ROYAL SWEDISH
GEOTECHNICAL INSTITUTE
PROCEEDINGS
No. 4

THE LANDSLIDE AT SKÖTTORP ON THE LIDAN RIVER

FEBRUARY 2, 1946

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STEN ODENSTAD

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Ivar Hæggströms
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Preface

The large landslide at Sköttorp in 1946 presented very intricate problems as to the initiation and the mechanics of the slide. Two new tools used in the borings on the site, viz. the Vane borer and the Sampler with metal foils, were still in the experimental stage. For these reasons, the investigation of the slide, which was carried out by the undersigned Institute, extended through several years.

When a still larger landslide occurred at Surte in 1950, the interest in slide questions increased further, as was shown by numerous inquiries from abroad. Therefore, it was deemed appropriate to make the results of the Sköttorp investigation known to the international public. Thus a comparison will be possible with the Surte slide, which will be treated in a following number of the Proceedings of the Institute.

The investigations were carried out by field engineers and laboratory personnel of the Institute under the guidance of Mr S. Odenstad, at that time head of the Research Department. The tentative explanations of the initiation and the mechanics of the slide were developed by Mr Odenstad, partly after discussions with colleagues at the Institute.

The report was prepared by Mr Odenstad.

Stockholm, July 1951.

ROYAL SWEDISH GEOTECHNICAL INSTITUTE

§ 1. Introduction.

During the night from February 1st to 2nd, 1946, a large landslide occurred at Sköttorp, on the left bank of the Lidan River, some 20 kilometres upstream of Lake Vänern in the west of Sweden. Before the slide the river flowed between steep clay banks cut 15 to 20 m below the level of the surrounding plain.

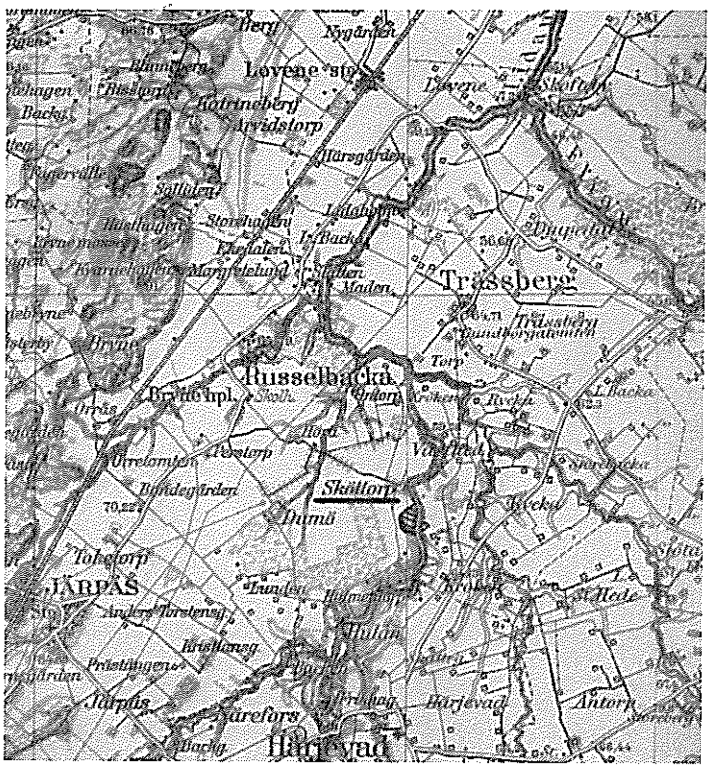

Fig. 1. Situation of site. Topographical map, sheet Nos. 42 and 43. Scale 1: 100 000.

During the slide, a mass of earth from an approximately semi-circular area of the plain, with a radius of 175 m, slipped towards the river, damming it completely. Fig. 1 shows the location of the landslide on the topographical map. Fig. 2 shows an aerial photograph of the slide area, Fig. 3 gives a plan[1], and

[1] The survey was made by Mr P. O. Fagerholm, C. E., by means of the terrestrial photogrammetric method.

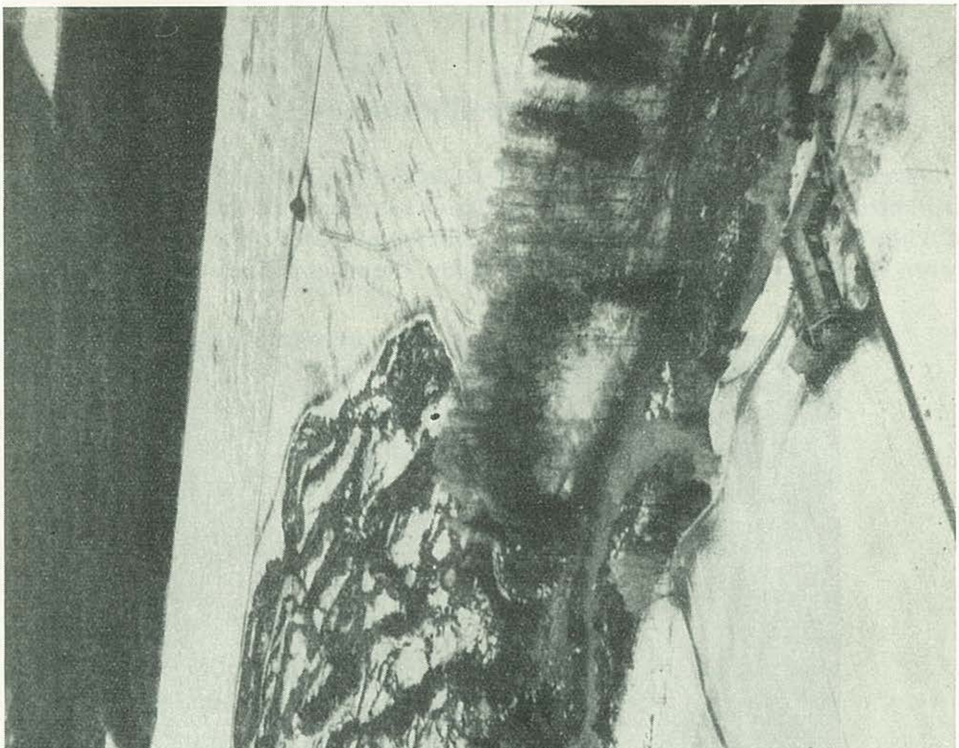

Fig. 2. Aerial photograph of site. (Copyright Ostermans Aero AB.)

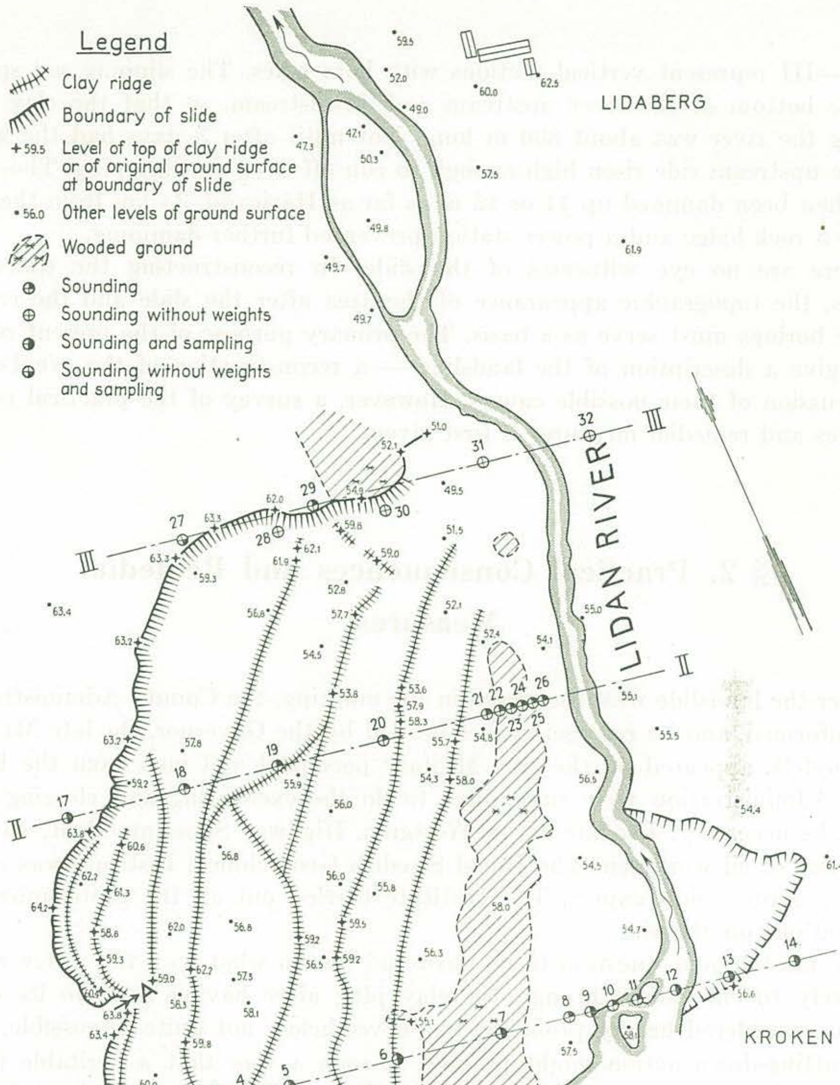

Fig. 3. Map of slide area. (Slide on right bank at Kroken is a secondary one, and occurred in May, 1946.) Soil layers were investigated in Sections I, II, and III. Arrow at A indicates direction in which the stereo-photograph in Pl. V was taken.

Pls. I—III represent vertical sections with bore holes. The slipping soil spread on the bottom of the river upstream and downstream, so that the clay plug closing the river was about 800 m long. Not until after 3 days had the water on the upstream side risen high enough to run off over the clay plug. The river had then been dammed up 11 or 12 m as far as Härjevad, 3.5 km from the site, where a rock ledge and a power station prevented further damming.

There are no eye witnesses of the slide. In reconstructing the course of events, the topographic appearance of the area after the slide and the results of the borings must serve as a basis. The primary purpose of the present report is to give a description of the landslide — a reconstruction of the events and a discussion of their possible causes. However, a survey of the practical consequences and remedial measures is first given.

§ 2. Practical Consequences and Remedial Measures.

After the landslide was discovered in the morning, the County Administration was informed, and its representatives headed by the Governor, the late Mr Carl Mannerfelt, appeared on the site. Military personnel and men from the Highways Administration were summoned to do the excavating and clearing that might be necessary. The late Mr A. Westgren, Highway Superintendent, was put in charge of all workmen. The Royal Swedish Geotechnical Institute was called in as a geotechnical expert. The Institute carried out all the geotechnical investigations on the site.

The most urgent question to be answered was in what way the water would be likely to cut down through the clay plug after having risen to its crest. It was considered hardly probable, but nevertheless not quite impossible, that the cutting-down action might proceed in such a way that a veritable flood-wave would run down the river to Lake Vänern. To dig a new river channel in advance through the clay plug was naturally not possible, but the trees and brushwood in the path of the future watercourse were cleared away as quickly as possible, to reduce the danger of jamming at the bridges downstream of the landslide. It was also important to ensure that, after the damming-up, the water should make its way over the clay plug roughly in the horizontal location of the original river bed, so that the slides to be expected in connection with the cutting-down of the new river channel would not affect any new areas. For this purpose, a low wall of logs and clay was built in the upstream part of the slide cavity in a line behind which a lower stretch would otherwise have directed the water in a loop through the cavity. A groove was also dug in the desired location through the crest of the clay plug.

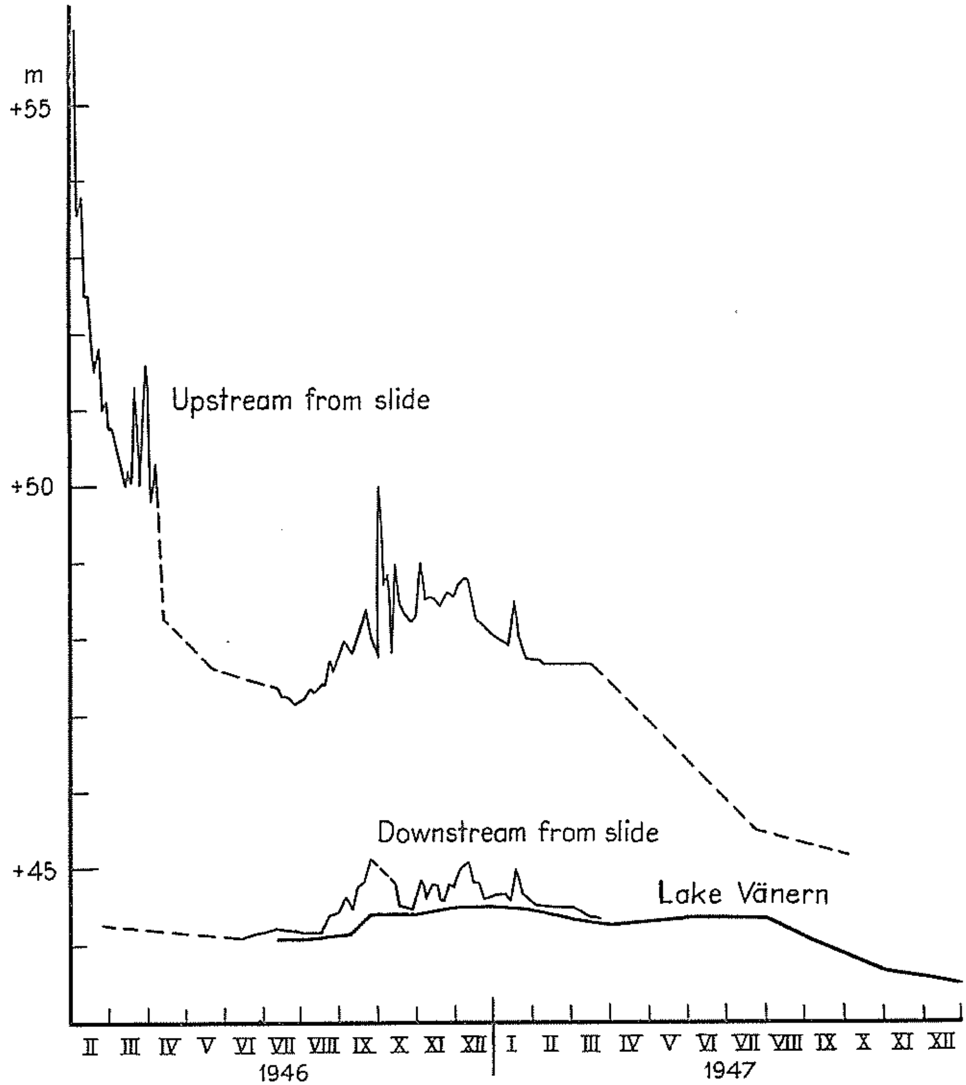

Fig. 4. Diagram showing variations of water levels upstream and downstream from slide, and in Lake Vänern.

Fortunately, the fear of a flood following the cutting-through did not materialize[1]. The cutting-through proceeded very slowly, as shown in Fig. 4, which represents the variations in upstream water level up to October 1947. The

[1] By the way, the Author does not know of any authenticated case of catastrophic cutting-through the clay plug left by a slide. However, the wording of the accounts of the great landslide in Guldalen, Norway, on September 14th, 1345 — described in (1), see the bibliography at the end of this report — indicates that a catastrophic cutting-through took place there.

Fig. 5. River channel in slide area in December, 1946.

