SVERIGES GEOLOGISKA UNDERSÖKNING

SER. Ca. Avhandlingar och uppsatser i 4:o NR 27

THE LANDSLIDE AT SURTE ON THE RIVER GÖTA ÄLV

A GEOLOGICO-GEOTECHNICAL STUDY

By

CARL CALDENIUS AND RUNE LUNDSTRÖM

SPECIAL CHAPTERS

By

BROR FELLENIUS AND ERIK MOHRÉN

WITH 5 PLATES

Pris 16:— kronor

STOCKHOLM 1956

Photo Rikets allmänna kartverk.

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PLATE A. Air photograph taken on the 6th of october 1950, 7 days after the slide, showing the slide-area from the west. In the foreground is the river Göta älv with the elevated river-bottom and behind it the two broad slide elements in which the low terrain was splitted. The roof of the sunken railwaystation is visible in the crack between them. The main part of the displaced houses moved with the initial slide elements. The well marked rows of numerous arched slidecrests in the eastern part of the slide have been gradually developed towards the east during the far extended retrogressive part of the slide.

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1. Preface.

A landslide, which had a devasting effect, occurred at Surte, in the valley of the river Göta älv, in the south-western part of Sweden, about 8.10 a.m. on September 29th, 1950. An area of ground, some 400 m in width and about 600 m in length, was cut into slide elements, which slipped towards the river, disintegrated, and were pressed together. The maximum fall of the ground level in the interior part of the slide area was about 12 m and the maximum rise of the ground level in the exterior part of the slide area was about 4 m. At the same time, the width of the river channel was reduced from 120 m to 20 m, and the river bottom was raised about 5 m above the water level in the river. There were 31 dwelling-houses in the slide area. These houses were displaced 50 to 140 m towards tre river. The highway was broken, tilted, and caused to bulge in a wide arc-shaped bend and the railway line was partly buried in the earth masses deposited by the slide.

Fortunately, the slide occurred at a time when most persons employed in their daily work had already left the area. Mothers and children were still indoors, so they were saved from being engulfed and caught in fissures, which reached a considerable depth in some places. About 300 persons became homeless, 50 persons were hurt, most of them slightly, and only one person was killed, crushed to death in a basement which was demolished by the slide.

The volume of the earth masses involved in the slide was estimated at about 3 000 000 m^3. Eye-witnesses have stated that the slide lasted 2 to 3 minutes.

The highway and railway traffic interrupted by the slide was rapidly resumed over temporary trafficways and by-pass routes, whereas the canal traffic was not completely restored until the next day after the slide, since the river channel was blocked. Investigations of the stability conditions were started immediately in order to plan the reconstruction works and determine the causes of the slide. These investigations were jointly conducted by the Royal Swedish Geotechnical Institute, the Geotechnical Division of the Swedish State Railways, and the Geological Survey of Sweden.

The Royal Swedish Geotechnical Institute has published the results of its researches in "The Landslide at Surte on the Göta River, September 29, 1950" by B. Jakobson (Jakobson, 1952). Since the reports on the investigations made in the slide area by the Geotechnical Division of the Swedish State Railways and the Geological Survey of Sweden were not possible to combine advantageously with the account given by the Royal Swedish Geotechnical Institute, it was considered convenient to present them in a publication issued jointly by the former two institutions, in order that the nature of the slide and the investigations dealing with the slide might as far as possible be subjected to an all-sided treatment.

The headings of the chapters show the shares of the authors in this collective work. We have of course discussed and elaborated the results in common. In those cases where our subjects overlapped, their treatment was concentrated in that chapter with which they seemed to be associated most closely, so as to avoid unnecessary repetition.

Stockholm, June 1955.

Carl Caldenius,
Geological Survey of Sweden.

Rune Lundström,
Geotechnical Department,
Swedish State Railways.

2. Introduction.

By Carl Caldenius.

Cavities left after landslides are not uncommon in flat land areas bordering the channels of brooks and rivers in Sweden. However, these cavities very seldom form topographic features which are so dominant as to justify the use of the term "slide topography". Properly speaking, only in some valleys in the western coastal region of Sweden slide cavities are situated so close together, sometimes one depression in another, as to create a morphology characterised by the wide, open hollows and other form elements which are left after slides. The area extending from Åkerström to Lilla Edet, in the valley of the river Göta älv, is famed above others for its beautiful slide topography. The slides which have formed this topography were probably in most cases due to river erosion, which has increased the height and steepened the slope of the high river banks consisting of clay and fine sand (G. Frödin, 1919).

Traces of slides are furthermore very frequently met with in the series of the Quaternary, fine-grained sediment strata. Disturbances, folds, and crush zones in clay, silt, and fine sand strata have been observed since long ago. These phenomena cannot be explained in any other manner than by assuming that the original deposit was divided into slide elements, which were set in motion, with the result that the original structure of the material was deformed. The highly accurate measurements of the annual varves in varved clays required for geochronologic investigations have shown that an extremely small number of profiles were quite free from slips, flattened-out zones, overthrusts, or other phenomena which indicated lateral displacements in the sediment mass. It was usually possible to attribute these mass displacements to changes of equilibrium conditions in Quaternary lake and sea bottoms. These changes were probably due not only to those alterations in the relative position of the bottom with reference to the water surface resulting from the change of the sea level, but also to the load caused by the successive development of gravel and clay shore terraces, formed at the same time on the non-consolidated, thick strata of clay and silt.

The earliest investigations of slides in Sweden were conducted on a purely geological basis. Statements made by witnesses of landslides and observations in slide areas established at an early stage that the slides proceeded in a series of separate shocks. The ground was gradually cracked into segments, which were set loose and began to slip. These segments left a more or less wide depression filled with slide elements which had slipped down. In cases where it was possible to locate the initial slide area at the bank of a brook or a river the release of the slide was ascribed to the undermining of the bank due to erosion. On the other hand, when no visible, external cause of the slide was to be detected, it was assumed that the cohesion of certain clay strata was reduced by wetting, as it was not yet realised that very soft clay was irreversible with respect to water. This assumption appeared to be reasonable since the slides frequently occurred during periods which were particularly abundant in precipitation. At the outset, moreover, it was difficult to distinguish between cause and effect, and the clay which was crushed by the violent slide movements so as to form mud streams was regarded as a proof which indicated that the clay had gushed in this state from the clay wall, and had entrained the cracking superficial dry crust.

In the early 1920ies our knowledge of the physical properties of loose soils and the mechanics of slides advanced so far as to express our present-day conceptions. The method of sampling (piston sampling) evolved at that time permitted the extraction of clay samples of unchanged, natural consistency, and thus afforded materials for empirical determination of the shear strength of clay. From that time on, it was therefore possible to base calculations of stability on real data, and not on hypothetical values. Furthermore, it became possible to compare various methods of calculation with one another and to estimate their reliability in a manner which was previously unknown. In some cases it proved practicable to reconstruct the situation and the shape of the slip surface as well as to throw light on the intricate process of development of some slides. It became evident that the banks of brooks and rivers are highly unstable in some places, and that initial slides starting in such places can cover wide ground in certain areas, e. g. those in which the easily deformable quick clay has an important share in the series of strata.

3. Geology of the Valley of the Göta älv.

By ERIK MOHRÉN.

Topographical Features, Bedrock, and Tectonics.

The river Göta älv is the outlet of the largest lake of Sweden, Lake Venern (44 m above sea level), into Kattegat, a branch of the North Sea. The rapids and falls due to rock thresholds in the river bed at Vargön, Trollhättan, and Lilla Edet have been utilised for water power plants and are canalised, with the result that the Göta älv is now navigable by ocean-going vessels, and constitutes one of the most important inland waterways of Sweden. A short distance north of Surte, the river divides into two distributary branches which flow round the island of Hisingen. The northern branch, which is called Nordre älv, opens out into the sea at a point situated 11 km north of the outlet of the southern branch, which retains the name of Göta älv. The city of Gothenburg lies at the mouth of the latter branch.

Immediately downstream of the falls at Lilla Edet, the water surface of the Göta älv is only 0.6 m above sea level. At Surte, some 35 km farther downstream, the mean water level in the river is practically even with the sea level. During the periods of high water in the sea, the sea water, as a salty bottom current, sometimes flows a long distance up the river. At Surte, the Göta älv is about 200 m wide and some 7 m deep. The discharge is ample, about 500 m^3 per sec. on an average. Therefore, in spite of the inconsiderable fall in the lower reaches of the river, no appreciable sedimentation occurs in the river channel.

The valley of the river Göta älv is a depression formed in crystalline bedrock. This depression is about 1 km in width and about 200 m in depth below the even, peneplain-like surface of surrounding primary rocks. The valley is filled with Quaternary deposits, till, glacifluvial gravel and sand, as well as with thick layers of glacial and postglacial clays. The latter ones cover the major part of the ground surface in the valley, and often form terrace-shaped elevations, which rise from the riverside to a height of 30 to 40 m above sea level at the steeply ascending face of rock.

The eastern slope of the valley frequently coincides with steep cleavage planes in the gneiss, which do not afford any reliable support for loose soils. Moreover, this slope was largely laid open to the attack of the waves in the late epochs of the Glacial period, and is now exposed to persistent western winds. Therefore, this rock surface is either completely naked, or is covered with scanty vegetation consisting of pine and birch trees. The western slope of the valley has an entirely different appearance. It is also steep, but its surface is rugged on account of the outcropping edges and slabs of the gneiss. Furthermore, at the top of this slope there are talus-like accumulations of blocks, gravel, and sand, which are wooded with exuberant deciduous trees and dense undergrowth.

The bedrock forms part of the extensive gneiss region of West Sweden, and consists of grey to greyred gneisses. They were formed during the Gotho-Karelian cycle in the Archaean group. The strike of the gneisses is usually N—S or NNE—SSW. Their dip in the surroundings of Surte is 50° to 60° west. This dip is predominant in the area under consideration, but there are also other directions owing to the folds produced in this formation. The valley of the river Göta älv, just as the neighbouring valleys, was formed along the strike of the rock, and follows the comparatively marked cleavage of the gneiss, the zones of crushing, and other zones of weakness. As regards its origin, this valley is therefore a pronounced rift valley.

The crystalline rock surface, worn down nearly to a peneplain, has probably once been covered with Cambro-Silurian and other Paleozoic formations. Nothing is left of them except some insignificant remnants in the form of rare fillings of fissures in the gneiss. The northern parts of the Fenno-Scandian block have undergone an uplift of the land during the Tertiary period, and it seems that this uplift has also manifested itself

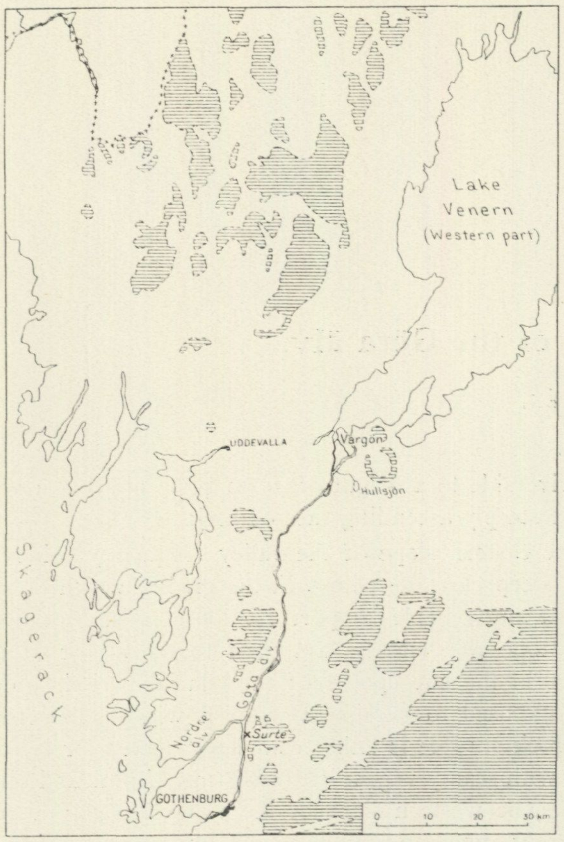

Fig. 1. General map of the valley of the river Göta älv. Horisontally striated = area above the highest marine limit.

in the region under review by lowering the base of erosion and by carving out the bottoms of the valleys. Borehole tests have shown, for instance, that the deepest parts of the bedrock in the valley of the Göta älv near the mouth of the river at Gothenburg are as low as 100 to 150 m below sea level. The hills in the surroundings of Gothenburg reach a height of 70 to 100 m above sea level (Sandegren and Johansson, 1931, p. 7; Munthe, Johansson and Sandegren, 1924, pp. 9—17; Alin and Sandegren, 1947, p. 36).

