.45$  $s_{av} = 3.71$

$s_{re} = 3.70$  $s_{av} = 4.11$
LIST OF PUBLICATIONS
FROM THE ROYAL SWEDISH GEOTECHNICAL INSTITUTE

Proceedings

Meddelanden
Nr 1. Kortfattad kompendium i geoteknik 1946 .............. 1946
2. Redogörelse för Statens geotekniska instituts verksamhet under åren 1944—1948 ......................... 1949
3. «Bra borrat — bättre byggt». Meddelande utgivet till institutets deltagande i utställningen «Bygg bättre» Nordisk Byggnadstag V ......................... 1950