Lidan cut successively down through the clay in a canyon-like form. Slides occurred from time to time in the steep clay banks, and were sometimes so large as to cause temporary damming. However, the peaks of the water level graph in Fig. 4 are generally due to increase in runoff after abundant precipitation. Fig. 5 represents the river bed through the area of the slide in December 1946, and Fig. 6 gives the appearance of the river in October 1950. The eddies in the

Fig. 6. River channel in slide area in October, 1950.

Fig. 7. The Lidaberg slope, viewed from the upstream end of the island, in process of erosion.

latter photograph show that the river is still slightly dammed up; before the landslide the water was relatively calm at this place.

Downstream of the slide, soil masses from the slide had been deposited on the bottom of the river and formed an island, whose downstream end was located straight in front of the Lidaberg farm. The island is visible on the plan in Fig. 3 and in the lower right-hand corner of the aerial photograph in Fig. 2. Soon after the water had begun to run over the clay plug, the channel on the Lidaberg side of the island was found to develop considerably faster than that on the Sköttorp side. As a result, after some days, all the water was flowing on the Lidaberg side. The island, at least its upstream end, consisted of very firm clay, which was not visibly eroded. On the other hand, considerable continuous erosion took place on the Lidaberg slope (Fig. 7). The erosion reached its maximum off the two ends of the island owing to the more marked change of direction of the bed at those places. Borings in and behind the 15 to 20 m high Lidaberg slope showed that the erosion, if allowed to continue, was liable to produce a new slide in that slope. The danger of this slide was considered so great that the occupants of the Lidaberg farm temporarily moved from the farm, and spent there only the time necessary for their daily work. To prevent a slide, it was very important to help the river to move to a safer location. It was therefore decided to dig a new channel through the island from end to end and to close the Lidaberg channel at the upstream end of the island. Moreover, the then dry channel along the Sköttorp side was to be filled in,

Fig. 8. Protective measures for the Lidaberg slope. Lowering the frame into the water.

so as to eliminate the danger of cutting there if the water should rise. The channel was filled in without difficulty. A groove was then dug by hand through the island. At the upstream end, the bottom nearly reached the level of the water. The intention was that the water itself should continue the digging after the closing of the Lidaberg channel at the upstream end had been completed. Thus everything turned on the success of the closing. At first an attempt was made with a frame of logs and beams, with deals nailed to that edge which was to be on the bottom. The frame was lowered into the water (Fig. 8) on the Sköttorp side somewhat upstream of the dam site. It was then moved by means of cables in order that — after having been carried by the current to the dam site — it should be raised by the water pressure upon the deals into such a position as to form a support for sheet piling to seal the frame. However, the raising succeeded only partly (Fig. 9). Recourse was then had to a supporting structure of pile yokes with wooden piles, 8 to 10 m long. The frame was then used to support a working stage. Fig. 10 shows the construction of the pile yokes, and Fig. 11 represents the erection of the sheet piling. When this work had been completed, the water in front of the dam rose high enough to make its way through the groove dug on the island. After a short time, however, the water broke through under the sheet piling, and the groove on the island dried up. Another attempt with more pile yokes and with sheet piling driven down deeper into the bottom gave the same result. Then the attempt to construct a dam at the upstream end of the

Fig. 9. Protective measures for the Lidaberg slope. Frame in position.

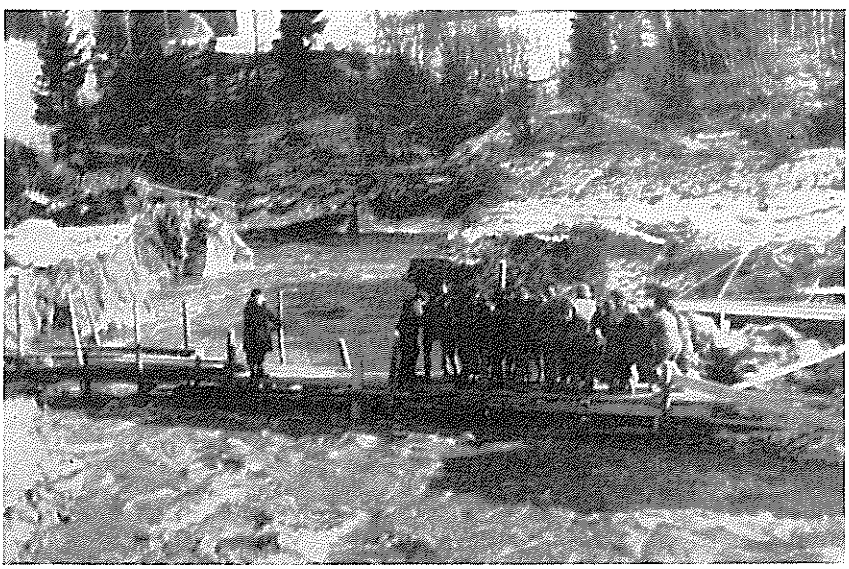

Fig. 10. Protective measures for the Lidaberg slope. Constructing pile yokes.

Fig. 11. Protective measures for the Lidaberg slope. Driving sheet piles.

Lidaberg channel by fairly simple means in order to conduct the water in the channel through the island had to be given up, and the water ran as before along the Lidaberg slope. However, we had gained the instructive experience that, with the simple means tried here, building a dam in running water on clay — a rather unusual site, it is true — has hardly any chance of success. We then tried widening and deepening the groove through the island by means of a scraper, whose winch was mounted downstream of the island on the Lidaberg bank in the extension of the centre line of the island, and whose anchor was placed upstream of the island on the Sköttorp side. Fig. 12 shows the scraper at work. In this way the groove was made wide and deep enough for all the water to run through it, and then a strong dam of clay was built to close the Lidaberg channel permanently at its upstream end. The occupants of the Lidaberg farm then moved back. The river has since continued to dig out the channel through the island, and now runs in a straight line approximately in its original position.

When the excavation work on the island had been completed, the scraper was moved to the upstream part of the slide, where a channel, about 100 m long, was dug at the crest of the rapids. In this way the level of the dammed-up water was lowered more quickly to the advantage of vegetation in the flooded area.

Among the practical considerations we must also include the estimation of the danger of slides in the terrain at the Kroken holdings, on the eastern bank of the river, directly opposite the large slide. This estimation was made after a secondary slide which occurred there. On Kroken, see § 6.

Fig. 12. Protective measures for the Lidaberg slope. Scraper opening channel through island.

In spite of the magnitude of the slide — it can be assummed that 1 to 2 million cubic metres of soil were moved — and the subsequent heavy damming-up — 11 to 12 m — of the water upstream of the slide, the damage was small, and was confined to losses of material. The slide area itself was unbuilt upon, and mostly consisted of fields, which of course were destroyed completely. Since the banks of the Lidan between Sköttorp and Härjevad are generally rather high and steep, the area flooded was not particularly large. The most heavily damaged properties were the power station and the mill at Härjevad, which were completely inundated, and a small workshop in Vassdalen, between Sköttorp and Härjevad, whose walls were made of dried clay, and were therefore entirely demolished.

§ 3. Investigation of the Nature of the Soil.

Weight sounding by the Swedish method [see (2) pp. 25—29 and (9) pp. 276—277] and extraction of undisturbed soil samples with a piston sampler [see (3) pp. 23—25] were carried out in Sections I, II, and III in the locations indicated on the plan in Fig. 3. The samples were tested in the laboratory of the Institute. The results of the soundings and the tests are summarized in Pls. I—III.

The soundings were made with a steel rod, 19 mm in diameter, composed of 1 m lengths and fitted at the bottom with a special point. The figures on the left of the bore hole state the load in kilograms and those on the right express the number of half-turns required to drive the sound. The marks at the lower end of the bore hole indicate in most cases a stop at what was judged to be rock, but in certain cases (oblique ruling) they show that the sound could not be turned more, or (filled-in rectangles) that the sound could be turned, but could not be driven down farther, the obstruction not being judged to be rock.

In the laboratory, the kind of soil (not shown on the plates), the unit weight γ, and the water content V (in per cent of dry weight) were determined. Further, the "finlekstal" F and the "hållfasthetstal" H_3 for undisturbed soil and H_1 for remoulded soil were determined by the cone test. For the significance of F, H_3, and H_1, see (2). From H_3 the shear strength was computed. In addition, the shear strength was determined by the unconfined compression test. On the execution of the cone test and the unconfined compression test, see (3), pp. 14—16.

The depth to rock (or moraine) was determined by sounding without weights. The results are shown in Fig. 13.

The strength was also determined directly in the ground with a vane borer — see (4) — in three bore holes, with the results shown in Pls. I and III.

In addition, two vertical cores extending from the surface down to the bottom of the clay deposit were extracted by means of the soil sampler with metal foils (5). The cores were taken in Section I in the proximity of Bore hole 4, one at the top of a clay ridge (see § 4) and the other between two clay ridges. The cores were cut up lengthwise and ocularly examined by Mr Carl Caldenius, State Geologist. The results are shown in Tables 1 and 2 at the end of this report. Fig. 14 shows a photograph of various parts of the longitudinal section surface of one core.

Within the slide area to be, the soil consisted of a layer of coarse silt and fine sand, 1 to 2 m thick, at the surface, and below this, of clay down to the rock, which is 15 to 35 m below the plain behind the slide. The clay contains layers of coarse silt and fine sand here and there.

The detailed examination of the clay cores extracted by the sampler with metal foils (Tables 1 and 2) shows that grey, partly silty, black-stained clay alternates with brown, dark-banded varved clay down to a depth of approximately 8 m in both holes; the contact surfaces between the different clay strata are folded and heavily perturbed. According to Caldenius, the varved clay is partly proximally formed, and the alternations of strata must therefore

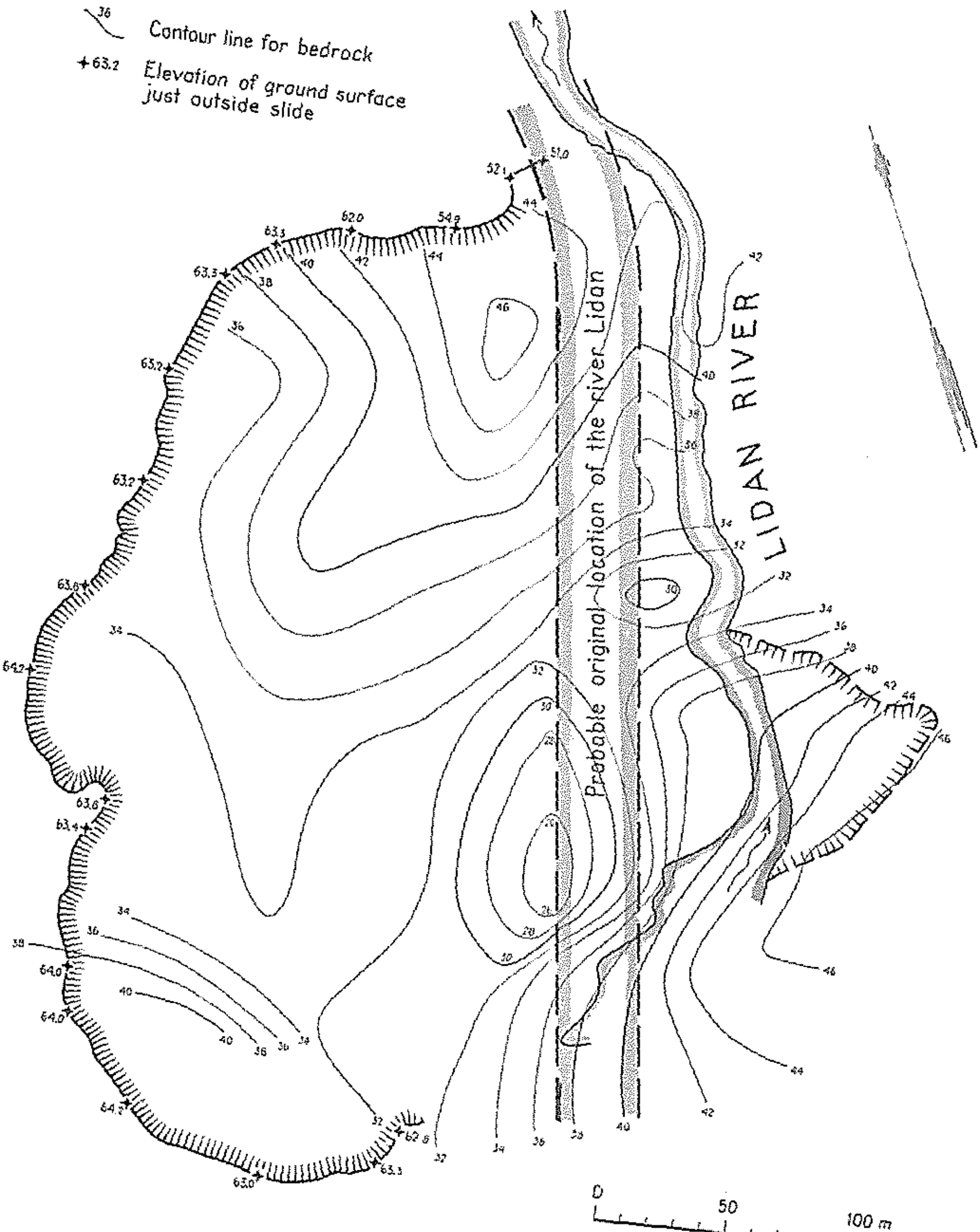

Fig. 13. Contour lines for bedrock in slide area. Probable location of the Lidan River before slide is indicated.

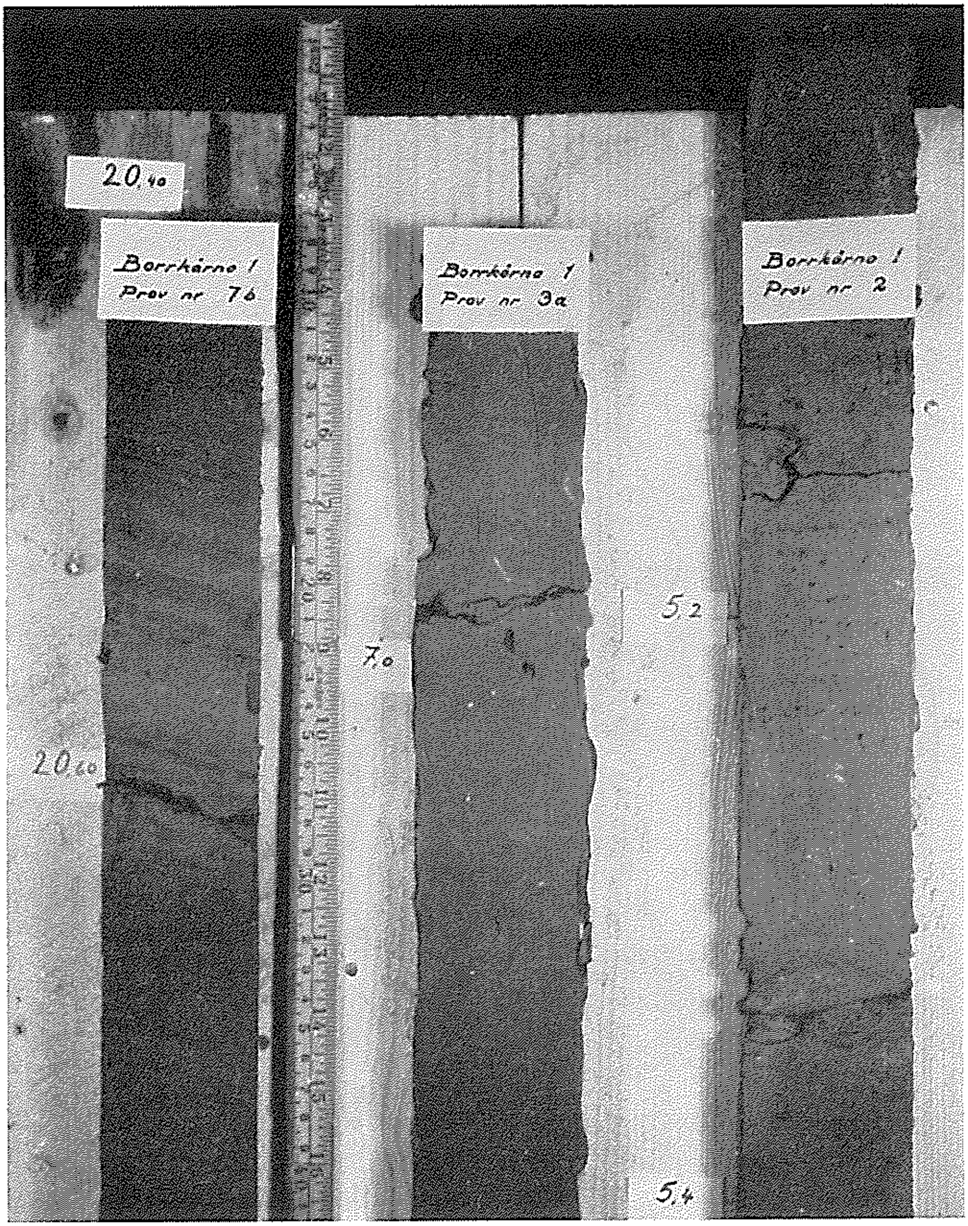

Fig. 14. Clay core taken in Section I in vicinity of Bore hole 4. Appearance at depths of 5.2, 7.0, and 20.6 m.