The borehole tests made in a section of the Göta älv at Surte (see the profile in Fig. 7) have shown the rock bottom of the valley to be situated at a minimum depth of 36 m, whereas the greatest heights of the hills on the east side of the river rise to 130 m. At Nol, 11 km north of Surte, the minimum depth to bedrock is 54 m. In this connection, it is to be noted that the maximum depth of the water in Lake Venern is 98 m. Since the water level in this lake is 44 m above sea level, it follows that its bottom is 54 m below sea level, including the Quaternary filling.

On the whole, if the Quaternary soil cap were removed from the inland landscape, it would exhibit the same typical features as the fiord regions which are to be seen today in the outer parts of the province of Bohuslän, although the valleys would be deeper. In spite of its fluviatile Tertiary development, the valley of the Göta älv has not the character of a V-valley. In fact, its bottom is smoothly rounded and U-shaped. It is therefore probable that the ultimate form of this valley was fashioned during the Quaternary period. In the course of this process, the valley was uncovered from Tertiary sediments (if any), before glacial and glacifluvial deposits were accumulated on its bottom as the ice sheet melted.

Quaternary Glacial Deposits and Change in Level.

It is now commonly assumed that the Glacial period in North Europe consisted of three or four glacial epochs. In the central parts of Scandinavia, however, most of their stratigraphic traces have disappeared.

In general there is only *one* moraine bed in those places where it has been developed or preserved at all. The major part of this region consists of naked, rugged hills, which are separated by valleys filled with sediments. Moraine is sometimes to be found on the bottoms of these valleys. As far as is known, ground moraine proper dates entirely from the last epoch of the Glacial period. Judging from the glacial striae, due to ice action, the ice sheet moved in the direction from N 50—70° E during the last stage of that period. Ground moraine in these regions is closely compact and usually very thin. In the moraine which has not been washed out by running water, the preponderant fractions are 2 to 0.2 mm (sand) and 0.2 to 0.02 mm (fine sand). The presence of stones in this moraine is not particularly marked. It seems that the finer fractions (silt and clay) seldom exceed 10 per cent of the fine-grained soil mass.

It follows from the above that real ground moraine is rarely met with in the region under consideration. The till material is usually found to be accumulated either at right angles to the direction of advance of the ice sheet (terminal moraines) or in parallel to this direction. Even if the terminal moraines are more or less scattered and situated at wide intervals, it appears, nevertheless, that they may be imagined to form continuous rows, which mark various stages of halt or oscillation in the retreat of the ice sheet (Björsjö, 1949, Pl. 2).

It is remarkable that this region contains such a small number of real eskers. The glacifluvial materials usually occur in the form of marginal plateaus in which the sequence of strata often seems to have been disturbed by oscillations in the advance or retreat of the ice sheet. The large gravel field, east of Bohus, is of this type. A similar field is also situated at Rösered, a short distance south of Surte.

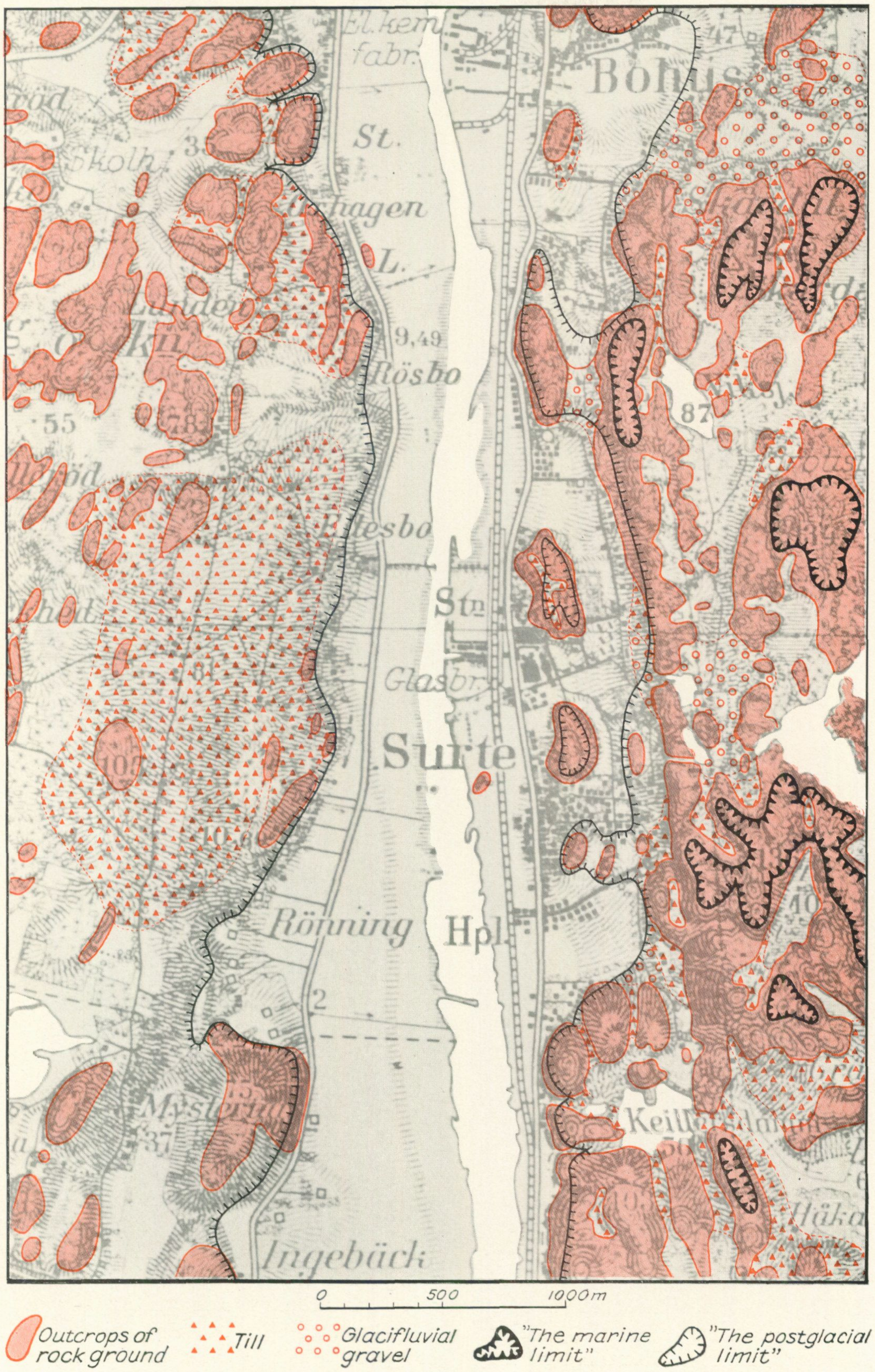

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Fig. 2. Map of the surroundings of Surte with the marine limit (MG) and the post-glacial limit (PG). Scale 1:25 000.

Those natural features of a region as marine terraces, outwash etc. which indicate the outline of the seashore at the moment of the melting of the ice sheet constitute "the highest marine limit" (MG). As the retreat of the ice sheet took place at successively later stages as it proceeded towards north-east, the marine limit becomes, consequently, progressively younger in this direction.

The marine limit at Gothenburg, which developed 13 000 to 14 000 years ago according to Gerard De Geer's geochronology, has an altitude of about 95 m above the present sea level. Furthermore, the altitude of the marine limit is 109 m at a point 5 km south of Surte and 112 m in the north-east corner of the map shown in Fig. 2. The marine limit is plotted on this map by interpolating between the two subsequent values, in order to give an idea of the approximate distribution of land and sea during the period immediately after the melting of the ice sheet in the Surte area, although the marine limit does not represent a synchronous shore line. The maximum thickness of the ice sheet may have been of the order of 2 000 to 3 000 m. Depressed under this burden, the earth's crust was more or less elastically uplifted, as the ice melted.

By using subsequent seashore features which indicate synchronous shore lines, it is possible to reconstruct a wide bay of the ocean, extending at the end of the Late Glacial period into the present basin of Lake Venern. The waters discharged into this bay comprised the water formed by melting of the ice sheet in the north and also, during some time, the water from the Baltic Sea, which first flowed through the wide sound — the Central Swedish Sound — that was opened across Sweden owing to the depression of the land surface, and then passed through a progressively narrowing river — the Svea älv (von Post, 1928). Large quantities of cold fresh water were drained into the Bay of Venern. The clay mud, suspended in this water, was rapidly sedimented in the bay, precipitated by the electrolytes present in the salt water which formed a counter-current flowing close to the bottom in a direction opposite to that of the fresh water surface current mowing south-westwards. The clay sediment was deposited as a sheet of more or less uniform thickness, and was spread over the deep valleys, partly filled with moraine or glacifluvial materials, as well as over mountain plateaus, which were still situated in the zone of sedimentation. The general features of the subjacent topography are therefore visible through this sedimentary sheet. In the deeper valleys, where for natural reasons, the duration of sedimentation was longer, the thickness of the clay layer was correspondingly greater, and often reached several decametres.

The till layer covering the heights above the marine limit remained in a more or less undisturbed condition. In the plane of wave erosion, on the other hand, the rocks were washed completely clean. Only a few isolated blocks might possibly have been left over. In the valleys below the zone of abrasion, the moraine material removed by washing was sedimented in the form of marine outwash gravel on the clay and on sand layers of glacifluvial origin.

Owing to the continued uplift of the land, the seashore level was progressively lowered. New moraine areas, and subsequently also sediment regions, were submitted to wave action. As this process advanced, the rock masses were increasingly freed from all Quaternary deposits. Therefore, the landscape becomes more and more naked in a westward direction.

Geographical Development during the Late Glacial and the Postglacial Periods.

The arctic character of the Late Glacial sediment manifests itself most distinctly in the molluscan and foraminiferan fauna as well as in the diatomacean and pollen flora. The only mollusc represented in those layers which were closest to the ice sheet is Portlandia arctica. The most easily recognisable elements which appear after that are thick-shelled forms, such as Saxicava arctica, Mya truncata, Astarte borealis, etc. Their frequency is in general relatively low, unless the shells have accumulated so as to form shell gravel banks owing to special circumstances.

The foraminiferan fauna in the high-arctic strata is very poor in specimens, and consists almost exclusively of Elphidium clavatum incertum (Brotzen, 1951). The diatoms have not been investigated in the samples taken at Surte, but in the boreholes put down at Gothenburg (Mohrén, 1945), in the mouth area of the river Göta älv, they exhibit a peculiar mixture of fresh-water and salt-water elements, especially plankton forms of both, during the whole Late Glacial period on account of the hydrographic development outlined in the above.

The arboreal pollen flora is also poor both in species and in specimens. This is to be expected as the severe arctic or subarctic climate did not permit the development of rich vegetation. The region was first characterised by scattered skerries and then by an archipelago with islands covered only by a thin layer of soil suitable for vegetation. Fir is completely predominant in this area, and birch comes next, but more thermophilic elements are also represented. Moreover, when the pollen was embedded in the sediment, it was strongly diluted with minerogenic materials owing to ample supply of mud. Unfortunately, the pollen content of the moraines has not been investigated. It is therefore impossible to decide with certainty whether and to what extent the pollen in the Late Glacial clay was primarily deposited or in part secondarily redeposited. In fact, there are some types of pollen which seem to indicate secondary redeposition. Nevertheless, it appears most probable that the major part of the pollen is primary.

When the discharge of cold fresh water into the basin of Lake Venern was reduced, it should have been easier for the sea water to imprint its marks on the hydrographic development of this basin. At the same time, however, the upheaval of the land caused the sills at the present outlet of Lake Venern to approach so closely to the surface of the sea that they began to prevent the salt water from flowing into the new-formed lake. And further, the outflow from Lake Venern was also directed into that channel which subsequently became the river Göta älv, as the mountain plateaus west of the river rose above the sea level. It is known that the sea level at Gothenburg dropped to about + 15 m during that epoch, *i.e.* the Ancylus period of the Baltic basin (Alin, Niklasson, and Thomasson, 1934). If we try to reconstruct the geographical conditions in an upstream direction in the valley of the Göta älv, then we find that the sea level at Surte was at the same time probably just above the + 20 m level. In the very uneven ground on both sides of the river, this arm of the sea can only have been a fiord which was so narrow that its hydrography may have been influenced to a large extent by the water from the river a long distance downstream of the outlet from Lake Venern.

Nevertheless, we also find at the same time that the occurrence of marine diatoms is very strongly marked in the deposits originating from the Ancylus period up to the elevations of Önaforslandet, near Vargön (von Post, 1928, p. 91). Furthermore, the conditions in the Gothenburg area indicate a very pronounced influence of fresh water immediately before and at the beginning of the Ancylus period. However, this influence ceases altogether towards the end of the Ancylus period.

The + 15 m level of the seashore at Gothenburg marked, moreover, a turning-point in the sinking of the sea level for the time being. The isostatic intensity of the uplift had by then diminished to such an extent that it was surpassed by the eustatic elevation of the ocean. Consequently, the seashore began to regrede landwards. This resulted in transgression and in superposition of marine sediments on terrestrial deposits (if any). One of the causes of the eustatic elevation was a progressive increase in the warmth of the climate. The ice sheet remaining on the surface of the land was therefore rapidly melted, and the water flowed back into the sea. Furthermore, the warmer climate influenced the marine fauna. The arctic species disappeared or their number was considerably reduced in favour of recently immigrated species which were more thermophilic.

On account of the transgression, the sea level at Gothenburg rose from the above-mentioned altitude of + 15 m to + 22 m. The corresponding shore line produced the Postglacial limit (PG) in the middle part of the Early Stone Age. This limit is indicated by raised beaches or terraces. As will be shown further on, the corresponding shore line at Surte can be located between the levels of + 27 and + 28 m. The altitude of the Postglacial limit at Lilla Edet is + 36 m (cf. Munthe, Johansson, and Sandegren, p. 150). The absolute rise from the level during the Ancylus period to the Postglacial limit decreases as the uplift of the land in the north becomes greater, so that *status quo* is practically reached at the elevations near Vargön. Thus, it seems that an influence of salt water during the Postglacial period is not to be reckoned with in the basin of Lake Venern, and that this influence is scarcely to be expected in the upper part of the river channel. There is a small lake, Lake Hullsjön, 8 km south of Vargön (von Post, 1928, p. 55), with the present water level at an altitude of + 38.4 m and with a probably original pass threshold at an altitude of + 43 m. In this lake, the sequence of strata originating from that time exhibits only slight traces of the influence of salt water. On the other hand, there are comparatively many Arenaria-forms, dating from the epoch immediately after the Ancylus period, which characterise large, clear lakes, such as the Ancylus Lake and Lake Venern. Consequently, the salty bottom water was not able to pass over the threshold at Lake Hullsjön, whereas the surface water from Lake Venern was able to rise above that level. The diagram of this site published by von Post does not reach the depth of the deposits dating from the same period as those represented in the diagram referring to the locality Önaforslandet. Therefore, there is no perfect correlation between these two sites for the same period.

After having accidentally reached maximum values in the course of the Postglacial transgression, the sea level in these regions began to descend again. Apart from slight oscillations or halts, this descent continued until the sea level reached its present state. Below the gravel-covered terrace at + 27—28 m (PG) these oscillations seem to have left extremely small traces in the Surte area. A bench at an altitude of + 19 m and a wave-built terrace at an altitude of + 12 to + 13 m represent two pauses in the descent of the shore to the present plane of the river. The present river channel was cut in this plane to a depth of about 7 m, which corresponds to the present discharge.

Sequence of Strata at Surte.

The sequence of strata in the landslide area at Surte will now be scrutinized against the geological background outlined in the above. One of the first measures taken after the slide was to put down boreholes in order to estimate the risk of new slides and at the same time, if possible, to study the mechanics of the slide and to determine is causes. In order to reconstruct the original stratification in the slide area, a borehole section situated immediately outside the slide area was used as a standard in examining the soil cores taken in the slide area proper.

The micropaleontological analysis of the samples was entrusted to the Geological Survey of Sweden, which charged Mr. R. Hägg, Former Assistant, Paleozoological Department, State Museum of Natural History, Stockholm, with the examination and determination of molluscs.

Borehole Section 464 + 966.20 outside the Slide Area.

For practical reasons, this description begins with an account of the sequence of strata in the borehole section situated outside the slide area. In this section the following boreholes are dealt with: E 14, E 226, and E 376.

Each soil core taken from the boreholes was provided with a field record, which specified the colour, the type, the shell content of the sediment, etc. These observations were noted and marked on a calculating machine paper tape, which was stretched along, and attached to, the timber board trough used as a container for the soil core. After that, three types of samples were cut out of the central portions of the core, viz., first, samples 25 cm in length each, at intervals of 0.5 m, for the determination of the shearing strength by compression tests, etc., second, samples 10 cm in length each, at intervals of 0.5 m, for the Swedish cone test, the weight loss analysis, the determination of the water content, etc., and third, samples 10 cm in length each, at intervals of 0.5 m, for the analysis of foraminifera. Finally, samples for pollen analysis were taken from the parts of the core left over between the above-mentioned samples, that is to say, at approximate intervals of 1 or 2 dm. In addition, mollusc shells were also extracted in this borehole section, wherever this was possible. In the first place indeed, these shells were obtained from the sedimentation residue in the analysis of foraminifera.

Borehole E 14[1]. Altitude above sea level + 1.42.

Level, metres below the soil surface.

0.00 to 1.00 Auger boring through surface soil and dry crust.

1.00 to 2.78 Core boring. Clay, greenish-grey, muddy, homogeneous, loose. Rich in shells between the levels 2.0 and 5.0. Turritella communis, Nassa reticulata, Corbula gibba, Venus ovata, Raphistoma brachystoma, Tellina ferruginosa.

2.78 to 3.78 Clay, greyish-green, muddy, homogeneous, relatively loose.

3.78 to 6.06 Clay, greyish-green, muddy, homogeneous, firmer. Between the levels 5.0 and 6.5: Hydrobia ulvae, Thyasira flexuosa, Venus gallina, Cardium echinatum, Cardium minimum, Corbula gibba, Cyprina islandica, Montacuta bidentata.

6.06 to 7.75 Clay, greyish-green, muddy, homogeneous, relatively firm. Mytilus edulis, Retusa nitidula, Nucula tenuis, Thyasira flexuosa, Montacuta bidentata, Abra nitida, Corbula gibba, Thracia convexa.

7.75 to 8.84 Clay, greenish-blue, with weak flame-shaped stains of ferrous sulphide.

8.84 to 11.02 Clay, greenish-blue, with weak flame-shaped stains of ferrous sulphide. Between the levels 8.5 and 9.5: Litorina rudis, Retusa nitidula, Nucula tenuis, Thyasira flexuosa, Montacuta bidentata, Corbula gibba, Cultellus pellucidus, Arcinella plicata. Between the levels 9.5 and 11.02: Hydrobia steini, Nucula tenuis, Abra nitida, Cardium echinatum, Corbula gibba, Montacuta bidentata.

11.02 to 13.92 Clay, greenish-blue, with distinct flame-shaped stains of ferrous sulphide.

13.92 to 16.48 Clay, greenish-blue, with distinct flame-shaped stains of ferrous sulphide in the uppermost part. At the level 14.0: Cardium fasciatum, Montacuta bidentata, Nucula nucleus.

16.48 to 19.62 Clay, greyish-green, very muddy; containing little ferrous sulphide in the uppermost part, but more in the lower portions. Worm holes and worm tubes in the lowest part. At the level 16.80 a shear crack, 85°. At the level 17.60 to 17.90 two parallel shear cracks, 85°. At the level 18.3 a shear crack, 70°, At the level 18.25 a *fine silt layer;* at 19.4 *distinct presence of silt,* diffusely spread.

19.62 to 22.30 Clay, slightly muddy, *distinctly silty;* rich in diffusely spread ferrous sulphide. The part of the core between 19.62 and 19.80 was deformed during the extraction. At the level 21.40 a shear crack, 80°. At the levels 21.60, 21.75, and 22.25 thin layers of clayey fine sand. At the level 19.9: Nucula. In the lowest part worm holes and remains of vegetable matter. At the level 20.0: Abra alba.

22.30 to 22.91 Clay, slightly muddy, distinctly silty. Clearly visible varves of ferrous sulphide.

22.91 to 25.45 Clay, distinctly silty, very slightly muddy; rich in ferrous sulphide, which is concentrated in horizontal layers. The part of the core between 22.91 and 23.05 was deformed during the extraction. Between the levels 23.20 and 23.25 layers of medium sand with remains of shells. At the level 24.30 a centimeter-thick layer of clayey fine sand; ditto at 24.40. The clay is slightly quick at the level 25.15. Molluscs are rare.

25.45 to 28.01 Clay, bluish-black, very slightly muddy. No pronounced siltiness, but distinct varves of ferrous sulphide. Owing to the firmness of the clay, the ends of the core were deformed during

[1] "E" mean east. "W" means west. The figure expresses the distance, in metres, from the position of the railway line before the slide.

	the extraction. In spite of its firmness, the clay is nevertheless slightly quick.
28.01 to 30.87	Clay, bluish-black, very slightly muddy, firm, somewhat quick. Distinct presence of ferrous sulphide, which is varved down to 30.6 and more uniformly greenish-bleu below this level. *In the uppermost part a Portlandia artica.* Worm tubes are abundant.
30.87 to 31.16	Clay, bluish-black, very slightly muddy. Varves of ferrous sulphide. Worm tubes are abundant. For the rest, similar to the foregoing part of the core.
31.16 to 31.44	Clay, bluish-black, very slightly muddy. Flame-shaped stains of ferrous sulphide. (This part of the core was heavily deformed during the extraction.)
31.44 to 33.97	Clay, bluish-black. Varves of ferrous sulphide. About the level 32.0 two thin layers of clayey fine sand.
33.97 to 36.58	Clay, bluish-black. Marked and thick varves of ferrous sulphide. In the lowest part a layer of clayey fine sand, 5 cm in thickness. It proved impossible to continue the borehole below this depth. End of core.