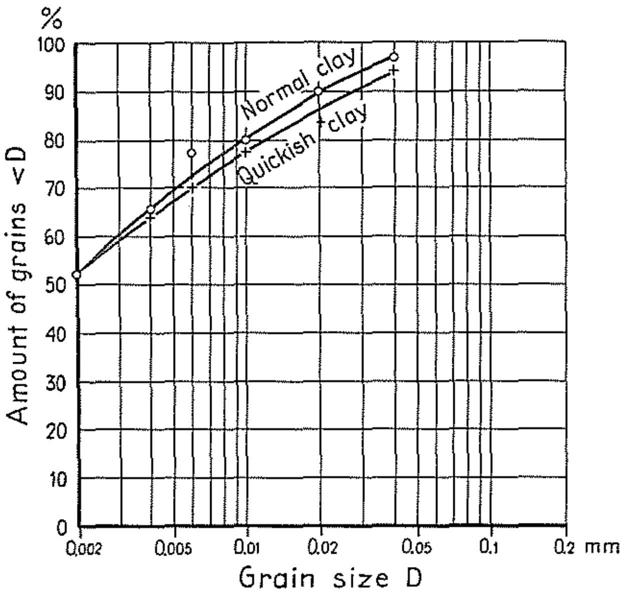

Fig. 15. Grain size distribution for two clay samples from Section I. One sample, taken from Bore hole 4 at a depth of 10 m, is neither quick nor quickish ($H_3 = 172$, $H_1 = 7$). The other, taken from Bore hole 1 at a depth of 22 m, is quickish ($H_3 = 172$, $H_1 = 1.1$).

be interpreted as bearing witness to considerable displacements in the ground. However, no soft perturbed zones, which could have originated with the slide of 1946, were encountered. A grey, homogeneous clay without visible stratification begins at the depth of 8 m. Below 13 m in one bore hole and 17 or 18 m in the other, the clay is distinctly varved. Perturbed zones occur here also without reduction of strength. In one bore hole, between the levels 16 and 18 m, the core ran out of the sampler, while being extracted, and this may possibly be attributed to a disturbance of the clay caused by the slide. To sum up, we may state that the cores have not given the requisite information on the location and the properties of the slip zones, the slip surfaces or the bottom of the slide.

In some bore holes near point 200 m in Section I, use was made of a piston sampler of the type employed by the Geotechnical Department of the Swedish State Railways [see (6) and (3) p. 23]; the samples were spaced so closely that they give a nearly continuous picture of the sequence of strata. Several slip surfaces thus observed were characterized by the fact that the varves on either side of the slip surface were displaced in relation to one another. It is not clear whether these slip surfaces date from this slide or from older slides, or whether they were produced during the sampling owing to imperfection of the sampler.

When the structure of clay is destroyed by remoulding, its strength is reduced. In extreme cases the reduction of strength is so great that the remoulded clay almost resembles a liquid. Such a clay is called a quick clay. In approximate agreement with Per Holmsen (7), quick clay is here defined as a clay in which the H-ratio H_3/H_1 is greater than 50, while H_1 is at the same time less than 1. (The H-ratio is thus a measure of the sensitivity of the clay.) Where the H-ratio is greater than 50 but H_1 is greater than 1, the clay is designated here as quickish. Pls. I—III show that quick and quickish clays occur to a considerable extent in and close to the area of the slide. The investigation made by Rosenqvist (8) shows that quick clay has not a higher percentage of coarse material than ordinary clay. The grain size distribution — only above the diameter $2\,\mu$ — has been determined for two Sköttorp clay samples. One of them was quickish, and the other was neither quickish nor quick. The results are stated in Fig. 15. In this case, too, the grain size distribution does not indicate anything about the sensitivity. According to the Norwegian geologist Gunnar Holmsen, quick clay is produced by fresh ground water gradually washing the salt out of a clay formed by sedimentation in sea water; as a result, the structure of the clay becomes less stable and more sensitive to remoulding.

§ 4. Mechanics of the Slide.

In the cavity caused by the slide there remained a system of beautifully formed ridges, between which the ground surface was sunk in flakes of varying size. Some of the flakes were inclined in one direction and some in another. On the aeriel photograph (Fig. 2) the clay ridges show as dark bands, while the snow-covered ground surface between them is white. On the plan (Fig. 3) most of the clay ridges are traced. One of the stereo-photographs of the slide area taken for the mapping is reproduced in Pl. V as an anaglyph. This photograph was taken from point A on the plan (Fig. 3) in the direction indicated by the arrow, and shows a number of clay ridges, one behind the other. Pl. VI shows by the anaglyph method a detail of a clay ridge. (On the sections, Pls. I—III, the clay ridges are not marked.)

The slide cavity has a topography which is characteristic of many retrograde slides. Thus, according to our conception of such slides, the Sköttorp slide was initiated when the high bank, where the ground was under the greatest stress, slipped out into the river, and then the slide successively extended into the area behind, so that piece after piece started moving towards the river.

This section deals with the mechanics of the slide after it had started, while the cause of the initiation of the slide is described in the following section.

In all those places where the clay in the ridges showed varving it was found that the layers were inclined only slightly or not at all. For the first few days after the slide the surface layer of fine sand and greensward was also left here and there on the tops of the ridges. These circumstances justify the conclusion that the ridges did not rotate, but mostly performed a translatory movement

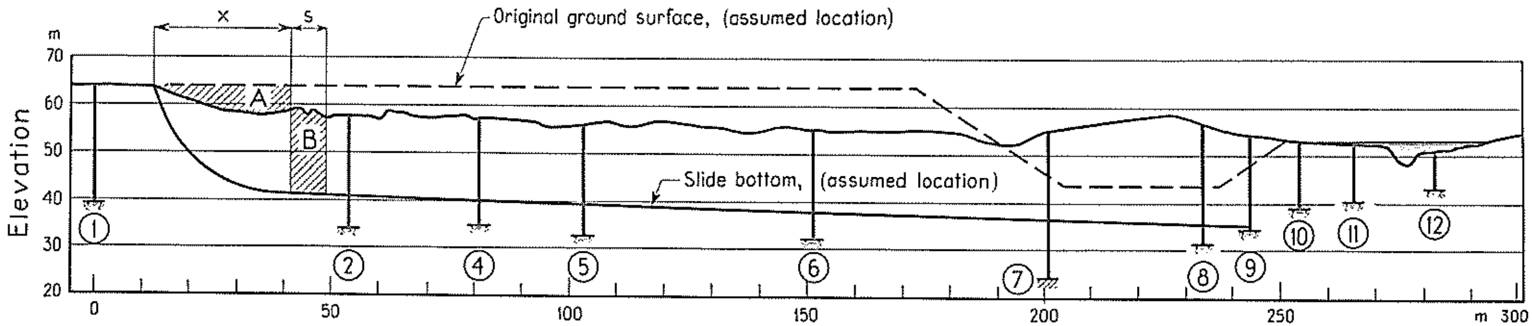

Fig. 16. Assumed locations of slide bottom and original ground surface, for calculating horizontal displacements in Section I.

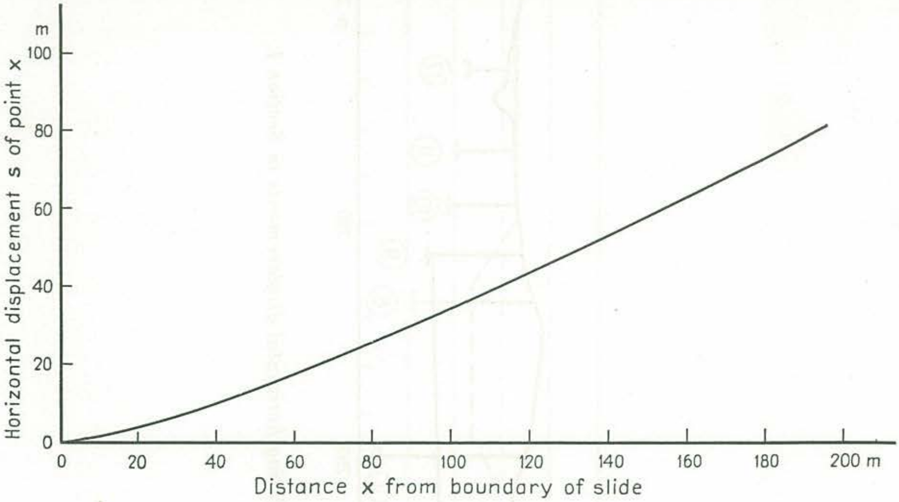

Fig. 17. Horizontal displacement s of point x metres from boundary of slide, computed by relationship A = B (Cf Fig. 16) under assumption that slide bottom and original ground surface are situated as in Fig. 16.

during the slide. The elevations of some crests given on the plan (Fig. 3) show that the clay ridges sank only very little during their movement towards the river; in other words, their translatory movement was mostly horizontal.

A rough estimate of the size of the horizontal displacement at various distances from the edge of the slide has been made, using Section I and assuming that the original ground surface and the bottom of the slide are located as shown in Fig. 16. The displacement of any point of the ground surface of the cavity is assumed to be equal to the average displacement, s, of the vertical line between this point and the bottom of the slide. The displacement $s = s\ (x)$ of a point located at the distance x from the edge of the slide is then determined by the condition that area B = area A. The result is given in Fig. 17; from this it will be seen, for instance, that a point originally located 150 m from the edge of the slide was displaced 50 to 60 m towards the river. This value agrees quite well with the measure of the displacement of the river in Fig. 13, where the previous location of the river is indicated with the guidance of a map (admittedly questionable) dating from 1796.

The clay ridges should be regarded as a sort of horsts, between which the ground has subsided and broken as the ridges moved away from one another. The slide process seems to have been as follows: a flake consisting of clay ridges separated by sunk and broken patches of ground, slipped towards the river on a relatively plane, only slightly inclined slide bottom. This flake probably comprised the larger part of the length of the slide area along the river, and grew retrogressively (i. e. in the direction away from the river) during the slide. As shown by the following description, the growth of the slipping flake was prob-

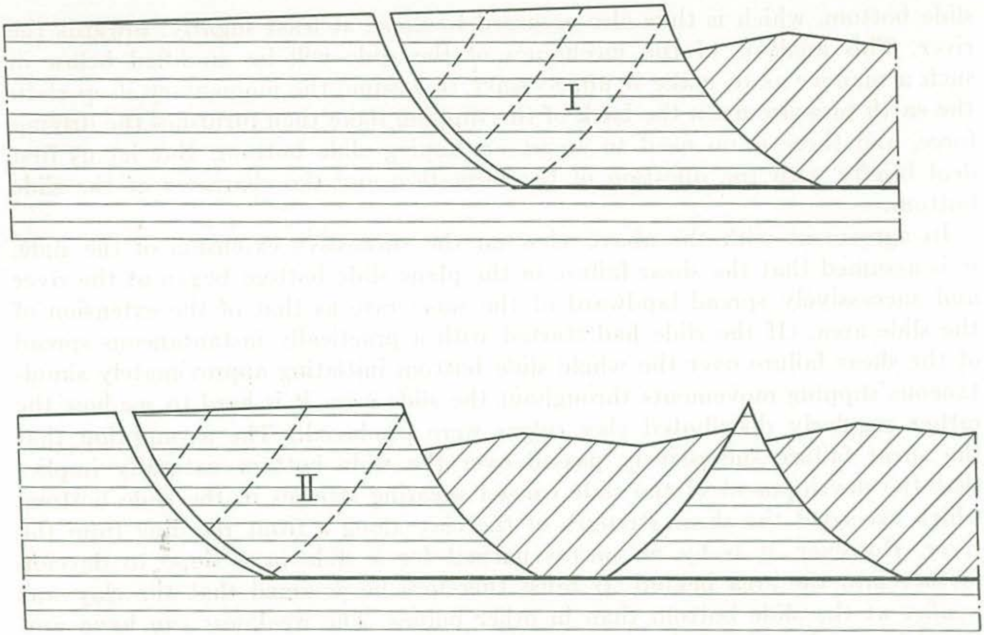

Fig. 18. The ground pieces slip and break down. Sloping layers. A deep cleft is supposed to open behind each slipping piece and to remain in the first moments.

ably discontinuous, so that each additional mass of earth consisted of a horst in process of formation, and of sinking ground behind.

Fig. 18 represents an attempt to reconstruct the course of events during the formation of the clay ridges. After mass I has started slipping to the right, its rear part falls into the cleft produced behind, and then the procedure is repeated for mass II. This reconstruction follows the explanation of the formation of the clay ridges already stated in the Closing Report of 1922 by the Geotechnical Commission of the Swedish State Railways (2), where the caption under a picture of a clay ridge in the Hammarby slide, on page 16, reads: "The front boundary surface of the ridge is formed by the back (upper) part of the surface of rupture of a slipping element of the first order moving towards the canal. The rear boundary surface of the ridge is a surface of rupture of a slipping element of the second order moving away from the canal. The latter slipping element was produced by a slipping element of the first order causing a very deep cleft between this element and the steep clay wall remaining behind it for a moment. When the cleft became deep enough, the back part of the slipping mass broke and slipped backwards towards the cleft." It has been assumed in this hypothesis that the driving force which starts and sustains the movement of the slipping flake is its weight component parallel to the slide bottom, which is thus also assumed to slope, at least slightly, towards the river. This analysis of the mechanics of the slide will be modified below in such a manner as to make it unnecessary to assume the momentary deep cleft; the earth pressure upon the back of the slipping flake then furnishes the driving force, and there is no need to assume a sloping slide bottom. But let us first deal briefly with the question of the formation and the character of the slide bottom.