Borehole E 226. Altitude above sea level + 6.79 m.

Level, metres.	
0.5 to 0.90	Dry crust, greenish brown-yellow. Markedly sandy at the level 0.75.
0.90 to 1.35	Dry crust clay, brownish-yellow in the uppermost part, greenish-grey with rusty stains in the lower parts, firm.
1.35 to 2.85	Clay, greyish-green, muddy, loose in the uppermost part, firmer in the lower parts.
2.85 to 5.14	Clay, greyish-green, muddy, relatively loose, firmer in the lower parts. At the level 4.25 a shear crack, 40°, and a transverse crack. Molluscs are abundant.
5.14 to 5.70	Clay, greyish-green, muddy, homogeneous, relatively firm. Molluscs are comparatively rare.
5.70 to 6.40	Clay, blackish-blue, slightly muddy, relatively firm. Flame-shaped stains of ferrous sulphide. Cardium echinatum.
6.40 to 8.00	Clay, greyish-green, muddy, relatively firm, homogeneous. Some accumulations of ferrous sulphide between the levels 7.5 and 8.0.
8.00 to abt. 9.00	Clay, greyish-green to greenish-grey, muddy, relatively firm, homogeneous. Some accumulations of ferrous sulphide. (The uppermost part, 15 cm in length, was deformed during the extraction.) Astarte elliptica.
9.00 to 9.90	Clay, light bluish-grey. Several Mytilus shells at the level 9.00. Mollusc shells are abundant in the lowest part. The clay is relatively firm in the uppermost part, looser in the lower parts.
9.90 to 10.05	Clayey gravel to clayey medium fine sand.
10.05 to 10.10	Sandy clay.
10.10 to 10.15	Clayey fine sand.
10.15 to 10.85	Clay, light bluish-grey, with varves of ferrous sulphide, very loose in the lowest part.
10.85 to 11.21	(Deformed by the cutting edge of the sampler.) Clay, bluish-grey. Varves of ferrous sulphide. Stones and fine sand on the bottom.
11.21 to 11.24	Clay, bluish-grey, without ferrous sulphide.
11.24 to 12.55	The main material is medium sand, grey, relatively coarse in the lowest part. Irregular lumps of grey, loose, flattened clay are embedded in this material.
12.55 to 12.78	Medium fine to fine sand, grey, clean, homogeneous.
12.78 to 12.93	Clay, brown, varved, with rusty layers of medium fine to fine sand or clayey fine sand.
12.93 to 13.15	Medium fine to fine sand, homogeneous, grey or tinged with rusty colour. The upper boundary is not sharply defined.
13.15 to 13.33	Clay, grey, tinged with brownish-violet, loose, very soft, containing some sand. A rusty lump of sand is embedded in this clay.
13.33 to 13.46	Alternate varves of fine sand and clay. Distinct stratification.
13.46 to 13.48	Stones, which damaged the cutting edge of the sampler.

Another sample was taken between the levels 11.20 and 13.48 by means of a piston sampler with a view to a closer examination of the peculiar lumps of clay observed at the levels from 11 to 12 m. The second sample was taken at a point about 1 m south of the first. The results of its examination are given below.

10.50 to 11.90	Clay, blackish-blue, with varves of ferrous sulphide.
11.90 to 12.15	Clay, bluish-brown, varved with layers of sand.
12.15 to 12.25	Sand, varved with layers of clay.
12.25 to 12.35	Clay, varved with layers of sand.
12.35 to 12.70	Medium fine to fine sand, indistinct varves.
12.70 to 13.00	Fine sand, strongly rusty-coloured in the uppermost part, slightly yellowish in the lower parts. End of core.

Borehole E 376. Altitude above sea level + 13.42 m.

Level, metres.	
0.00 to 0.80	Auger boring through sand and dry crust clay.
0.80 to 1.20	Dry crust clay, brown, tough, with slight indications of varves.
1.20 to 2.00	Clay, brown, with thin sand layers. Relatively distinct varves.
2.00 to 2.49	Clay, brownish-blue, with weak layers of ferrous sulphide and thin layers of sand.
2.49 to 5.04	Clay, brownish-blue to bluish-brown, varved, with small layers of ferrous sulphide.
5.04 to 8.30	Clay, brownish-blue to bluish-brown, with small layers of ferrous sulphide and sand layers, varved.
8.30 to 10.60	Clay, varved, with varved sand. End of core.

A summary of the sequence of strata in the standard profile E 14 is also represented in Fig. 3. The sediment consists of clay throughout its thickness. There are no reliable guide layers, but certain main features can be distinguished owing to the presence of muddy substance and ferrous sulphide and thanks to the occurrence of small sand layers. However, the boundaries are rather vague.

Down to a depth of about 8 m, the colour of the sediment is uniform greyish-green on account of the comparatively high mud content. In the depth range from 8 to 16 m, the colour of the clay becomes bluish owing to the more or less distinct presence of ferrous sulphide, which is either diffusely disseminated or accumulated in dark, flame-shaped stains. This bluish colour disappears between the depths from 16 to 19 or 20 m, where the colour becomes greyish-green again. As well in this zone as further below, down to 22 m, there are abundant traces of vegetable matter and worm holes, or the like. Between 20 and 22 m the ferrous sulphide is diffusely spread again.

Below the level 22 m the ferrous sulphide is the dominant characteristic of the sediment, so that its colour is in some places entirely bluish-black. This is a sign of comparatively rich organic life, but indicates at the same time an inadequate supply of oxygen. As the depth becomes greater, the ferrous sulphide is to an increasing degree accumulated in horizontal layers of blackish-blue colour, whereas the clay between these layers is greyish-blue. The presence of relatively coarse terrigenous material is conspicuous in the zone between 22 and 25 m. This indicates an ampler supply of materials or erosion at the fiord shores and washing-out towards the middle of the valley. The sandy material is either more or less diffusely disseminated in the clay or accumulated in layers which are distinct but thin. Two thin clayey sand layers were found at a depth of 32 m, and a layer of clayey fine sand, 5 cm in thickness, was observed in the lowest portion of the core. It was probably a further increase of the sandy layers that offered a resistance which was so high as to prevent continued boring.

In addition to the stratigraphic indications given by the type and the colour of the sediment, useful information is also furnished by the molluscan fauna. The table on this page contains a list of the molluscan fauna found in the borehole E 14. This table is based on field observations as well as on the determinations of the shells which were obtained from the samples, used for foraminifer sedimentation tests.

Since the material in this core had mostly to be utilised for other purposes, which have been mentioned in the above, it was by pure chance that some samples happened to contain molluscs. In view of the important part which has been played by molluscs in the Quaternary stratigraphic investigations, at least formerly, it would have been desirable that a whole core passing through an undisturbed sequence of strata might have been examined in this respect. Unfortunately, this was not possible under the circumstances. Nevertheless, the list of molluscs given in the above table is sufficient to show that, even in the small volume of a core, the

	Depth, metres									
	2	5	6.5	8	9.5	14	17	18	20	28
Abra alba									×	
Abra nitida			×		×		×			
Arcinella plicata				×						
Cardium echinatum		×			×					
Cardium minimum		×								
Cardium fasciatum						×				
Corbula gibba	×	×	×	×	×					
Cultellus pellucidus				×						
Cyprina islandica		×								
Leda minuta							×			
Montacuta bidentata		×	×	×	×	×				
Mya truncata								×		
Mytilus edulis				×						
Nucula nucleus						×			×	
Nucula tenuis	×		×	×	×					
Portlandia arctica										×
Tellimya ferruginosa	×									
Thyasira flexuosa		×	×	×						
Thracia convexa			×							
Venus ovata	×									
Venus gallina		×								
Hydrobia steini					×					
Hydrobia ulvae		×								
Litorina rudis				×						
Nassa reticulata	×									
Retusa nitidula			×	×						
Raphistoma brachystoma	×									
Turritella communis	×	×								

molluscs are fairly abundant as well in species as in individuals down to a depth of 14 to 17 m. This relatively young fauna is markedly characteristic of a warm environment, in contradistinction to the extremely scanty fauna which occurs below the 17 m level.

A similar observation was made in the borehole E 226, where the boreo-lusitanian species Cardium echinatum was found at a depth of 6 m, whereas the arctico-circumpolar species Astarte borealis occurred at a depth as small as 8.5 m. No molluscs were observed at lower levels in this borehole.

All the same, an examination of the walls of the slide scar which were open in the arctic sequence of strata showed that the molluscan fauna was not particularly poor in individuals, even though the number of species was not great.

Borehole Section 464 + 764 within the Slide Area.

This borehole section was situated about 200 m north of Section 464 + 966.20, that is to say, the starting-point of the section under consideration was close to the former site of Surte South Railway Station. The cores taken in this section are dealt with below in the order of their distance from the railway line, viz. borehole W 137, E 19, E 99 a—c, E 190, and E 280. Swedish cone tests were made immediately after the extraction of the cores. Then each core was cut through its whole length, and was accurately examined on the site in order to determine the tectonics of the slide, particularly the slip surface, by means of the type, the colour, and the macrofossil content of the sediment.

Borehole W 137. Altitude above sea level + 4.07 m.

This borehole was put down west, *i.e.* on the right side, of the railway line, close to the river Göta älv. The stratigraphically youngest parts of the strata are to be found in this place. The borehole W 137 was put down before all others in order to estimate the risk of new slides which might be involved in the dredging of a new river channel passing through the earth masses displaced by the slide. In general, no molluscs were observed in the core. On the other hand, the following molluscs were found on several occasions in the course of the dredging and excavating operations, *e.g.* in the cuts: Astarte elliptica, Cyprina islandica, Corbula gibba, Isocardia cor, Lucinopsis, Pecten septemradiatus, Venus ovata, Apporhais pes pelecani, and Buccinum undatum.

Level, metres.	
0.00 to 0.44	Muddy clay, greyish-brown, coarse, with remnants of vegetable matter.
0.44 to 0.46	Clay, grey, homogeneous.
0.46 to 0.78	Muddy clay, as in the above.
0.78 to 7.00	Clay, grey homogeneous (ligther medium clay). Frequent occurrence of mollusc fragments between the levels 1.4 and 1.8; a whole Cyprina shell at 1.7 m. A weakly marked, but intact layer of ferrous sulphide at 1.8 m. At 4.4 m a water-filled cavity, some two cm in length and about 0.5 cm in width. It is probable that this cavity formed part of some crack, but this crack was not to be detected. At 4.8 m a straight shear crack, 60°. A curved crack at 6.0 m. A slightly curved crack at 6.15 m. Irregular cracks at 6.20 to 6.30 m.
7.00 to 7.30	Clay, as in the above, with a few isolated flame-shaped stains of ferrous sulphide. Curved cracks at 7.00.
7.30 to 7.62	Clay, as in the above, but of darker, greyish-blue colour.
7.62 to 10.16	Clay, dark greyish-blue, with weak flame-shaped stains of ferrous sulphide. Between 7.85 and 9.0 curved cracks. At 8.80 a straight shear crack, 50°. At 9.15 curved cracks.
10.16 to 13.02	Clay, greyish-blue, slightly tinged with ferrous sulphide, with a few isolated mollusc fragments. At the level 11.20 a distinct, undisturbed layer with remnants of vegetable matter. A similar layer at 12.40 m. A curved crack at 12.60.

As the boring was carried on to a greater depth, the cores were taken so as to overlap. The new borehole was put down at a distance of about 1 m from the original location.