In agreement with the above view on the successive extension of the slide, it is assumed that the shear failure in the plane slide bottom began at the river and successively spread landward at the same rate as that of the extension of the slide area. (If the slide had started with a practically instantaneous spread of the shear failure over the whole slide bottom initiating approximately simultaneous slipping movements throughout the slide area, it is hard to see how the rather regularly distributed clay ridges were produced.) The assumption that the shear failure successively passed over the slide bottom naturally implies that the development of the slide caused shearing stresses in the slide bottom, which exceeded the shear strength of the clay along a front receding from the river. However, it is by no means normal for a slide in a slope to develop further into the area behind. It must therefore be assumed that the clay was weaker at the slide bottom than in other planes. The weakness can have consisted in a reduction of the strength by a high water pressure in water-bearing sand layers in the clay. It can be assumed either that this water pressure has permanently been rather high, or — which appears more probable — that it reached peak values at the time of the slide owing to the general conditions affecting the ground water of the area. Another explanation of the weakness may be that the clay layer through which the slide bottom passes consisted of clay of lower strength, perhaps, owing to a mineral composition differing from that of the other clay. A third explanation is that the layer in question had been weakened because its salt had been washed away by fresh ground water. A fourth explanation may be that the slide bottom generally follows the layer surfaces and that the shear strength in these surfaces is considerably lower than in other surfaces.

In support of the latter hypothesis we may adduce an observation made at the landslide at Surte in the autumn of 1950.[1] Just inside the boundary of this slide, farthest from the river, naturally deposited clay was exposed with even, upwardly convex surfaces (suggestive of smooth rock). By excavating in several such places with varying slopes it was found that the clay is black-banded, the bands being parallel to the convex surfaces, which, therefore, must be layer surfaces in the clay. No traces of sand layers were to be seen in those surfaces which the Author examined. These layer surfaces are evidently at the same time also slip surfaces. Since they deviate radically from the upwardly concave form which is usual in ordinary slides, their existence appears, according to the Author, to be due to the fact that the shear strength of the clay in the layer surfaces is considerably lower than in other directions.

[1] A report on this slide is being prepared by the Institute.

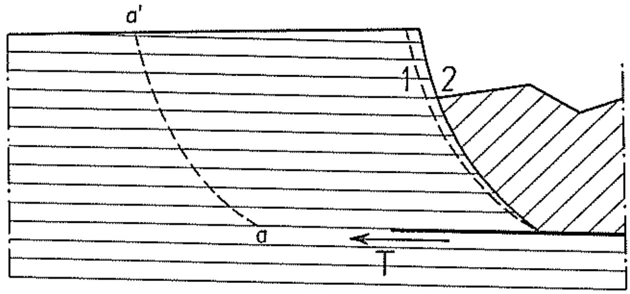

Fig. 19. The clay shears in a layer surface behind the bottom of a cleft when the remaining soil mass extends horizontally.

The course of events at the slide bottom at Sköttorp during the successive spreading of the slide away from the river can now be described as follows. Let us consider the remaining clay behind the cleft or break surface, in front of which the clay mass has begun to slip (Fig. 19). When the pressure on the wall of the cleft becomes zero, or — if no cleft is produced — when the pressure on the break surface is reduced, the remaining ground extends outward from position 1 to position 2. However, it is prevented from freely and immediately deforming because it is pasted, so to speak, to the base in the extension of the slide bottom already formed. Thus a stress concentration is produced in the extension of the slide bottom close to the cleft or the break surface, resulting in shear failure there. The stress concentration then travels in the slide bottom away from the river and the shear failure moves with it. As the failure spreads along the slide bottom, the shear force T, which can be mobilized on the right of each point, *a*, to maintain, together with the other forces in action, the equilibrium of the remaining ground to the right of section *a*—*a'*, is reduced. This can also be expressed as follows: the strain which *a*—*a'* must be able to withstand in order to prevent the slide area from spreading further increases with the retrogressive development of the rupture at the slide bottom. Eventually the moment comes when the most strained section, *a*—*a'*, does not hold any longer, rupture occurs there, and another mass slips away.

Let us now deal with the case in which no deep cleft opens behind the mass during the moments after it has started to move. We carry out the examination for the case where the slide bottom is horizontal, and assume that the shear strength falls to a very low value (as is the case in sensitive clays, particularly in quick clay) in that part of the slide bottom which the retrogressive rupture has passed. The soil mass, h_2 (Fig. 20 a), to the right of the 45° slip surface[1] AC moves to the right owing to the earth pressure J_2; the ground to the left of AC remains stable. When this slip started, J_2 was equal to the active pressure

[1] The inclination of the slip surfaces should rightly be $45 - \frac{\varphi}{2}$ but the true angle φ of internal friction is disregarded here for the sake of simplicity.

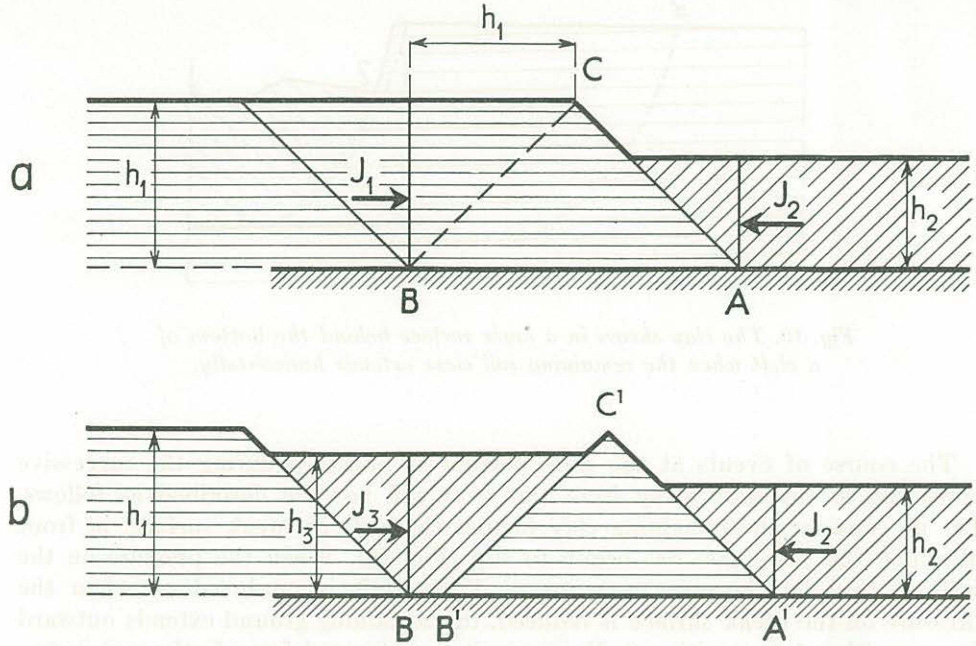

Fig. 20. The ground pieces slip and break down. The pressure exerted by the earth behind the piece acts as a driving force.

$\frac{\gamma h_1^2}{2} - 2\, ch_1$. We now assume that the clay is quick, or at least sensitive, so that the reduction of strength in the two 45° slip surfaces through A transforms J_2 into a liquid pressure, with the result that J_2 rather quickly rises to a maximum[1] somewhere between the just mentioned active pressure and the value $\frac{\gamma h_1^2}{2}$. After that J_2 falls with falling h_2 until it is no longer able to prevent the next portion of the ground from slipping away. The active pressure, to which the earth pressure J_1 on the vertical plane through the remaining mass of clay may fall, is denoted by J_{1a}. It reaches its full value corresponding to the height h_1 in the vertical planes to the left of the point B, where a 45° line from C reaches the slide bottom; it is lower in the vertical planes to the right of B. We further assume that the retrogressive rupture at the slide bottom has at least reached point B, before the next slip occurs. Fig. 21 shows the pressure J_2 as a function of the horizontal distance x from point C to the point reached by the progressive rupture at the slide bottom; this diagram also gives J_{1a} in the vertical plane through point x. The next slip occurs when h_2 becomes low

[1] This temporary high pressure not only keeps the soil to the left of AC stable, it also accelerates the movement of the soil to the right of AC. Thus, it explains the violent horizontal translation, and it helps to explain the large horizontal extension of the slide.

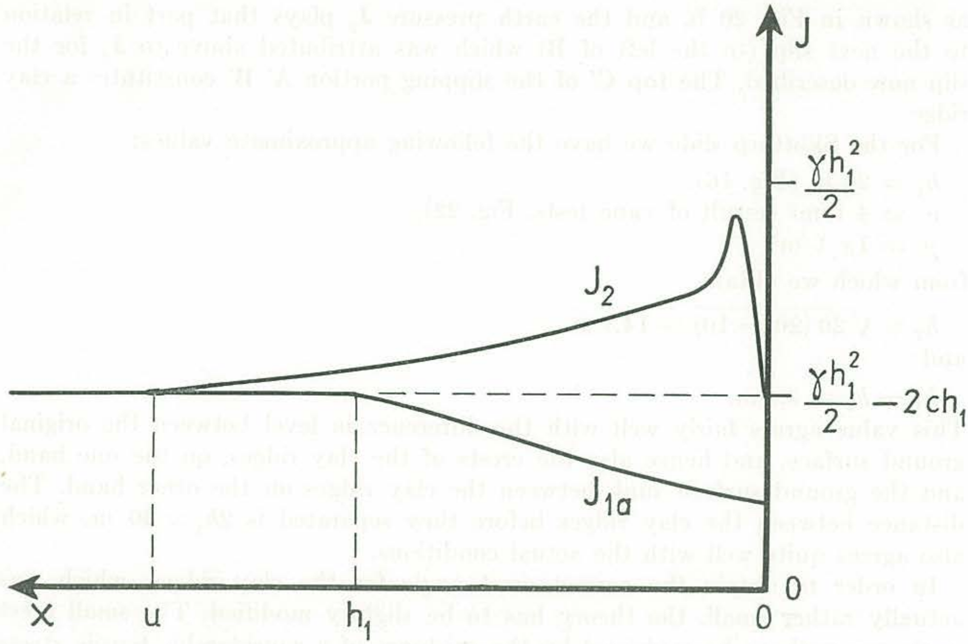

Fig. 21. Earth pressure produced when ground slips according to Fig. 20. J_{1a} *= active pressure on vertical plane at distance x behind top of latest slipping ground piece.*

enough, so that J_2 can begin to fall below $(J_{1a})_{max}$. The intersection of the curves J_2 and J_{1a} in Fig. 21 at a point, u, to the left of h_1, implies that the failure at the slide bottom has then passed point B in Fig. 20 a. The new slip surface should start in (or near) point B, because the resultant of the active pressure in a vertical plane through B and the remaining resisting force in the slide bottom to the right of B is greater than the corresponding resultant for any other point. For points to the left of B the resisting force is somewhat greater than, and the active pressure is the same as, for B. For points to the right of B the resisting force is somewhat smaller, and the active pressure is considerably smaller, than for B. Portion BA starts slipping when

$$\frac{\gamma h_1^2}{2} - 2\,ch_1 - \frac{\gamma h_2^2}{2} = 0$$

i. e.

$$h_2 = \sqrt{h_1\left(h_1 - \frac{4\,c}{\gamma}\right)}$$

if the shear resistance at the slide bottom is disregarded. When h_2 has reached this value and slip has started, the ground on either side of the vertical plane through B slips down the main slip surfaces through B. The slide develops as shown in Fig. 20 b, and the earth pressure J_3 plays that part in relation to the next slip (to the left of B) which was attributed above to J_2 for the slip now described. The top C′ of the slipping portion A′ B′ constitutes a clay ridge.

For the Sköttorp slide we have the following approximate values:

$h_1 = 20$ m (Fig. 16),

$c = 4$ t/m² (result of vane tests, Fig. 22),

$\gamma = 1.6$ t/m²

from which we obtain

$h_2 = \sqrt{20\,(20 - 10)} = 14.1$ m

and

$h_1 - h_2 = 5.9$ m.

This value agrees fairly well with the difference in level between the original ground surface, and hence also the crests of the clay ridges, on the one hand, and the ground surface sunk between the clay ridges on the other hand. The distance between the clay ridges before they separated is $2h_1 = 40$ m, which also agrees quite well with the actual conditions.

In order to obtain the correct crest angle for the clay ridges, which was actually rather small, the theory has to be slightly modified. The small crest angle can perhaps be explained by the existence of a considerable tensile stress in the ground surface before rupture; the fissures thus produced grew downward and gradually passed into 45° slip surfaces when a greater depth was reached.

In the case of an inclined slide bottom the mechanics of the slide can naturally be considered in a way similar to that used in Fig. 20. Then the component of the weight of the slipping ground along the shear surface also acts as a driving force.

According to the above description of the mechanics of the slide, there is a particularly serious danger of an initial slide starting a large retrograde slide either if the clay strata slope towards the initial slide, or if quick (or at least sensitive) clay occurs to a greater or lesser extent. From Fig. 13 it can now be seen that the firm bottom at Sköttorp does not slope towards the river, and for this reason it cannot be assumed either that the layers of the clay do so. It thus appears probable that the sensitive clay at Sköttorp is the reason why a large retrograde slide followed after the bank had slipped into the river.

§ 5. Initiation of the Slide.

The slide was initiated by the bank slipping into the river. It is obvious that this initial slip was very violent since pieces of ice from the frozen river were flung into the fir grove on the bank with such a force as to damage several tree trunks. Fish have also been found washed ashore.

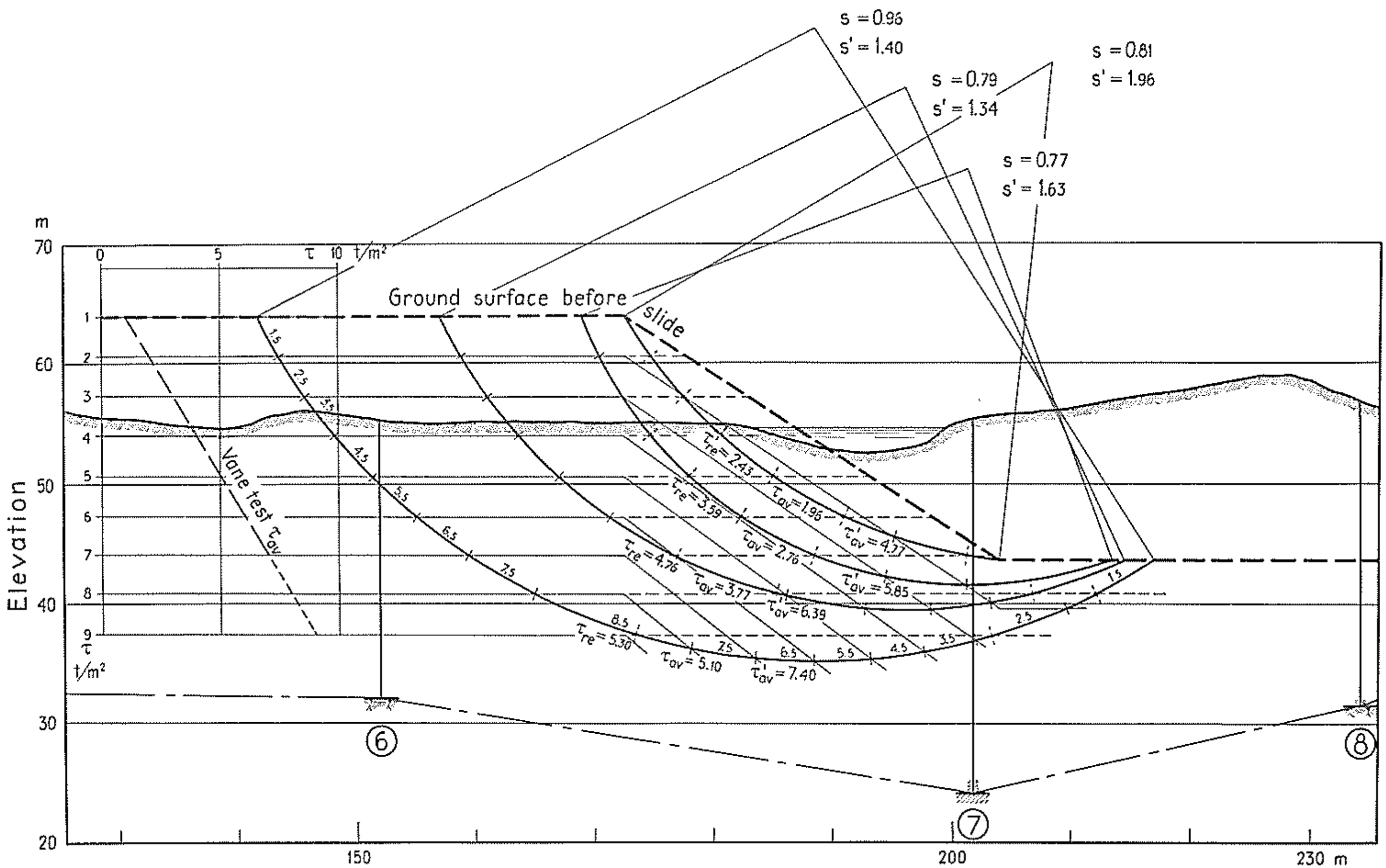

Fig. 22. Stability of river bank computed by Swedish circular-arc method.

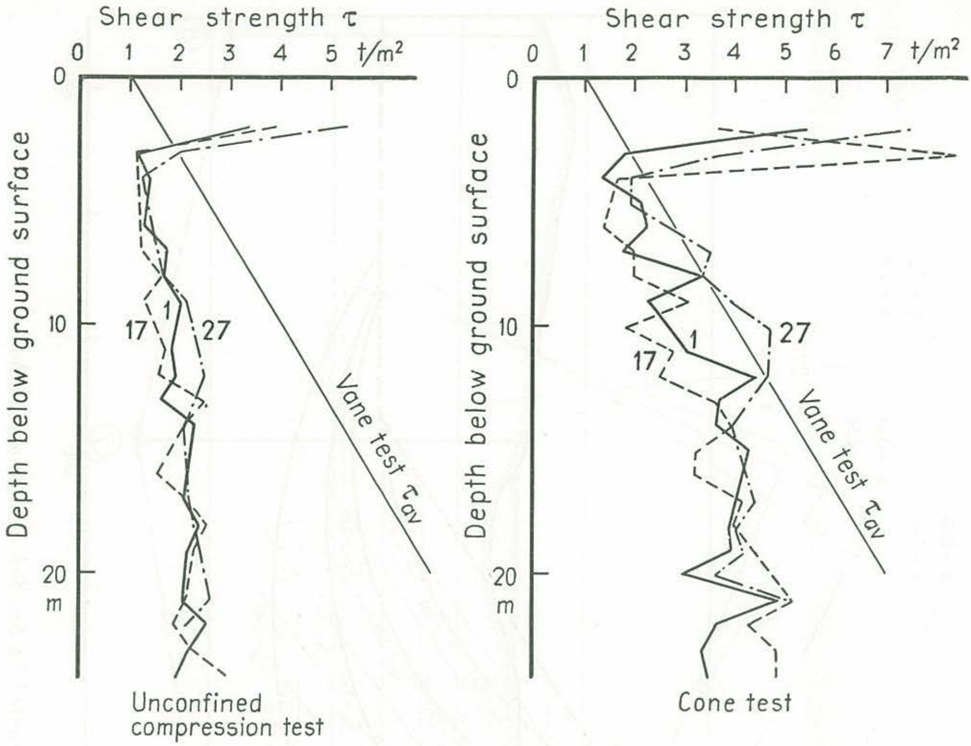

Fig. 23. Shear strength from unconfined compression test and cone test in Bore holes 1, 17, and 27—the values are representative for all bore holes—and the average result of the vane boring.

The appearance of the bank before the slide is not known with certainty, but assuming that it was as shown in Fig. 22, its stability was computed by the circular-arc method. The shear strength of the soil behind the slope was assumed to vary with the depth below the surface according to the straight line in Fig. 22, which represents an average of the results from the three bore holes made with the vane borer. For the variation of the shear strength below the slope two assumptions were made: that the lines of constant shear strength are horizontal, and that they are parallel to the slope. Using the vane test results in this way, the factor of safety of the bank was found to have been between 0.77 and 1.34.

Fig. 23 shows the shear strength values obtained by different methods from various bore holes. For the sake of clarity, only the results from some of the bore holes are given, but these results are representative. It is seen that the shear strength values from the unconfined compression test and from the cone test are lower than those from the vane test; if used for computing the stability of the slope, they result in safety factors of, say, 0.4 and 0.6 respectively. This result confirms that the slope was severely strained before the slide.

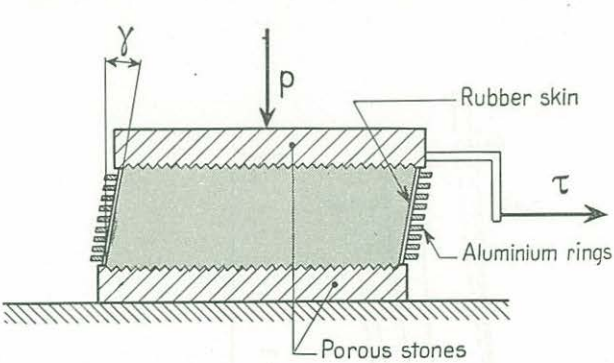

Fig. 24. Direct shear apparatus.

The cause of the initial slide cannot be found with certainty from investigations on the site, since the original slope was entirely destroyed. Certain phenomena which preceded the slide and which reduced stability can be pointed out. The river had certainly reached, or nearly reached, its base-level (the quiet waters below Sköttorp had made the site a popular excursion place for motor boats), but a minor blasting operation in the river bed directly downstream of the slide area, made some time before 1930, may have caused a small deepening of the river progressing since then. Another factor reducing stability is the grove which had grown up on the crest of the slope and which increased the load on the bank more and more. Both these factors, i. e. the cutting-down of the river and the growth of the grove, have been proceeding very slowly. If they had been the sole factors endangering stability, the bank would probably have yielded to them slowly by plastic deformation, so that the violent initial slide would perhaps not have been produced.

Another factor slowly reducing stability may have been the loss in strength of the clay which may take place when it is made quick by the leaching-out of salt in accordance with Gunnar Holmsen's theory (see § 3). If the quick clay comprises only thin layers in the bank, it may perhaps be more reasonable to expect that the slow weakening may in due course start a violent initial slide.

The most important influence of the above-mentioned stability-reducing factors on the initiation of a slide is probably that they have in course of time made the area exposed to the initial slide more sensitive to the stability-reducing effect which can be produced by a temporary increase in ground water pressure in sand and silt layers in or under the clay. If the ground water pressure increases under the circumstances, a slide can be started by rupture in a surface, already under severe stress, between the clay and the water-bearing layer. Then there is no distinct deformation to give warning of the slide.

For those readers who are not familiar with neutral and effective pressures in clay, the following tests may demonstrate the effect with which we are concerned here. We made 3 series of direct shear tests, each series comprising 4 tests. The samples consisted of soft clay taken from a locality in Stockholm; they were cylindrical, 6 cm in diameter and 2 cm

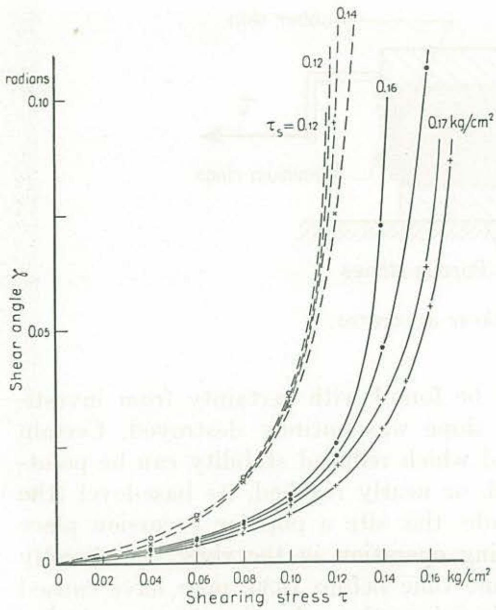

Fig. 25 Results of two series of direct shear tests. Consolidation pressure = 1 kg/cm². Water pressure in porous stones 0 for full curves and 0.2 kg/cm² for dash curves. Shear strength = τ_s.

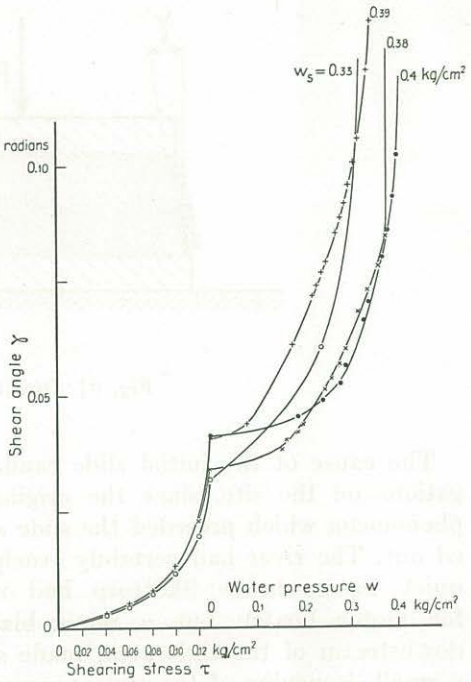

Fig. 26. Results of a series of direct shear tests. First, consolidation at 1 kg/cm². Then shearing stress 0.12 kg/cm² applied. After that rising water pressure (w) in the porous stones. w_s = water pressure at rupture.

in height. The principal features of the shear apparatus are shown in Fig. 24. The cylindrical surface of the sample is covered by a rubber skin on which a number of aluminium rings are placed. Shearing takes place between two porous stones, which are submitted to a normal stress p, under the influence of the shearing stress τ. When the angle of shearing strain γ begins to increase at a rapidly rising rate, the applied shearing stress is assumed to equal the shear strength. In all series a normal stress of $p = 1$ kg/cm² was first applied. The shearing stress was applied after the consolidation was finished.

In the first two series the shearing stress was successively increased to rupture, while the water pressure in the porous stones was kept at 0 in one series and at 0.2 kg/cm² in the other. The results are shown in Fig. 25. As seen, the shear strength was reduced from between 0.16 and 0.17 kg/cm² to between 0.12 and 0.14 kg/cm² when the water pressure was increased from 0 to 0.2 kg/cm².

The third series of tests resembled more directly the conditions prevailing under an increasing ground water pressure in sand layers in the clay *in situ*. After the normal pressure had completed its action, a shearing stress was applied and successively increased to 0.12 kg/cm². It thus equalled the lowest shear strength in the preceding series. Then the water pressure in the porous stones was increased. As shown in Fig. 26, rupture was obtained at the water pressure of 0.3 to 0.4 kg/cm².

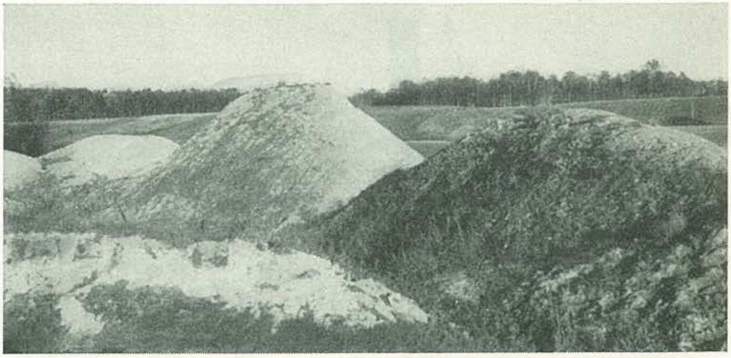

Fig. 27. Clay ridges at Sköttorp in October, 1950.

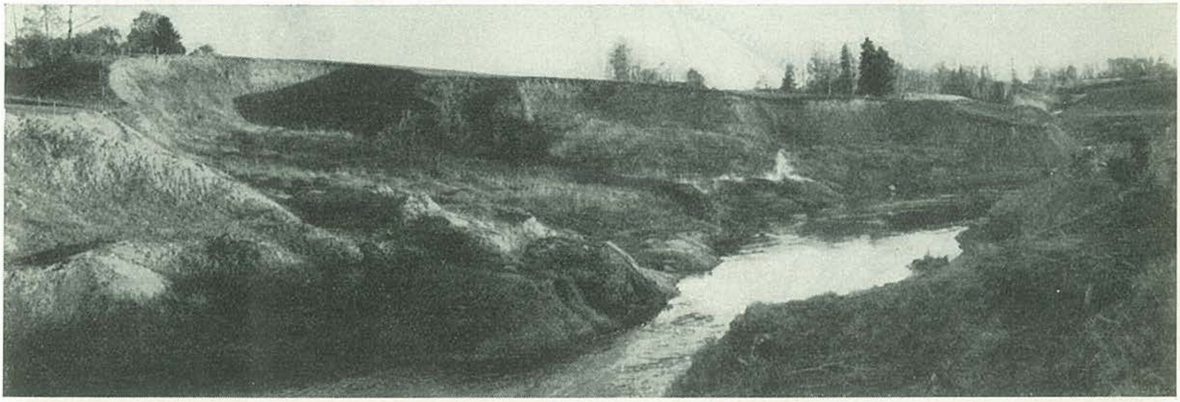

Fig. 28. Cavity after slide at Kroken.

Terzaghi-Peck, (9) p. 366, also state that an increase in the ground water pressure frequently is the initiating cause of a landslide. In support of this view they adduce the fact that large slides often occur approximately at the same time in consequence of the fact that the ground water pressure simultaneously rises in several places. In this connection it may be mentioned that in 1648 two large slides occurred in Sweden, one at Intagan (Åkerström), in the valley of the Göta River, the other at Partille, in the valley of the Säve River. Moreover, Wenner (10) has quite recently listed Swedish landslides, and has found that they have occurred most frequently in autumn, i. e. in the wet season. However, Wenner only states that the autumn rains increase the slide danger by increasing the soil weight (they fill with water the fissures of the dry crust of the clayey ground and saturate the sand cover and other sand layers in the clayey soil); he does not mention that the ground water pressure increases. An interesting circumstance, which also supports the view that the slide at Sköttorp was started by a high ground water pressure, is that Bergsten (11) believes to have found that the ground water level in large parts of Sweden rose from the end of the 1930's to a maximum in 1946.