11.80 to 14.20	Clay, dark greyish-blue, with a few flame-shaped stains of ferrous sulphide. At the level 11.85 an undisturbed layer with remnants of vegetable matter. At the level 12.35 a continuous layer of ferrous sulphide. At 13.9 m a walnut-sized stone. At 13.70 a weak but undisturbed layer with remnants of vegetable matter. At 13.90 m a dark-coloured zone with more marked and more frequent flame-shaped stains of ferrous sulphide.

The location of the borehole was moved 1 m again, and the boring was continued to a depth of 23.80.

12.10 to 15.30	Clay, greyish-blue, with a few black stains. Mollusc fragments are frequent. At the level 13.70 a layer, possibly somewhat disturbed, with remnants of vegetable matter. At the level 13.80 cracks, 60°. Between the levels 14.10 and 14.15 a dark layer with more frequent flame-shaped stains of ferrous sulphide. At 15.30 a layer with remnants of vegetable matter.
15.30 to 15.80	Clay, greyish blue.
15.80 to 18.40	Clay, greyish-blue, with a few dark stains. Between the levels 17.00 and 17.30 there are fine cracks in the clay ("dilatation cracks"; this term refers to cracks which are usually vertical. The opposite faces of such a crack are uneven and irregularly pitted or bossed. These cracks seem to be caused by dilatation due to the presence of gas in the sediment which manifested itself when the core was pulled out of the sampler tube.)
18.40 to 19.40	Clay, greyish-blue. The ferrous sulphide is accumulated in darker, relatively dense strips, about 1 dm in width, particularly in the upper part. Mollusc fragments are comparatively abundant at the level 18.40. Between the levels 18.85 and 19.15 there are six layers of medium fine sand, partly with small faults.
19.40 to 20.25	Clay, as in the above, but with the ferrous sulphide accumulated in darker, irregular stains. Between the levels 19.60 and 19.73 a layer of medium fine sand. About 20.0 and 20.5 irregular fine cracks ("dilatation cracks"?).
20.25 to 20.90	Clay, grey, with a lower ferrous sulphide content.
20.90 to 21.70	Clay, with numerous irregular stains of ferrous sulphide. At the level 21.30 an irregular lens of medium sand. At 21.70 m a fault, 45°, completely healed, probably originating from old slides.
21.70 to 22.00	Clay, with a low ferrous sulphide content. Below the clay there are a few disturbed layers of fine sand or medium sand, 0.5 cm in thickness.
22.00 to 23.80	Clay. The ferrous sulphide stains are more abundant again.

Borehole E 19. Altitide above sea level + 3.50 m.

Level, metres.	
0.30 to 1.00	Dry crust clay, brown, firm.
1.00 to 2.25	Clay, greyish-green, relatively loose, homogeneous, but containing pieces of dry crust incorporated with the clay as by kneading. At 1.30 and 1.85 m very loose zones. No ferrous sulphide. Turritella (several specimens), Abra(?). Roots grown downwards.

2.25 to 4.40 Clay, greyish-green, plastic, slightly muddy, relatively loose, but not soaked or remoulded. At 2.80 m a crack running across the core. Fossils are rare; only small forms occurring in brackish water, such as Macoma baltica, Hydrobia, etc.

4.40 to 7.36 Clay, greyish-green, slightly muddy, highly homogeneous, relatively firm. At 6.20 m a shear crack, dip about 75°. Fossils are rare down to 6 m. As the depth increases, molluscs become more abundant, *e.g.* Lucinopsis (?), Cardium edule, and Cardium echinatum.

7.36 to 10.17 Clay, greyish-green, relatively muddy, increasingly firm in a downward direction. About the level 8.5 some indications of flame-shaped stains of ferrous sulphide. No soaked zones. Vertical "dilatation cracks", from 4 to 6 cm in length, without any visible slip. Abra montacuta, Thracia, or the like, thin-shelled forms. Nassa, Cardium cfr. minimum, Cardium edule, Cardium fasciatum, Neptunea, Nucula, Mytilus, Litorina.

10.17 to 13.10 Clay, greyish-green, muddy, homogeneous, firm, with the exception of the zone between the levels 10.55 and 10.65, in which the clay is somewhat looser, but does not appear to be remoulded. At 12.60 m a slip surface. Slight indications of ferrous sulphide. Cardium echinatum, Abra, Tapes (?), Mytilus (large), Litorina litorea (large).

13.10 to 13.75 Clay, greenish-grey, homogeneous, *loose,* with irregular "dilatation cracks".

13.98 to 16.48 Clay, greenish-grey, homogeneous, very firm, gritty in structure. "Dilatation cracks". Fossils are rare. Mytilus (a bank at 15.80 m), Mactra, Macoma baltica (?), Buccinum.

16.48 to 17.60 Clay, greenish-grey, homogeneous, very firm, gritty. "Dilatation cracks". Mytilus in layers. Worm tubes, root hair tubes.

17.60 to 19.63 Clay, bluish greenish-grey, with an increasing amount of flame-shaped stains of ferrous sulphide, firm, gritty. "Dilatation cracks". Individuals of Mytilus are abundant. For the rest, only a Balanus and a crab (?). As the depth increases, worm tubes and root hairs become more and more abundant.

19.63 to 19.95 Clay, bluish greenish-grey, with flame-shaped stains of ferrous sulphide, loose down to 19.85 (the core was deformed during the extraction), then very firm. Mytilus.

19.95 to 20.70 Clay, bluish-black, very firm, scarcely quick. Vertical "dilatation cracks". Mytilus, in layers in some places.

20.70 to 21.31 Clay, lighter in colour, bluish greenish-grey, with a slight admixture of ferrous sulphide, firm. "Dilatation cracks". Mytilus is abundant in some places.

21.31 to 23.96 Clay, bluish greenish-grey, homogeneous, very firm, gritty, very slightly quick. Small quantities of fine sand diffusely disseminated. Mytilus is abundant in the uppermost part; also Neptunea. Leaves of Salix (?). Fossils are rare in the lower parts. Mytilus, Hydrobia, and a shell resembling Nassa. Worm tubes.

23.96 to 24.50 Clay, bluish greenish-grey, very firm, not quick, gritty, with a few flame-shaped stains of ferrous sulphide. Small quantities of fine sand. "Dilatation cracks". Worm tubes, root fibres. Mytilus (a few isolated specimens).

24.50 to 26.50 Clay, greenish bluish-black, with a fairly high ferrous sulphide content. At 24.7 m a crack filled with sand. Mytilus, Macoma baltica, and several other molluscs, which were not determined.

26.50 to 27.10 Clay, bluish greenish-grey, homogeneous, with the exception of a layer of clayey fine sand at 26,55 m. Macoma baltica (or the like), several specimens.

27.10 to 27.25 Alternating horizontal layers of relatively pure fine sand and clayey fine sand. Fragments of fossils.

27.25 to 29.56 Clay, distinctly varved in greyish-blue and black (ferrous sulphide). The dip of the varves varies from 10° to 15°. Fragments of Mytilus; otherwise free from fossils. The varves in the lowest part of the core were disturbed during the extraction.

End of the core.

Borehole E 99 a. Altitude above sea level + 5.28 m.

Level, metres.

0.30 to 0.70 Clay, yellow, sandy, firm. Dry crust.

0.70 to 0.78 Clay, blue, very soft, remoulded, quick. Late Glacial (?).

0.78 to 0.82 This part of the core was damaged during extraction.

0.82 to 2.50 Clay, blackish-blue, loose, very soft, quick. In the uppermost part there are more or less undisturbed, concentrated, flame-shaped (marbling) stains of ferrous sulphide. In the lower parts these stains are flattened out, particularly between the levels 1.7 and 2.25. Open, vertical or nearly vertical cracks, with green oxide film on the faces; "dilatation cracks". No traces of shear on these faces. Macrofossils are rare, but foraminifers are relatively abundant. Remnants of vegetable matter. Mytilus, Macoma, Abra alba (?), Balanus.

2.50 to 3.00 Clay, blackish-blue, comparatively firm, with flame-shaped stains of ferrous sulphide slightly flattened out. A few isolated vertical cracks with green oxide on the faces. Fossils are extremely rare with the exception of foraminifers. Ferrous sulphide around root fibres. Late Glacial (?).

3.00 to 3.36 Clay, muddy, greyish-blue, with flame-shaped stains of ferrous sulphide. These stains are not flattened out. The core was removed from the cutting edge of the sampler.

3.36 to 4.30 Clay, muddy, greyish-blue. Fossils are rare. Only fragments of molluscs; remnants of vegetable matter. Oblique flame-shaped stains or layers of ferrous sulphide, flattened out.

4.30 to 4.60 Clay, grey, very soft and soapy, remoulded, with an oblique sand layer, about 1 cm in thickness. A *typical slip zone* between the levels 4.50 to 4.60. Mytilus, Saxicava, Macoma.

4.60 to 5.16 Clay, bluish-grey, firm, marbled with ferrous sulphide. *Undisturbed.*

5.16 to 5.30	Clay, loose, soaked, with flame-shaped stains of ferrous sulphide, which are irregularly flattened out.
5.30 to 6.22	Clay, bluish-black, firm, markedly marbled with ferrous sulphide in distinctly marked accumulations. Undisturbed.

Borehole E 99 b.

A new borehole for continued sampling down to a greater depth was put down at a point 0.5 m west of the borehole E 99 a. It was intended to begin sampling in the new borehole at a depth of about 3 m. On account of the loose consistency of the clay, the core was unsatisfactory at the depths less than 5 m. The depth figures ranging from 3 to 5 m are therefore uncertain. The core was heavily damaged during the extraction.

Level, metres.	
3.00 to 3.07	Clay, yellow; dry crust (formed a plug in the uppermost part of the sampler tube).
3.07 to 3.20	Clay, greenish-blue, relatively firm. In the lowest part: balanids.
3.20	*Rupture.*
3,20 to 4.85	Clay, greenish-blue, *loose, very soft and soapy, has partly flowed out.* Molluscs, etc., as follows:
3.30	Balanids are abundant. One Portlandia arctica.
3.40	One Mytilus. One Portlandia arctica.
3.50	Balanids are abundant. Three Portlandia arctica.
3.60	Balanids.
3.70	Mytilus, Saxicava (large).
3.80	Mytilus, Portlandia arctica, balanids.
3.90	Mytilus, balanids.
4.00	Mytilus, Saxicava, balanids.
4.10	Mytilus, Saxicava, two Cardium cfr. minimum, thin-shelled. Fragments of Mya.
4.20	Balanus.
4.30	Balanus.
4.40	Balanus, Mytilus.
4.50	Balanus, Mytilus, with lumps of firmer clay.
4.60	Balanus, Mytilus, with lumps if firmer clay.
4.70	Balanus, Mytilus (large), with lumps of firmer clay.
4.85	Balanus, Mytilus (large), with lumps of firmer clay.
4.85 to 5.00	Clay, greenish-blue, with sand and gravel, relatively firm. Mytilus (large).
5.00 to 5.44	Clay, slightly muddy, homogeneous. In the uppermost part a small number of flame-shaped stains of ferrous sulphide. Mytilus, Cardium (small), Abra (?), Macoma (?) (small). Leaves of Zostera or Potamogeton are abundant. *Postglacial, that is, younger than the overlying clay.* Undisturbed.
5.46 to 6.85	Clay, muddy, greenish-grey, homogeneous, relatively loose. Cardium edule (large), Venus, Macoma baltica, Lutraria elliptica, Astarte, Mytilus, Abra, Aporrhais, Balanus, Zostera. Postglacial.
6.85 to 7.10	Sand, very clayey, grey. Cyprina islandica, Mya (?) (large), Mytilus (large). Small stones.
7.10 to 7.45	Clay, greenish-grey, muddy, homogeneous, relatively firm. In the lower part a clearly visible, oblique stratigraphic boundary; uneven on the surface. No shear. Only indeterminable mollusc fragments.
7.45 to 7.80	Clay, slightly muddy, greenish-grey, marbled with ferrous sulphide; clearly marked black stains, not flattened out. Macoma calcarea, Portlandia arctica. Balanus. Obviously Late Glacial.
7.80 to 7.98	Clay, bluish-black, firm, not remoulded.
7.98 to 8.25	Clay, bluish-black, firm, but quick. A few scattered grains of gravel. *At a depth of 8.22 a plane of shear.* No fossils.
8.25 to 9.10	Clay, bluish-black, more or less tinged with flame-shaped stains of ferrous sulphide. Two to three parallel, vertical "dilatation cracks" in the core. *Very quick, but apparently not remoulded, with the exception of a sand layer at 8.75 m, which is vertically flattened out.* Saxicava, Balanus.
9.10 to 11.06	Clay, blackish-blue, relatively firm, but quick. Fossils are rare. Fragments of Macoma (?), Mytilus, and Balanus. A small stone at 10.1 m.