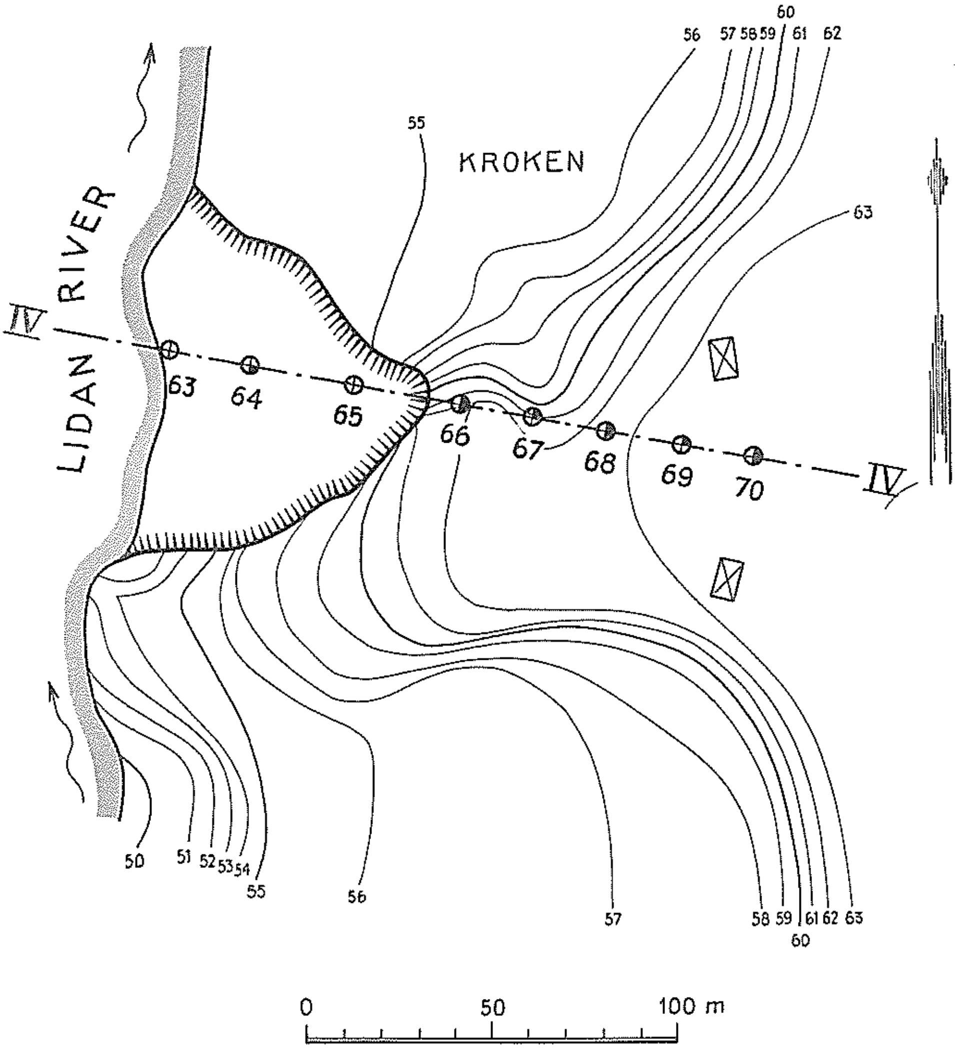

Fig. 29. Map of slide at Kroken. Contour lines refer to ground surface. For key to symbols cf. Fig. 3.

§ 6. Other Slides on the Lidan River.

As seen i Fig. 27, the clay ridges of the large slide described above had changed only little from 1946 to 1950. In time, however, the ridges will crumble and the cavity will take on the even appearance characterizing many cup-like formations which border on the Lidan in this area, and which certainly should be interpreted as old slide cavities. In the back-ground of the stereo-photograph, Pl. V, such an old cavity is seen on the eastern bank, showing how the site of the Sköttorp slide of 1946 will probably look in the future. Some kilometres upstream of Sköttorp, on the left bank in the Vassdalen, there is a large, cup-like formation with a narrow opening towards the river, where an important slide of quick clay may once have taken place.

At Kroken, on the eastern bank, directly opposite the upstream part of the Sköttorp slide, the Lidan has cut down since the slide into a more easterly position than formerly, as is also shown on the map, Fig. 13. In the elevated area, which juts out here between two old slide cavities, several slides have then occurred. The largest of them took place in the middle of May, 1946. A photograph of this secondary slide area taken in October, 1950, is shown in Fig. 28. Fig. 29 shows a plan of the area and Pl. IV represents the results from one of the sections which were bored to investigate the danger of slides to some farmsteads directly behind the area. (The bore section on Pl. I, which was made before the slide, is at the edge of the area.) It appeared that a considerable quantity of quick clay lies underneath the farmsteads, and is separated from the river bed by clay which is not quick. Both the stability analysis on the basis of the strength values and the slides which have actually occurred prove that the bank is under severe stress. As shown by the eddies in Figs. 6 and 27, the river, after the slide, has not yet cut down to its base-level. For this reason, the stress in the bank will increase somewhat even apart from the influence of any future, temporary increase of the ground water pressure. If a new slide should occur and should reach the quick clay, there is evidently danger of its spreading backward and affecting the farmsteads concerned.

§ 7. Summary.

In 1946 a large flake of the clay plain at Sköttorp suddenly moved towards the Lidan River and filled some 800 m of its channel. In a few days the upstream water rose 12 m and then began to run off over the clay mass. During the following two years the river cut down through this mass, the upstream water sinking successively nearly to its old level.

The slide caused a temporary inundation of the valley upstream of Sköttorp. Some secondary slides occurred and others were feared. A floodwave running downstream of Sköttorp was also apprehended. Remedial and preventive measures were taken, mainly consisting in building dams and digging channels to conduct the water through the site.

Extensive soil investigations were made on the site and in the laboratory; most of the results are given in this report. It was found that the river bank had been severely stressed before the slide. Several factors can have acted as "trigger agents" e. g. the erosion in the river bed, the increasing weight of the grove on the bank, the weakening of the clay due to leaching of salt, or, most probably, a temporary increase of the ground water pressure.

In order to explain how the slide could spread horizontally 200 m in the direction away from the river two assumptions must be made. One is that the

clay soil had a horizontal surface or layer that was particularly weak, owing to its constitution or to a high water pressure in an adjacent sand layer. The other is that the strength of this surface or layer was almost completely destroyed, when rupture was produced in it by stress concentration. Probably a front of such rupture travelled rapidly landward, thus forming the slide bottom. At the same time and rate, rupture in the soil above this bottom spread landward in the following way. Slip surfaces, parallel to the river and inclined 45° to the horizontal, appeared, forming a zigzag line in cross section. Those soil wedges thus formed which had their base on the slide bottom slipped apart without any appreciable deformation; their edges constitute the clay ridges visible in the slide cavity. The interjacent soil wedges subsided and were deformed so as to fit between the former.

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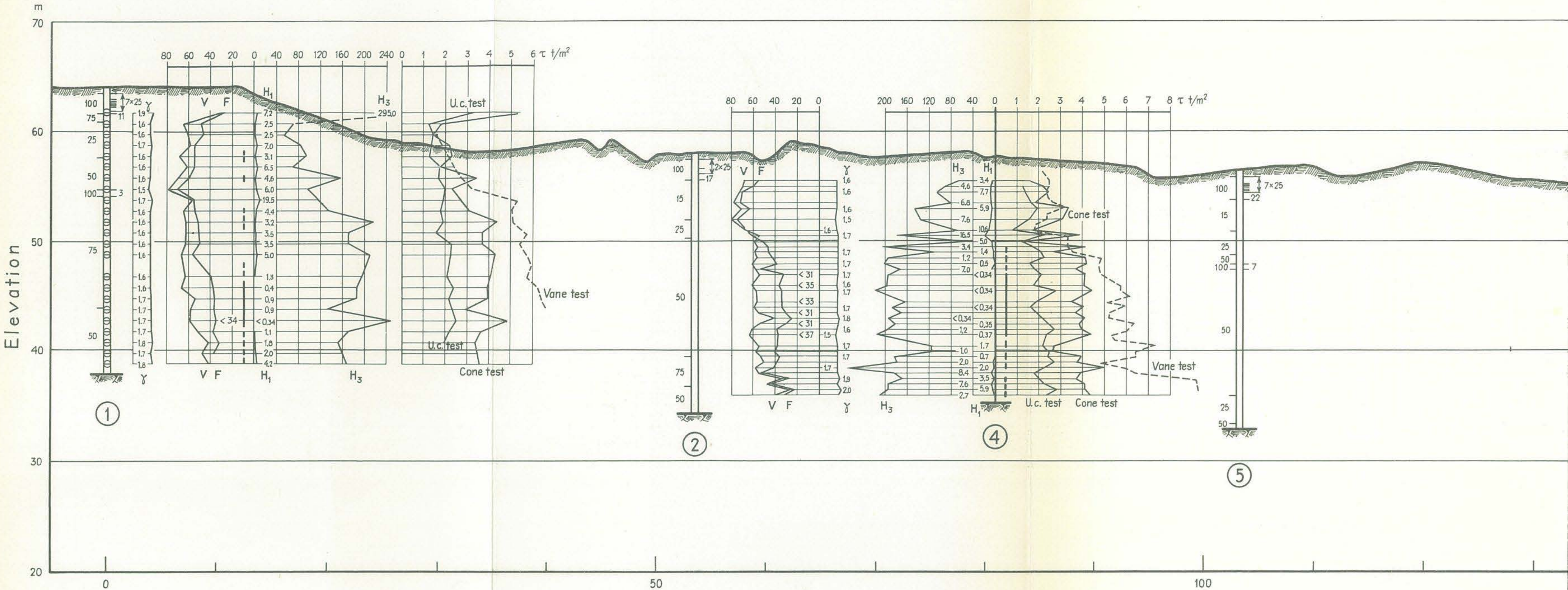
Table 1. Sequence of layers in a continuous vertical core extracted between two clay ridges.

Depth (m)	*Kind of soil and its geological character*
2.80— 3.20	Clay and fine sand alternating in about one-centimetre layers. Colour grey. Contacts in lower part of this region disturbed.
— 3.42	Clay with a few thin layers of coarse silt and fine sand.
— 4.70	Clay with very thin layers of coarse silt. Down to 3.60 m distinct rusty root channels. At 3.62 m very sharp contact between an upper grey clay and a lower black-stained clay, such that the layers of the black-stained clay are cut off. The layers in the black-stained clay are distinct, and some of them are silty.
— 5.27	Richly black-stained clay; about one centimetre wide, very regular, roughly horizontal strata.
— 5.31	Strata disturbed; abundant inclusions of thin bent strata of coarse silt and fine sand and a centimetre-wide lens of fine sand, which is connected to a thinner stratum and occupies 1/3 of the width of the core. Probable slip zone.
— 5.60	Black-stained clay of the same character as above the slip zone.
— 6.33	Grey clay with scanty small black stains. Stratification indistinct.
— 6.60	Abundantly black-stained clay with 1/2 to 1 cm thick strata. Strata inclined.
6.85— 7.45	Mostly grey clay, apparently without stratification and with indistinct and scanty black stains.
— 7.90	A basically brown clay with irregularly shaped zones of darker, probably glacial clay. At 7.83 m a thin stratum of coarse silt and fine sand with a wavy contour.
— 8.05	Alternating strata of fine sand and silt and clay.
— 8.31	Mostly grey clay with black stains.
— 9.85	Grey clay with faintly visible black stains.
—11.35	Grey clay with faint black stains, small and widely spread. No visible stratification.
—12.85	Grey-brown, silty clay with faint black stains. Partly distinct alternation of clayey and silty strata.
13.15—14.65	Grey-brown, obviously glacial, silty clay. Certain parts varved.
—16.15	Glacial, grey-brown, silty clay, in parts with distinct varves. Varve boundaries run across the core. At the bottom the varves are disturbed by slipping. No change in the consistency of the material.
—17.65	Varved clay, brown with distinct dark winter layers. 2 to 5 cm thick varves. Silty clay.
—18.90	Brown, somewhat greyish, varved, silty clay. Distinct stratification.
—20.40	Varved clay, varves about 1 dm thick, with layers of coarse silt and fine sand. About the middle of the core, folded varves and discordances.
—21.90	Glacial, beautifully varved clay. Brown. Proximal varves. Below 21.30 disturbances of layers, sometimes with discordances.

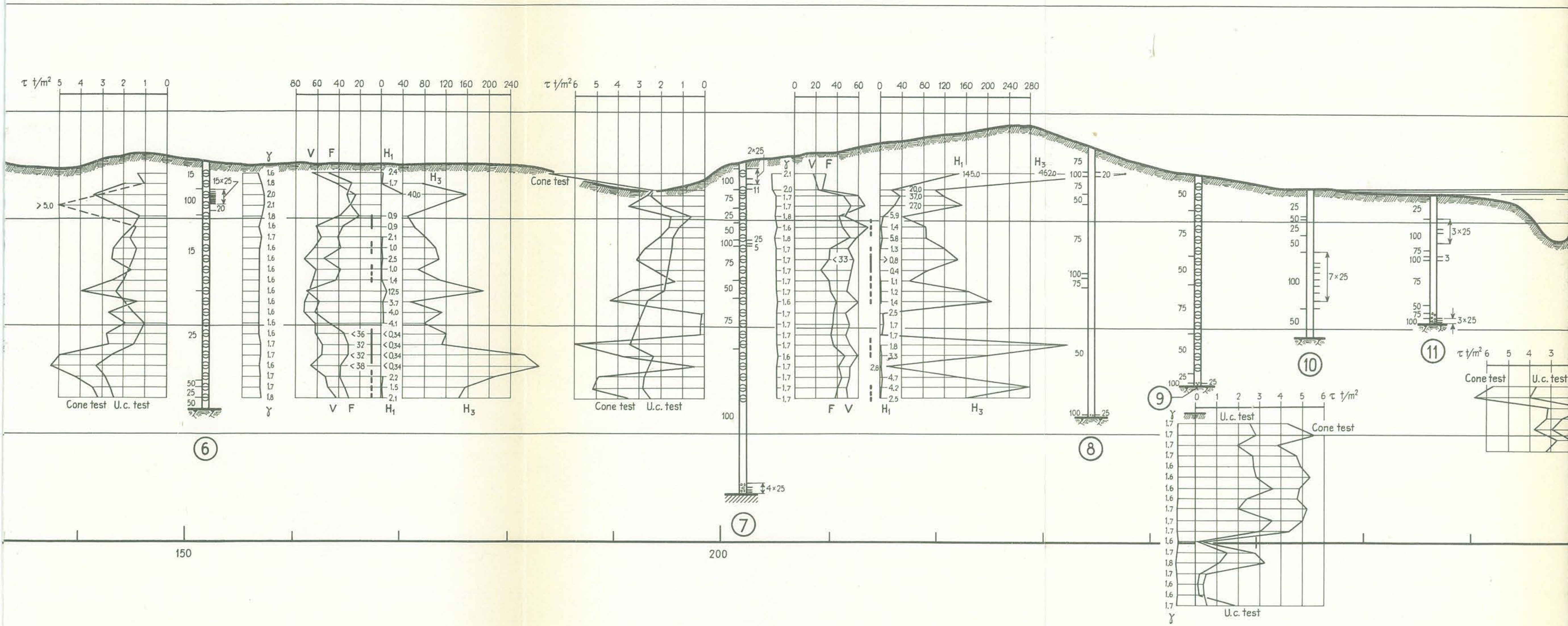
Table 2. Sequence of layers in a continous vertical core extracted through a clay ridge.

Depth (m)	*Kind of soil and its geological character*
1.50— 2.32	Grey, heavily black-stained clay with the black stains arranged in layers 0.5—1 cm thick. At 1.68, 1.76, 2.05, and 2.07 thin layers of fine sand, one to a few millimetres thick, with irregular boundaries.
— 3.25	More uniformly grey clay with occasional black-stains, mostly without regular occurrence. Layer boundaries at 2.89 and 2.96.
— 4.00	Still more uniformly grey clay with very irregular layers.
— 4.35	Grey-brown clay with remainders of dark boundaries of layers and traces of heavy folding (probably a brecciated glacial clay). Strength appears to be unchanged throughout.
— 5.06	Grey clay with faint black staining. Irregular stratification; torn and heavily folded layers.
— 5.43	Grey-brown, probably glacial clay with heavily disturbed layers. Passes gradually into overlying and underlying material.
— 6.19	Grey-brown clay, distinctly varved, ∾ 4 cm thick varves, folded, torn and displaced. Particularly heavy disturbances in the bottom half. Uneven lower boundary.
— 6.41	Fine sand with wavy lower boundary.
— 6.60	Coarse silt and fine sand; deformed lower boundary.
— 6.96	Grey-brown, silty clay, heavily disturbed with mixed-in coarse silt and fine sand at the bottom.
— 7.10	Varved clay, with irregularly mixed-in coarse silt and fine sand in its lower half. Stratification also much disturbed by folding and lamination. The lowermost decimetre distinctly silty.
— 7.37	Coarse silt and fine sand with clayey silt in broken and folded bands. Layer probably extends 30 cm deeper, since such a part of the core ran out.
— 8.00	Silty, grey-brown clay with remainders of dark layers (varve boundaries). Heavily folded. Below 7.80 much more diffuse stratification.
—11.00	Grey clay with faint black staining and without observable stratification.
—13.85	Same as above, but distinctly silty. Very quick.
—15.35	Same as above, except that a stratification with ∾ 3 cm thick strata can be detected in the uppermost 15 cm. No traces of regular stratification.
—17.20	Grey-brown, distinctly silty clay, partly brecciated in the uppermost 30 cm. Ran out when extracting the core, so that the diameter $<$ 6 cm. Quick clay.
17.80—18.21	Brown-grey, silty clay, apparently partly disturbed and brecciated.
—18.76	Brown-grey clay with indistinct stratification; the varves disturbed, 5 to 7 cm thick. At 18.63 a 4 cm stone.
—19.10	Distinctly varved clay with measurable varves.
—20.00	Glacial clay with beautiful, regular varves and layers of coarse silt and fine sand.
—21.70	Beautifully varved clay, proximal varves with layers of coarse silt and fine sand, partly displaced, broken up and mixed. Between 20.60 and 20.80 a more pronounced disturbance with overlapping layers of clay.



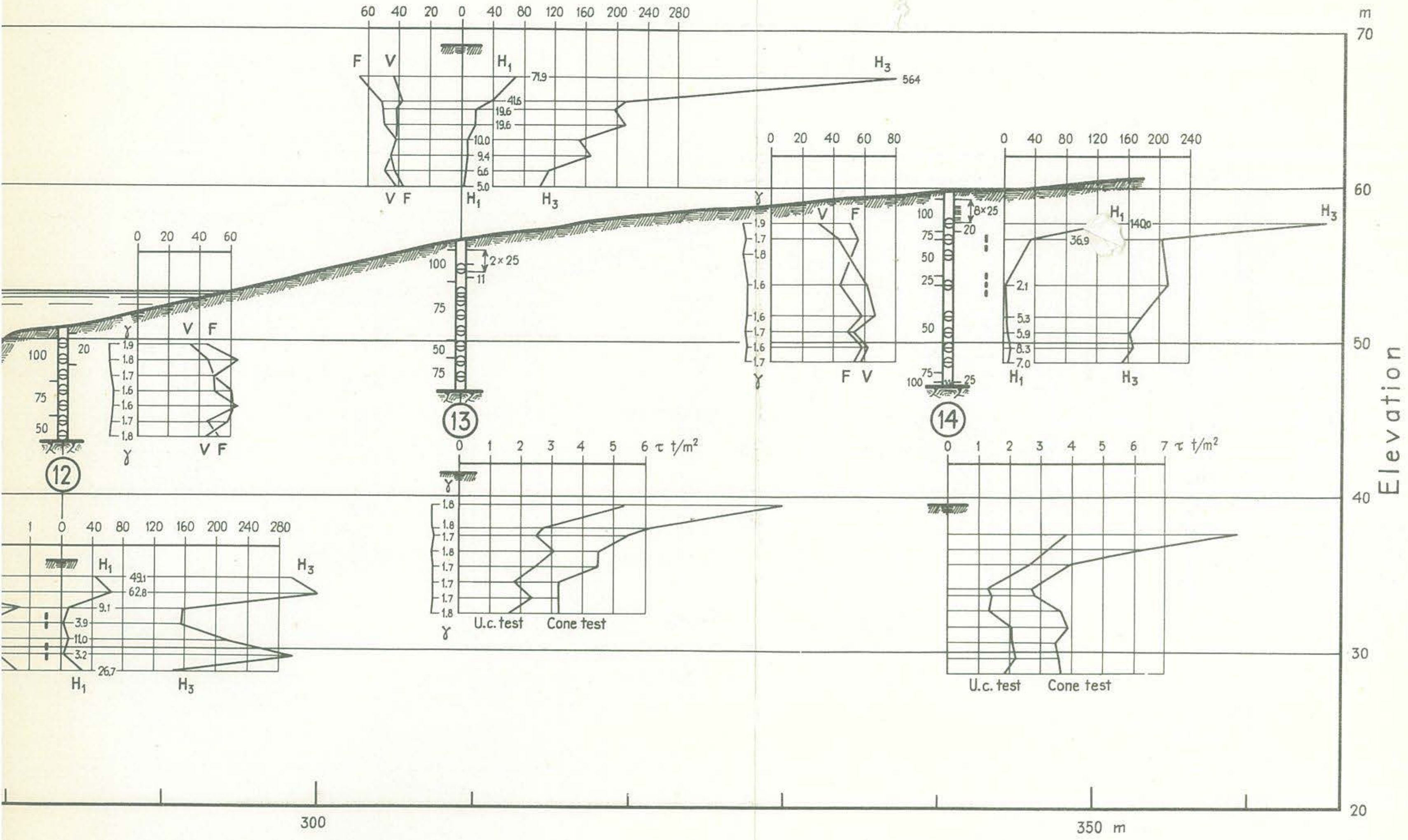
Quick clay $\left(\frac{H_3}{H_1} > 50 \text{ and } H_1 < 1\right)$ Quickish clay $\left(\frac{H_3}{H_1} > 50 \text{ and } H_1 > 1\right)$ U.c. test = Unconfined compression test

SECTION I-I

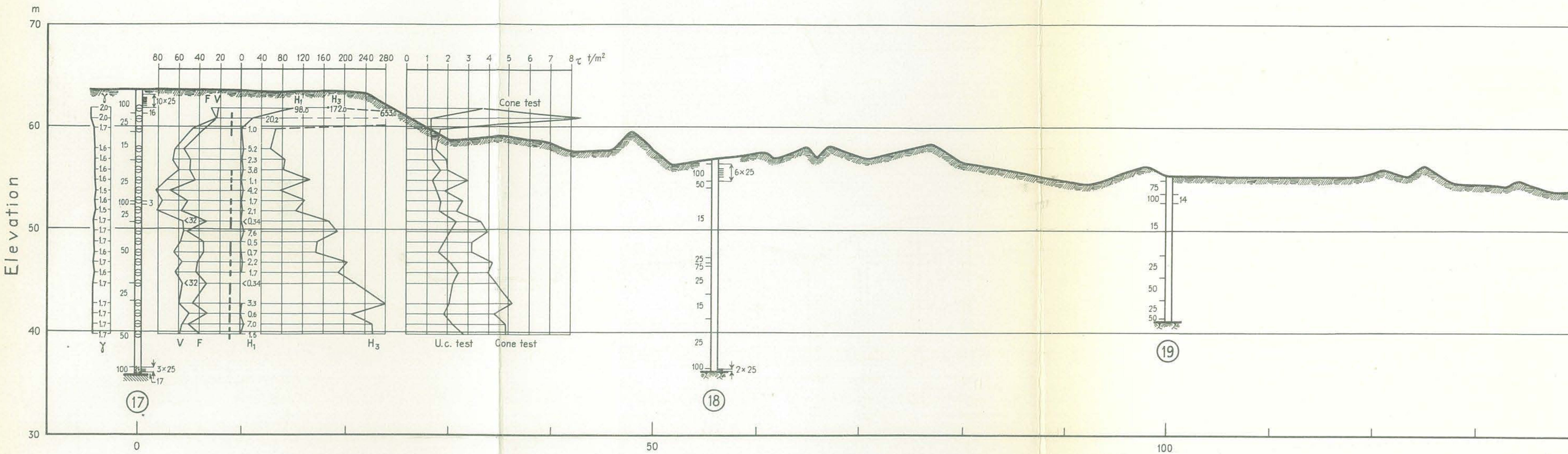


τ t/m²
Cone test
U.c. test
γ
V
F
H₁
H₃
2×25
15×25
7×25
3×25
4×25
145.0
462.0
6
7
8
9
10
11
150
200

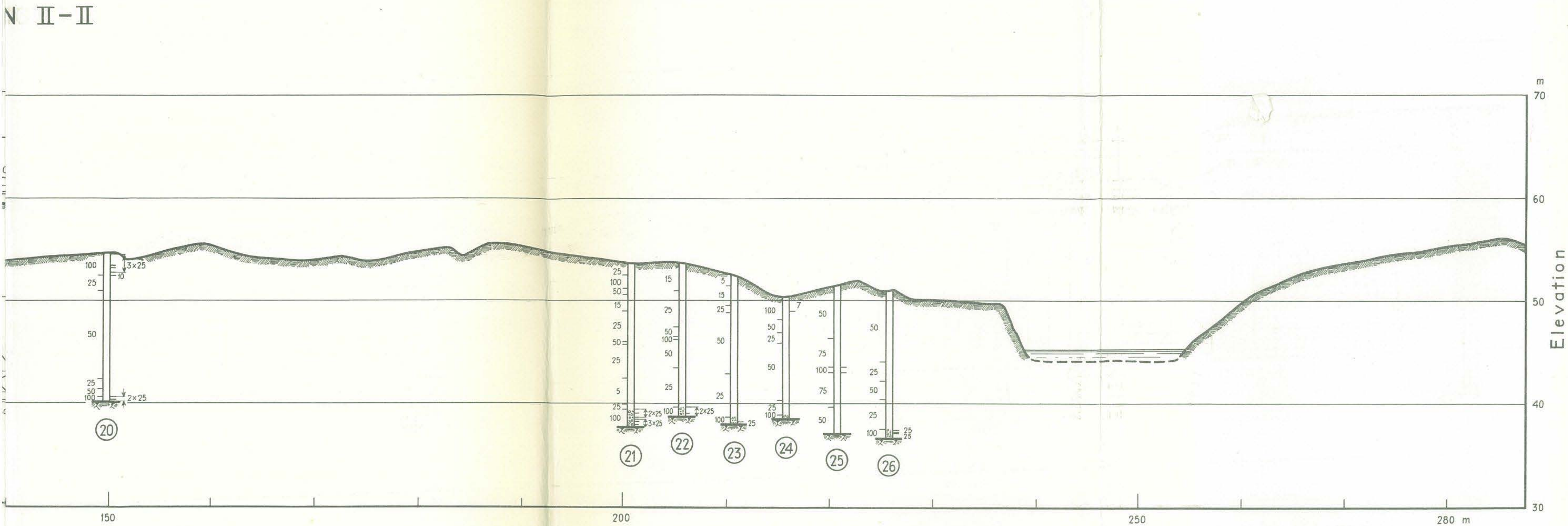
PL.I



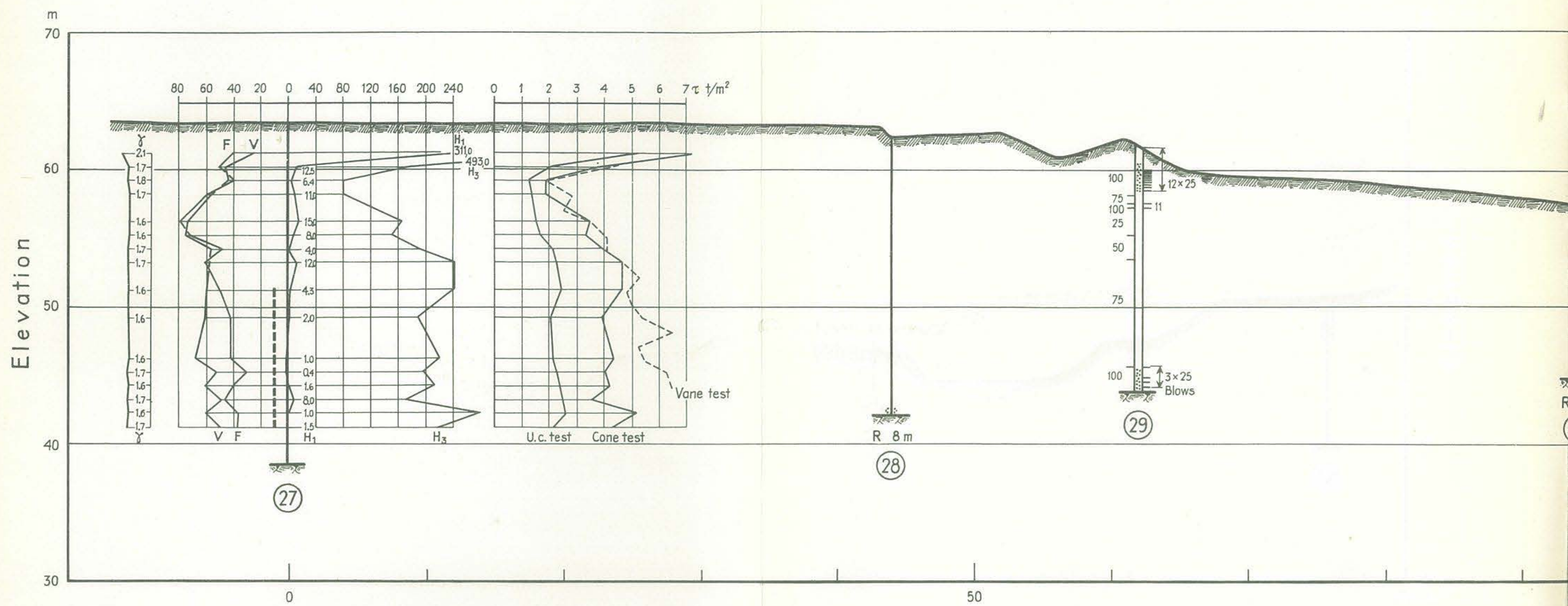
SECTIO



Quick clay $\left(\frac{H_3}{H_1} > 50 \text{ and } H_1 < 1\right)$ Quickish clay $\left(\frac{H_3}{H_1} > 50 \text{ and } H_1 > 1\right)$ U.c. test = Unconfined compression test