Owing to a misinterpretation of the depth figures, no core was taken in the borehole E 99 b between the levels 11.06 and 13.91. This mistake was considered to be corrected by putting down the borehole E 99 c, which was located 1 m west of the borehole E 99 a.

13.91 to 15.78	Clay, relatively firm, *undisturbed,* but slightly quick, homogeneous, greyish-blue, with weak flame-shaped stains of ferrous sulphide. Mytilus, Portlandia arctica (abundant), Portlandia lenticula, Saxicava, Leda, Balanus.
15.78 to 15.91	Sand (medium sand), largely mixed with clay. Astarte sulcata, Balanus.
15.91 to 16.10	Sand (medium sand), largely mixed with clay, with interjacent clay layers from 2 to 3 cm in thickness. Astarte, Leda,
16.10 to 16.70	Clay, slightly silty, firm, bluish-black, marbled with ferrous sulphide. *Undisturbed.* Portlandia arctica, Portlandia lenticula, Balanus.
16.70 to 16.95	Clay, bluish-grey, slightly stained with ferrous sulphide, homogeneous. The upper boundary has a dip of about 55°; uneven. Portlandia arctica, several specimens.
16.95 to 17.40	Sand, very clayey in the uppermost part. Shell fragments (resembling shell gravel) are abundant in the lower parts. Cyprina islandica, Mytilus, Astarte sulcata, Macoma calcarea, Litorina, Echinus sp., Balanus. Stones and grains of gravel.
17.40 to 18.62	Clay, bluish-black, marbled with ferrous sulphide. At 17.50 m a layer of sand mixed with clay. For the rest, the clay is homogeneous and firm. Vertical, fine cracks, without slip, but with (secondary?) oxidation. Portlandia arctica, Nucula, Buccinum, Balanus.
18.62 to 21.60	Clay, blackish-blue, very firm, with scattered accumulations of ferrous sulphide. As the depth increases, the quantity of ferrous sulphide becomes progressively smaller. Fine, vertical "dila-

tation cracks", without slip, but with oxidation. *At the level 20.30 a shear crack, 35°* On the whole, fossils are rare. Nucula, Portlandia arctica, Mytilus (fragments).

21.63 to 22.76 Clay, blackish-blue, very firm, interspersed with accumulations of ferrous sulphide, which are set more closely together between the levels 22.0 and 22.3. No flattening out or slipping. Vertical, fine cracks, with oxidation. A few small and badly preserved specimens of Nucula and Portlandia lenticula. A small number of isolated foraminifers.

22.76 to 25.26 Clay, blackish-blue, very firm, homogeneous, with scattered, distinctly marked accumulations of ferrous sulphide. A few isolated, thin, vertical cracks, with oxide on the faces — "dilatation cracks". Mytilus, Abra (?), Portlandia lenticula (or small Portlandia arctica); all of them rare.

25.26 to 28.10 Clay as above-mentioned. — Mytilus, Abra (?). Portlandia lenticula (or P. artica in small specimens). All of them rare.

Borehole E 99 c.

This borehole was put down 1 m west of the borehole E 99 a in order to supplement the latter by providing a core for the depth range from 11.06 to 16.55. *The clay was very loose and soaked.* The core was therefore unsatisfactory.

Level, metres.

0.00 to 11.06 No core was taken.

14.06 to abt. 12.25 Clay, greyish-blue, *remoulded,* very loose, soaked, and quick. No fossils.

12.25 to 13.15 Clay, greyish-blue, with black flame-shaped stains, soaked, but firmer than in the above part of the core. Quick. A few isolated grains of gravel. Ferrous sulphide. Many wide, swollen "dilatation cracks".

13.15 to 13.96 Clay, greenish-grey separated from the above stratum by a sharply marked but uneven boundary. No ferrous sulphide. The clay is firmer than in the overlying layer, but still loose. In the uppermost part: Portlandia arctica (fairly large). A few isolated grains of gravel.

14.00 to 15.55 Clay, greenish-grey, homogeneous, without ferrous sulphide, still relatively loose. A few isolated grains of gravel. Portlandia arctica (large but rare).

15.55 to 16.05 Clay, slightly muddy (?), blackish-blue, with flame-shaped stains of ferrous sulphide, which are flattened out. On one side *a nearly vertical sand layer, which is flattened out.*

16.05 to 16.55 Clay, slightly muddy (?), loose, greenish-grey to blackish-blue. A large amount of ferrous sulphide in flame-shaped stains and flattened-out layers. "Dilation cracks". Separated from the underlying stratum by a sharply marked but uneven boundary. Mytilus, Nucula.

16.55 to 16.85 Clay, greenish-grey, with a low ferrous sulphide content. No fossils.

Borehole E 190. Altitude above sea level + 4.90.

Level, metres.

0.25 to 0.77 Dry crust clay, brown, greenish in the lower part.

0.77 to 1.25 Clay, dry crust, greenish-grey, with rust concretions, very firm, but plastic. A few isolated, almost dissolved shells.

1.25 to 1.55 Clay, as in the above, slightly muddy, but loose, and containing small pieces of dry crust distinctly incorporated by kneading.

1.55 to 3.15 Clay greenish-grey, homogeneous, slightly muddy, firm, but plastic. Roots grown downwards. At the level 2.75 a crack running across the core, without slip. Mytilus, Macoma, Saxicava, Portlandia arctica.

3.15 to 3.32 Clay, greenish-grey, firm, homogeneous, plastic, with a few scattered small stones. Macoma, Saxicava.

3.32 to 3.70 Clay, greenish-grey, marbled with ferrous sulphide, firm. Portlandia arctica, Mytilus.

3.70 to 4.10 Clay, greenish-grey *(landslide zone), not very loose. Flame-shaped stains of ferrous sulphide, which are flattened out. An irregular sand layer, dip 75°.* Mytilus, Saxicava.

4.10 to 6.00 Clay, greenish-grey, slightly muddy, relatively firm, but somewhat quick. *Undisturbed.* Irregularly marked ferrous sulphide marbling. At the level 4.80 a sand layer 0.5 cm in thickness. Horizontal, undisturbed rupture surfaces. Vertical, undisturbed cracks filled with ferrous sulphide. Very badly preserved shells of Leda (?), Nucula, Portlandia arctica and Portlandia lenticula, Natica (?).

6.03 to 8.97 Clay, bluish-black to blackish-blue, relatively firm, but quick. Irregular ferrous sulphide marbling. At the levels 6.97, 8.12, and 8.85 black layers of ferrous sulphide varying from 5° to 10° in dip, with clearly marked and distinctly visible stratification planes. At 6.28 m a sand layer. Portlandia arctica, Portlandia lenticula, Mytilus, Nucula, Balanus. Worm tubes.
The sampler was moved 0.40 m westwards for taking the core described below.

8.25 to 9.55 Clay, greenish-grey, relatively loose. Between the levels 9.15 and 9.20 a black strip of ferrous sulphide, which is probably situated at a depth of 8.85 m in the preceding borehole. This strip is disturbed by an (older?) fault amounting to 3 cm in vertical displacement. At 8.80 m an irregular sand layer. The clay is possibly somewhat looser at the level 9.25. Portlandia arctica, Portlandia lenticula, Nucula. At 9.10 m a shrimp.

9.55 to 12.77 Clay, greenish-grey to blackish-blue, with dense ferrous sulphide concretions. At the levels 9.85, 10.45, and 11.75 layers, blackened with ferrous sulphide. In the layers at 10.45 m a fault (healed up, without any noticeable slip surface!). The clay is relatively firm, but quick. Fossils are rare. At the level 12.10, in a layer of clayey sand, shells of Portlandia arctica and Mytilus. For the rest, a few isolated specimens of Portlandia arctica.

12,77 to 13.48 Clay, blackish-blue, homogeneous, marbled with ferrous sulphide. The clay is loose in the uppermost part, about one decimetre in length (the core was damaged during extraction), whereas it is relatively firm, but quick, in the lower parts. Fossils are very rare. Balanus hameri.

13.48 to 14.15 Clay, bluish-black, marbled with ferrous sulphide. A few isolated grains of gravel. At the level 13.58 a layer of clayey gravel. The clay is relatively loose and quick, but there is no slip zone. The gravel in the layer resembles shell gravel, and contains Mytilus (large), Saxicava, Balanus, Macoma, a fragmentary shell.

14.15 to 14.55 Clay, brown, homogeneous, firm. Only fragments of fossils.

14.55 to 16.13 Clay, varved (oblique varves) in brown and black. In the lowermost part two thin layers of silt and fine sand, very firm. Tiny fragments of a small mollusc shell, probably Portlandia arctica.

16.13 to 16.25 Clay, as in the above (removed from the cutting edge of the sampler, and therefore slightly deformed during extraction). Small mollusc fragments.

16.25 to 17.15 Clay, brown, blue, and black mixed together, loose, heavily deformed in patterns of the above-mentioned colours. At the levels 17.10 and 17.15 distinctly visible planes of shear. No fossils. (Professor G. Beskow, who has seen this core, is of the opinion that the deformation has nothing to do with the landslide under consideration, since the clay is much too firm.)

17.15 to 17.60 Clay, varved, with relatively undisturbed varves, comparatively firm. At the levels 17.40 and 17.60 cracks with a slight shear.

17.60 to 18.54 Clay, brown, firm, mixed with clay, blue, loose. Heavily disturbed zone. No fossils.

18.54 to 18.80 Clay, remoulded, but firm, partly brown and partly blue, with flame-shaped stains of ferrous sulphide, which are flattened out. Mytilus.

18.80 to 19.05 Clay, varved, brown, with layers of medium to fine sand.

19.05 to 19.40 Sand, medium sand mixed with fine sand, grey, with thin completely horizontal clay layers. Balanus.

19.40 to 19.48 Clay, grey, sandy, firm. End of core.

Borehole E 280. Altitude above sea level + 5.40 m.

This borehole was situated in the upper part of the slide area.

Level, metres.

4.19 to 4.50 Clay, muddy, greenish grey, with scattered, diffusely, disseminated, flame-shaped stains of ferrous sulphide. Stratification planes varying from 25° to 30° in dip. Planes of shear varying from 55° to 65° in dip. Fragments of Mytilus.

4.50 to 5.00 Clay, muddy, particularly between the levels 4.7 to 4.85, with small quantities of sand and several scattered pea-sized grains of gravel. At 4.85 m a horizontal stratification plane with grains of gravel and fine sand diffusely disseminated. Below 4.85 m muddy clay, firm, gritty, greenish-grey, with flame-shaped stains of ferrous sulphide. Mytilus, Saxicava. Planes of shear varying from 55° to 65° in dip. Mytilus (large and numerous), Saxicava, Balanus (?).