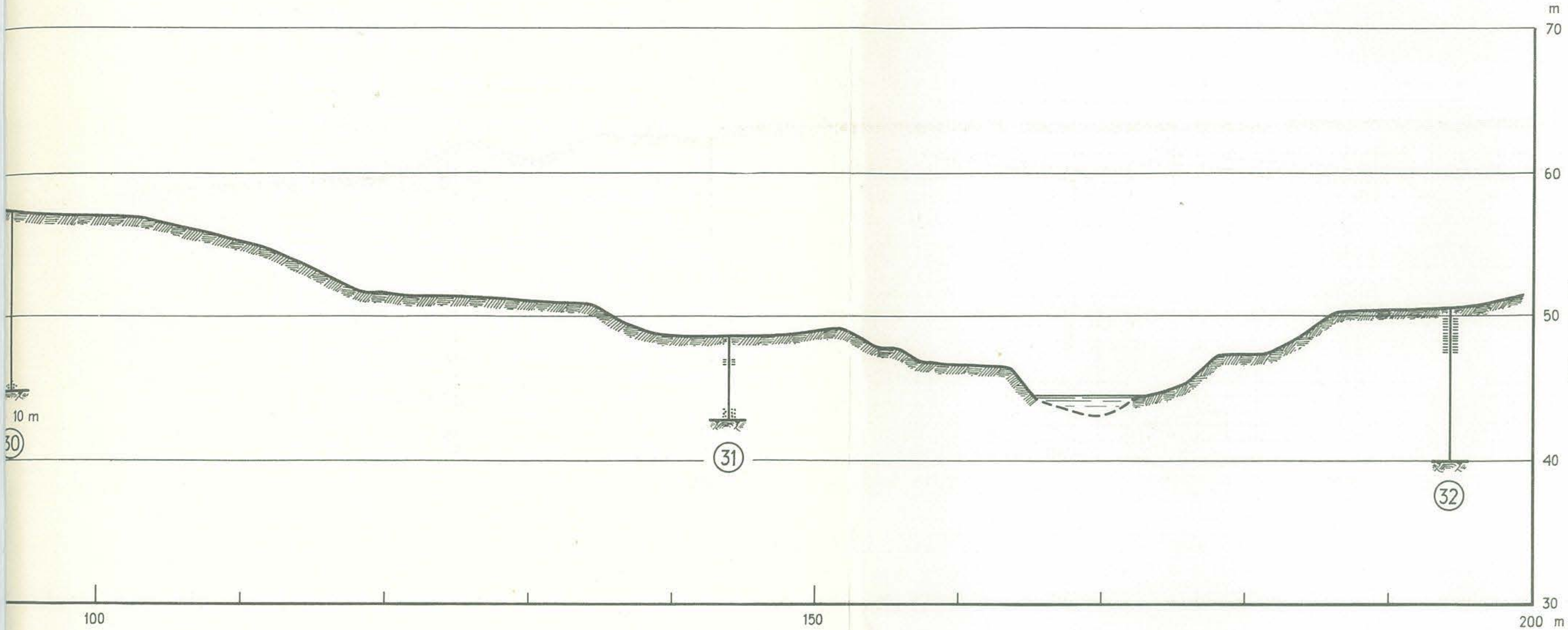

N II-II
m
70
60
50
40
30
Elevation
150
200
250
280 m
3×25
2×25
20
21
22
23
24
25
26

SECTI

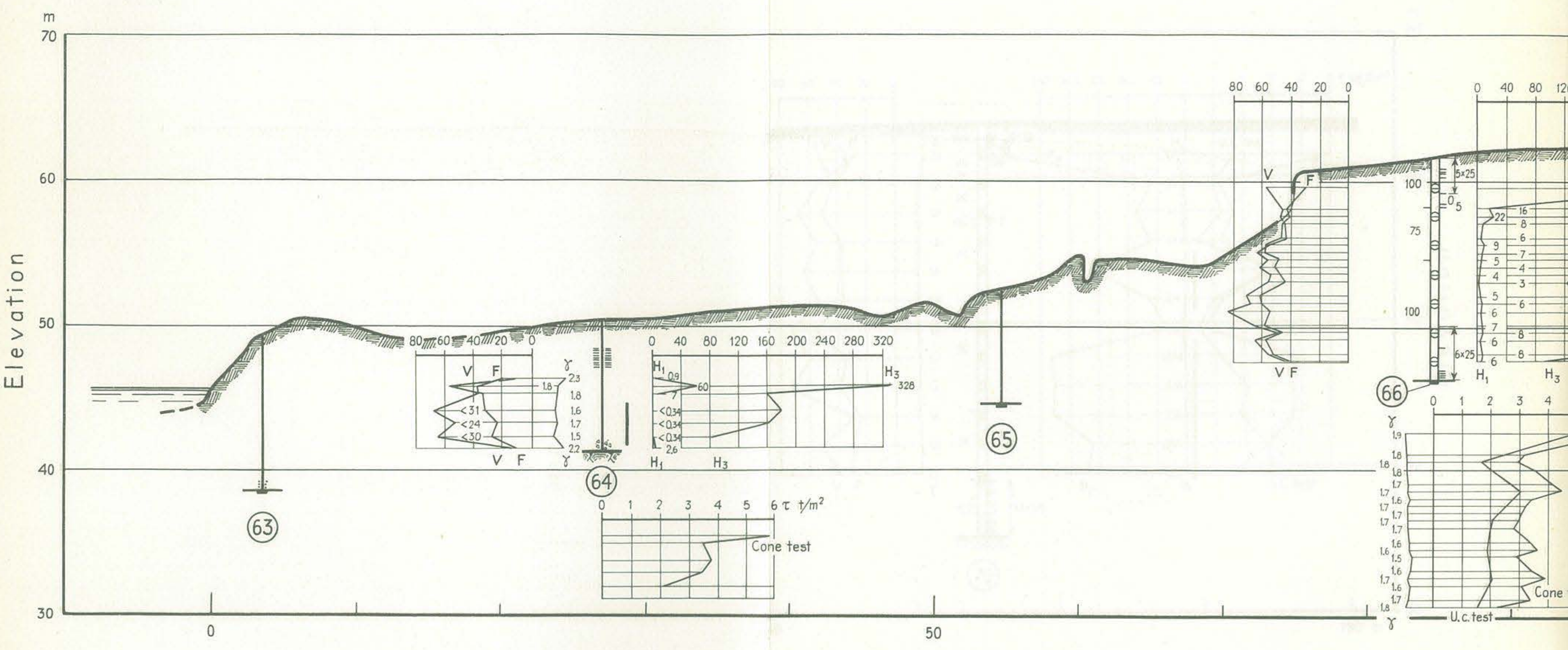


Quick clay $\left(\frac{H_3}{H_1} > 50 \text{ and } H_1 < 1\right)$ Quickish clay $\left(\frac{H_3}{H_1} > 50 \text{ and } H_1 > 1\right)$ U.c. test = Unconfined compression test

ON III – III

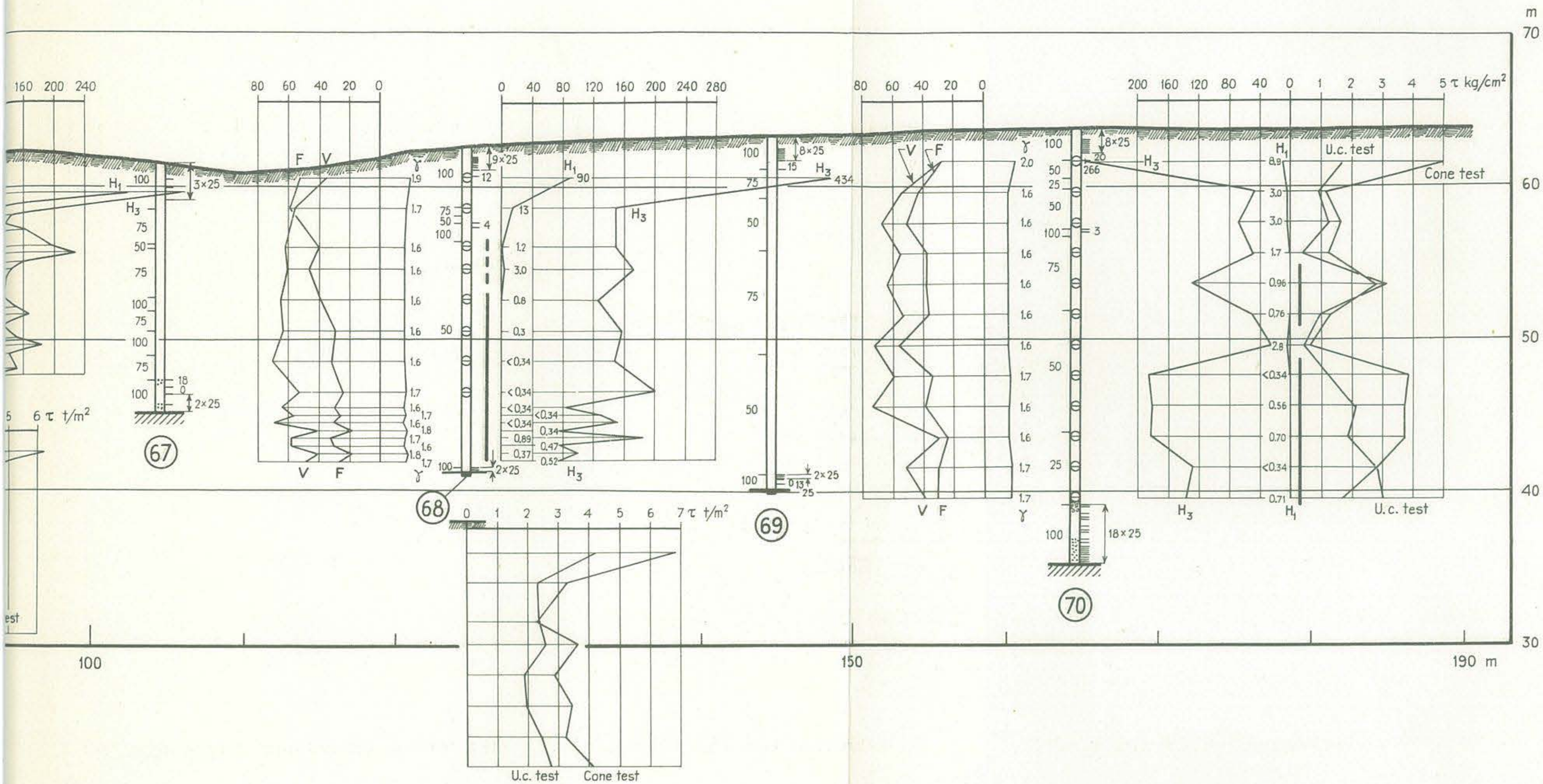


SECTION IV-I

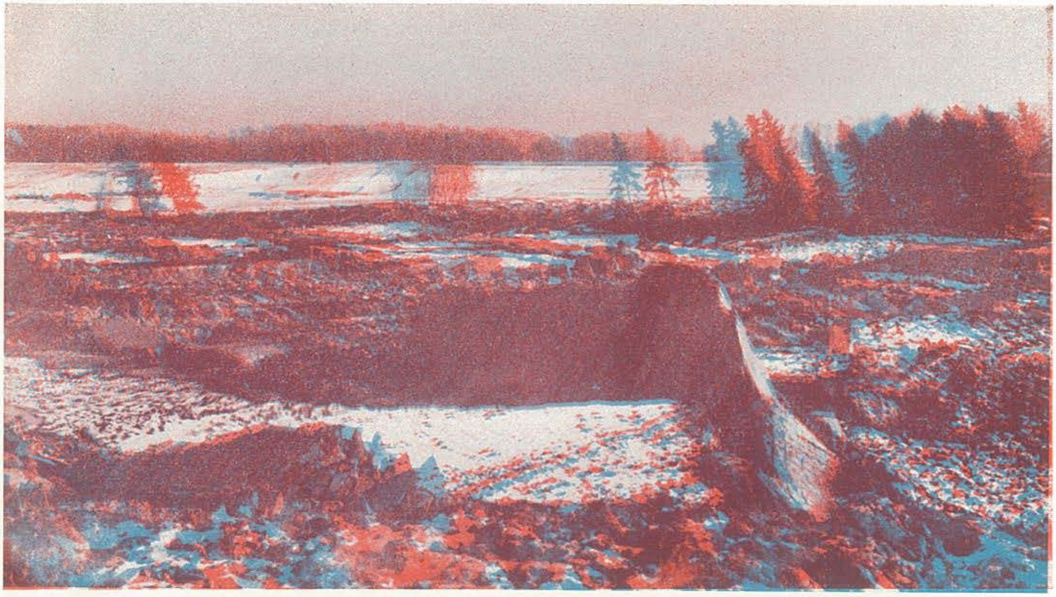


| Quick clay $\left(\frac{H_3}{H_1} > 50 \text{ and } H_1 < 1\right)$ | Quickish clay $\left(\frac{H_3}{H_1} > 50 \text{ and } H_1 > 1\right)$ | U.c. test = Unconfined compression test |

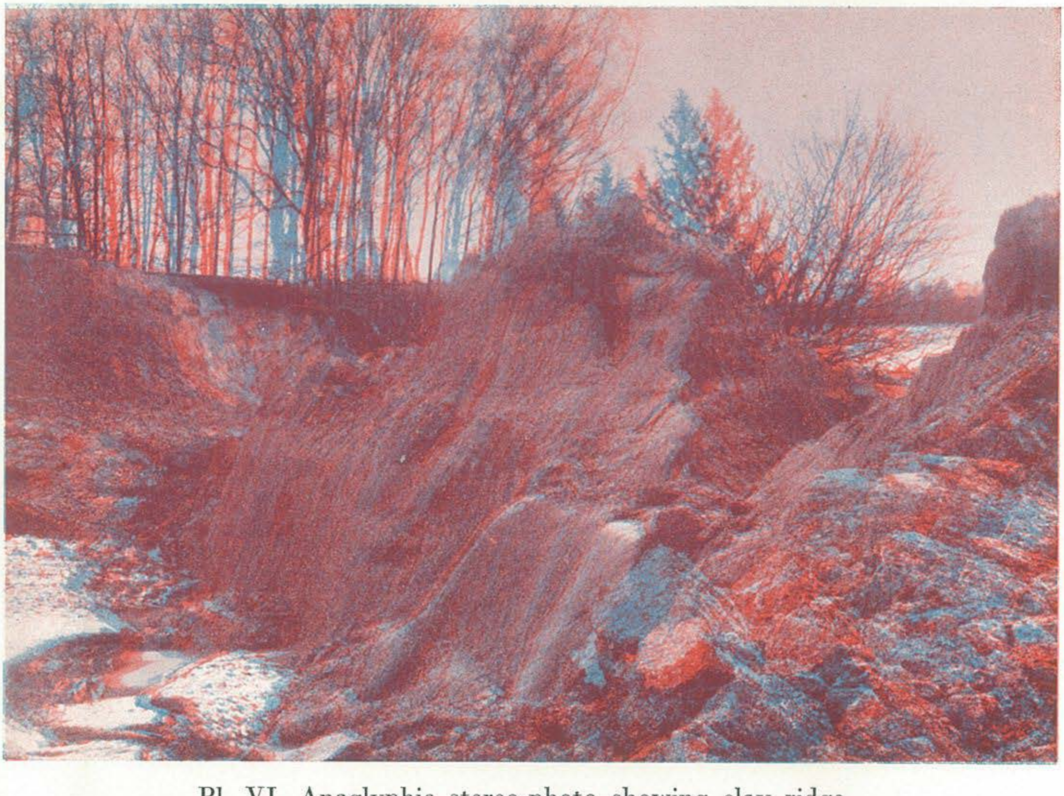
V, KROKEN



67
68
69
70
Elevation
m
70
60
50
40
30
100
150
190 m
τ kg/cm²
τ t/m²
V
F
γ
H₁
H₃
U.c. test
Cone test
3×25
2×25
9×25
8×25
18×25



Pl. V. View of cavity after slide. Anaglyphic stereo-photo taken from point A in direction of arrow, Fig. 3.



Pl. VI. Anaglyphic stereo-photo showing clay ridge.

LIST OF PUBLICATIONS
FROM THE ROYAL SWEDISH GEOTECHNICAL INSTITUTE

Proceedings

No. 1. Soil Sampler with Metal Foils. Device for Taking Undisturbed Samples of Very Great Length. *W. Kjellman, T. Kallstenius,* and *O. Wager* 1950

2. The Vane Borer. An Apparatus for Determining the Shear Strength of Clay Soils Directly in the Ground. *Lyman Cadling* and *Sten Odenstad* 1950

3. Device and Procedure for Loading Tests on Piles. *W. Kjellman* and *Y. Liljedahl* 1951

4. The Landslide at Sköttorp on the Lidan River, February 2, 1946. *Sten Odenstad* 1951

Meddelanden

Nr 1. Kortfattat 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 Byggnadsdag V 1950