5.00 to 5.20 Clay, muddy, firm, greenish, with flame-shaped stains of ferrous sulphide. Mytilus, Balanus, Abra (?).

5.20 to 5.50 Clay, muddy, greenish-black, firm, gritty. Mytilus, Nucula.

5.50 to 5.70 Clay, muddy, greenish-grey, firm. Nucula, Mytilus, Abra (?).

5.70 to 6.00 Clay, muddy, greenish-grey, with a few flame-shaped stains of ferrous sulphide, firm. Mytilus (a few isolated specimens), Nucula.

6.00 to 6.20 Clay, muddy, with flame-shaped stains of ferrous sulphide. Portlandia arctica, Portlandia lenticula, Mytilus.

6.20 to 6.67 Clay, muddy, soapy but firm, no stratification planes or planes of shear, with weak flame-shaped stains of ferrous sulphide. Mollusc shells, frequently in separate layers. Portlandia lenticula, Mytilus, Macoma calcarea. At 6.60 m a stone 2 to 3 cm in diameter.

6.67 to 7.00 Clay, muddy, with irregular flame-shaped (marbling) stains of ferrous sulphide, relatively firm. At 6.90 m the clay is somewhat softer, without being loose; slightly silty. No shear cracks. Fossils are rare. Mytilus, Nucula.

7.00 to 7.20 Clay, muddy, with a high ferrous sulphide content concentrated in (marbling) stains. A few isolated grains of gravel. The clay is slightly silty. Fossils are rare. Portlandia arctica and Portlandia lenticula.

7.20 to 7.60 Clay, slightly muddy, containing some ferrous sulphide, which is diffusely disseminated or more highly concentrated in a few isolated flame-shaped stains. At 7.60 m a layer of concentrated ferrous sulphide. Portlandia arctica, Portlandia lenticula, Nucula.

7.60 to 7.95 Clay, bluish-grey, slightly muddy. Shells are abundant: shells partly filled with medium sand (washed out!). Mytilus (large, in great quantities), Saxicava, Balanus.

7.95 to 8.40 Clay, bluish-grey, very slightly muddy, with concentrated flame-shaped (marbling) stains of ferrous sulphide. Fossils are rare. Portlandia arctica, Portlandia lenticula, Macoma calcarea, Mytilus (large specimens), Balanus.

8.40 to 8.90 Clay, completely black in the uppermost part, 15 cm in length, tough, very soft and soapy, but undisturbed. Portlandia arctica, Portlandia lenticula, Mya truncata, Nucula.

8.90 to 9.20 Clay, tough, very soft and soapy, with scattered, concentrated (undisturbed) flame-shaped stains of ferrous sulphide. No slips.

9.27 to 9.55 Clay, greyish-blue, marbled with ferrous sulphide. No fossils.

9.55 to 9.85 Clay, greyish-blue, with flame-shaped stains of ferrous sulphide; grains of gravel. Fossils are abundant. Macoma calcarea, Mytilus, Saxicava, Balanus.

9.85 to 10.25 Clay, greyish-blue, with flame-shaped stains of ferrous sulphide, very soft and soapy, but firm. No grains of gravel, but a few small stones. Fossils are rare. Saxicava, Mytilus.

10.25 to 10.50	Clay, brown, firm, with indications of varves, which are oblique with reference to the horizontal plane but parallel to the plane between the brown clay and the underlying stratum.
10.50 to 10.67	Clay,bluish-grey, passing into brown in a downward direction. Small fragments of fossils.
10.67 to 12.07	Clay, varved in brown and blue or black, firm, with layers which are disturbed but healed up. Here and there layers of sand or fine gravel with remnants of balanids.
12.07 to 12.63	Deformation of the core in the cutting edge of the sampler.
12.63 to 13.45	Clay, blue to bluish-brown, slightly varved, with disturbed varves and a few isolated layers of ferrous sulphide.
13.45 to 15.30	Clay, varved brownish-blue, with distinct and undisturbed varves, which are separated by layers of medium or fine sand. The lowest part of the core is deformed. The firm bottom is reported to have been reached.

Summary of the Field Examination as to the Geology.

The most conspicuous result obtained from the field examination of the cores taken by means of the soil sampler with metal foils is the fact that the zones of remoulding and the slip surfaces were so small in number and in extent. It was expected that there would be a certain mushy zone or a marked boundary between the remoulded and the undisturbed parts at the lower limit of the earth masses displaced by the landslide, which might be followed from one borehole to another. Actually, however, no such zone or boundary was to be found by the field examination.

The observations showed that there was quite a large number of shear planes and several, usually thin zones of looser clay, which were frequently superposed one upon another and which diminished more or less diffusely in a downward direction. In some places, *e.g.* in the borehole E 99, there were distinctly visible overthrust faults, in which older (Late Glacial) strata were thrust over younger (Postglacial) layers. In fact, the laboratory tests showed that such overthrust faults exist in other places too, but it has not always been possible to detect them with certainty in the soil cores for lack of reliable, macroscopically identifiable guide layers.

A summary of the observed disturbances, exclusive of "dilatation cracks", is given below.

Borehole W 137.

Altitude above sea level + 4.07 m.

Level, metres, (below soil surface)	
4.4	Crack.
4.8	Straight shear crack, 60°.
6.0	Curved crack.
6.15	Curved crack.
6.30	Curved crack.
7.0	Curved crack.
7.85 to 9.0	Curved cracks.
8.8	Straight shear crack, 50°.
9.15	Curved crack.
12.60	Curved crack.
13.80	Crack, 60°.
21.30	Irregular sand lens.
21.70	Crack, 45°.

Borehole E 19.

Altitude above sea level + 3.50 m.

Level, metres.	
1.30	Soft clay.
1.85	Soft clay.
2.80	Crack, 180°.
6.20	Shear crack, 75°.
12.60	Slip surface.
13.10 to 13.75	Soft clay.
24.7	Crack filled with sand.
27 to 29	Dip of varves 10° to 15°.

Boreholes E 99 b to E 99 c.

Altitude above sea level + 5.3 m.

Level, metres.	
0.8 to 2.5	Very soft clay.
3.20	Rupture.
3.2 to 4.8	Very soft clay.
4.8 to 5.0	Sand layer incorporated by kneading.
5.44	Overthrust.
5.5 to 6.8	Soft clay.
8.22	Shearing.
8.75	Sand layer flattened out.
11.06 to 13.15	Soft clay.
16.7	Boundary of stratum, dip 55°.
20.30	Shear crack, 35°.

Borehole E 190.

Altitude above sea level + 4.90 m.

Level, metres.	
1.55	Very soft clay.
2.75	Crack, 180°.
3.70 to 4.10	Slide zone. Sand layer, 75°.
4.10 to 6.11	Slip surfaces, 180°.
8.80	Irregular sand layer.
8.85	Dip of strata 5° to 10°.
9.25	Relatively soft clay.
10.45	Old fault.
16.25 to 17.1	Old deformation.
17.60 to 18.54	Large, old disturbance.

Borehole E 280.

Altitude above sea level + 5.40 m.

Level, metres.	
4.2 to 4.5	Clay varves dipping 25° to 30°.
4.5 to 4.5	Planes of shear dipping 55° to 65°.
10.7 to 12.1	Healed old disturbances.

If those disturbances which appear to be most recent indicate the lowest boundary of the slide, then it is seen from the above that the depth reached by the slide in the eastern, higher situated parts of the slide area was not greater than 5 m. In the two boreholes on the opposite sides of the railway line the lowest traces of disturbances are found at a depth of 13 to 14 m. In the borehole E 99 the probable lower limit of the recent slide was determined by combining the observations made in the boreholes E 99 b and E 99 c, and was found to be at a depth of 13.15 m. This is approximately the same value as that obtained from the two preceding boreholes.[1] The lower disturbances in this borehole may probably be attributed to earlier slides, which are now completely healed. In the borehole E 190 the lowermost disturbance is situated in a zone of relatively loose clay at a depth of 9.25 m.

If these values are inserted in a profile, then they seem to indicate, in the neighbourhood of the borehole E 190, an angle in the connecting line between the lowermost traces of the slide. If this "slide surface" is imagined to be extended in an upward direction to the ground of the eastern part of the slide area, this extension will intersect the surface of the ground approximately in the vicinity of the boreholes E 260 to E 280, that is, approximately at that point of the ground where the altitude before the slide was + 10 to + 12 m. Cfr Jakobson 1952, fig. 16. The map in Plate 1 shows that the original slope was steepest in this place.

If this level is followed as far as the standard profile in Section + 966, then it points to a place between the boreholes E 226 and E 376. As will be shown further on, the borehole E 226 still contains about ten metres of Postglacial muddy clay. On the other hand, the whole profile in the borehole E 376 consists of glacial material. Consequently, between these two points the Postglacial series of strata is thinning out, which, as may be seen from Fig. 3, is underlain by sandy materials, at least in Section + 966. Brown-coloured, sandy, peat-like mud overlain by sand was observed just after the slide at the southern boundary of the slide area, approximately at a level of + 10 m. Unfortunately, no samples of this mud were taken until the slide area was levelled by caterpillar shovel. The same type of soil was also observed within the slide area in the slide elements which apparently originated from this level.

Mr. Gustafsson, the inspector of a farm belonging to the Surte Glassworks, remarked that the slope situated precisely at the level in question had often been so wet in the spring time as to prevent both horse and tractor ploughing. A fairly well-preserved alder stump was found in the upper portion of one of the slide elements containing the above-mentioned brown, peat-like mud, immediately below the top soil layer. This indicates that sources and water-soaked soil have for a long time existed in this place.

Even if Postglacial strata had been present in the uppermost part of the borehole E 280, of which the original soil surface was situated at a ground level of + 12 m, these strata would probably have been so close to the surface that they would have moved downwards, and would have been superimposed by the late glacial materials which had slipped during secondary, retrogressive slides. Then, it was not to be expected that any materials other than late glacial would be found in this borehole. However, the uppermost strata which have slipped may be supposed to be older than the underlying, undisturbed strata. This assumption is also corroborated by the observations of the scattered gravel grains, the greenish-grey colour of the clay above a depth of 5 m, and the presence of large and numerous specimens of Mytilus and Saxicava as well as of balanids. Below this level we find the greenish-black or bluish-black clay containing ferrous sulphide. This clay represents the youngest Late Glacial strata in the standard profile, with Nucula, Portlandia lenticula, and crippled specimens of Mytilus. In fact, Portlandia lenticula is not to be found in the High-Glacial parts of the sequence of strata (Asklund, 1936); it does not occur until the climate becomes slightly less severe.

Similarly, the uppermost part of the borehole E 190 does not comprise any postglacial materials, possibly with the exception of the dry crust itself. Arctic molluscs were observed as early as in the depth range from 1.55 to 3.15 m. Any interstratified sand layer, which would indicate a stratigraphic discontinuity, as in the borehole E 266 in the southern section, was not found in the central parts of the slide area. The boundary between Late Glacial and Postglacial sediments which was outcropping on the original ground surface seems to have been displaced from the area between the boreholes E 260 and E 280 to some place between the boreholes E 190 and E 99.

Micropaleontological Investigation.

Determinations of pollen and foraminifers were made in order to get a more or less complete picture of the geological development in the nearest section of the valley of the river Göta älv and in order to date the various components of the series of sediments.

For practical reasons, the investigation of pollen had to be confined to E 14 and E 226 in Section 464 + 966, although an analogous investigation of the soil cores from the slide area would also have been valuable. Furthermore, an examination of the diatomaceous flora

[1] However, keeping in mind the difficulties of observing the recent slip zones, we must concede that the slide bottom really may have been situated still deeper.

would likewise have been of value, first, for a comparison with the hydrographical conditions farther downstream (Mohrén, 1945), and second, for the determination of the salt content of the water in which the sediments were deposited. However, an examination of diatoms would have required so much time that it had to be omitted.

The stratigraphical investigation was carried out most rapidly by examining the foraminifers. Dr. F. Brotzen was able to complete the stratigraphical survey of the boreholes E 14 and E 376 at an early stage (Brotzen, 1951). All the same, since the necessary points of support for the foraminiferal stratigraphy as well as for the paleontology in the Quaternary scheme of development were not yet available, the classification of the sequence of strata determined in this way had to be supplemented with the results of the pollen investigation. It seems that the foraminifer method may be expected to become the most adaptable method of investigation after having been sufficiently tested by applying it to the marine deposits in the Swedish coastal regions. In particular, this method is suited for the Late Glacial parts, which present great difficulties in pollen and diatom investigations. These difficulties are due to three causes, viz., first, to the treatment with hydrofluoric acid, which is necessary on account of the clay content, second, to the scantiness of primary pollen, and third, to the possible presence of secondary pollen.

A combination of pollen, foraminifer, and diatom analyses may be expected not only to give a detailed picture of the geological and the marine-hydrographical development, but also to serve as an additional stabilising factor in the estimation of the climato-historical development during the time after the Glacial period.

Attention is called to the fact that the uppermost portion, 1 m in thickness, of the sedimentary column from the borehole E 14 is not included in the diagram shown in Fig. 3. The pollen flora of the uppermost sample recorded in this diagram indicates that the sediment was deposited during a hot epoch of the Postglacial period, when the frequencies of the oak, the linden, the alder, and the hazel were relatively high. Apart from a few scattered traces, the spruce does not occur in the upper parts of the series of strata in question. The beech and the hornbeam have not been observed either. Hence it follows that the whole series of strata under investigation was deposited before the end of the above-mentioned hot epoch (cf. Sandegren and Johansson, 1931, p. 117), that is, prior to the beginning of the Sub-Atlantic period.

The most striking feature in the general character of the diagram shown in Fig. 3 is the enormous preponderance of the Pinus pollen. The general type of this diagram is the same as that which has been met with in the investigations of the river valley sediments both downstream of Surte (at Gothenburg, see Mohrén, 1945) and farther upstream (at Nol, see Sandegren, 1947, and near Lake Hullsjön, see von Post, 1928, p. 55). There is also a resemblance, though less obvious, to the diagrams published by Fries (1951) for the central parts of the province of Bohuslän and the southern parts of the province of Dalsland, where the birch is more predominant.

To facilitate comparisons between the pollen diagrams and the zonal divisions due to various authors, reference is made to the scheme on p. 23.

The zonal division of Gotland elaborated by von Post (1925) was used, with a few slight modifications, as a basis for the zonal division of Scania by T. Nilsson (1935). The latter division was applied by the author (Berlin and Mohrén, 1942; Mohrén, 1945) to the Gothenburg region. Sandegren (1931) designates the beginning of the alder curve as the zonal boundary V/VI. In 1947, however, Sandegren placed this important milestone (p. 32) at the basis of the zone VII. Thus he used in this case von Post's Gotlandic classification, which has also been adopted in the present investigation. In 1951 Fries accepted the Danish zonal classification, which is becoming increasingly popular in the north-west of Europe and on the Continent.

A detailed examination of the pollen diagram relating to the borehole E 14 shows that the empirical Tilia curve, with a few scattered streaks extending down to 15 m, can be located at a depth of 5 to 6 m below the ground surface. The Ulmus maximum, which is a characteristic of this level, is also reached at the depth in question.

The beginning of the Alnus curve can be located in the depth range from 14 to 17 m. It was assigned to 17 m, although the percentages of Alnus pollen up to a depth of 14 m are very low. The other pollen curves do not afford any particularly reliable points of support for fixing the exact position of the beginning of the alder curve. The location of the boundary VII/VIII was determined by two factors, viz., the fall in the hazel curve and the beginning of the QM-curve. These features recur in several pollen diagrams from the Gothenburg region and from the central parts of the province of Bohuslän. Nevertheless, the location of this boundary at a depth of 14 to 15 m would not involve any considerable error. In fact, at this depth there is a Pinus maximum, which seems to be equivalent to that in Sandegren's diagram from Nol (1947, p. 31). An investigation of diatoms could have given an answer to this question, since a substantial change in the hydrographical conditions in the Gothenburg region takes place approximately at this level (Mohrén, 1945).

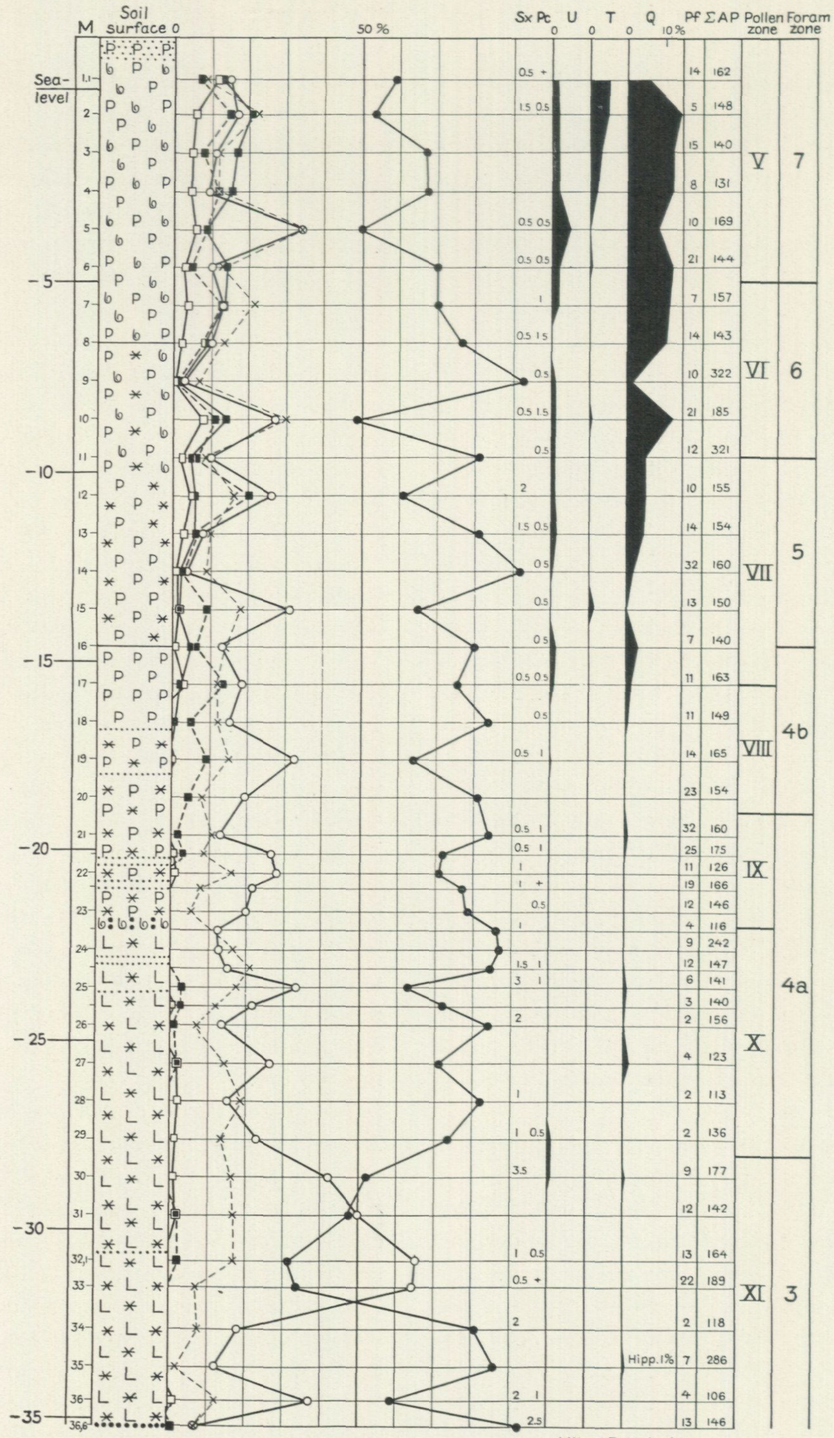


Fig. 3. Pollen diagram and sedimentary column E 14, Section + 966.
Symbols see Fig. 3 a, p. 23.

The great Betula maximum which initiates and dominates the zone IX must be that which is situated at a depth of 21 to 23 m in the borehole E 14, since it is bounded in an upward direction by the continuous hazel curve. However, this maximum is much less strongly marked in respect of its magnitude than usual. All the same, its existence has been so well established by analyses that there is scarcely any doubt about its identity.

The series of strata which lies below the abovementioned level and extends down to a depth of about 30 m is characterised by low Betula percentages and by

		Climatic Periods	v. Post 1925	Nilsson 1935	v. Post 1928	Sandegren 1931	Fries 1951	Pollen-Analytical Guide Levels
Postglacial		Sub-Atlantic	I	I		I		Picea limit in the Gothenburg region.
					I		IX	
			II	II		II		Picea limit in the central parts of the province of Bohuslän.
	Litorina Epoch	Sub-Boreal	III	III	II			Regression of mixed oak forests.
						III	VIII	Spruce limit at the river Svea älv. Beech limit in Scania.
		Atlantic	IV	IV	III			Marked regression of Tilia, Ulmus, and Corylus in mixed oak forests.
				V				
			V		IV	IV	VI	
				VI				Empirical Tilia limit.
		Boreal (Ancylus)	VI					
				VII	V	V	VI	
			VII					Empirical Alnus limit.
			VIII	VIII	VI		V	Empirical Corylus limit.
						VI		
		Sub-Arctic (Yoldia)	IX	IX			IV	BM = Finiglacial Betula maximum.
Late Glacial		Arctic (Yoldia, Dryas)	X	X		VII	III	Betula maximum, far-transported Pinus.
		Sub-Arctic (?) (Allerödian)	XI	IX			II	Betula maximum of local birch woods.
		High-Arctic		XII			I	Far-transported Pinus. Tundra.

a nearly complete absence of thermophile elements. The average Pinus percentage, being the image of the Betula-curve, is high. If this range is compared with that maximum which has been designated as the zone X in Sandegren's analyses from Nol (1947) or in those from the port of Gothenburg (Mohrén, 1945, p. 254), then they agree almost entirely. In all three profiles the general Betula minimum is interrupted by a small but clearly marked maximum. The corresponding Pinus maxima seem to be those which von Post (1947) has denoted by Pm² and Pm¹.

The shapes of the curves in the depth range from 30 to 34 m are likewise so strikingly similar to those in the range which is designated as the zone XI (Allerödian) in the above-cited profiles that their synchronism is certain. The remaining portion, 34 to 36.6 m, of the core from the borehole E 14 may also be supposed to belong to this zone. The frequency of Betula in this portion is higher than in any other part of the whole profile E 14, and rises above the Pinus curve. The alder frequency is low, but is represented by a continuous curve lying below the birch curve. The curve of non-arboreal pollens in these earlier stages exhibits on an average the same values as during the Postglacial period. This curve, including grasses and Cyperaceae, both of which seldom exceed 5 per cent, shows a pronounced tendency to follow the birch curve. This may probably be explained, at least as regards the older stages, by assuming that the islands and skerries rising from the water had a vegetation comprising varieties of the birch (Betula nana and Betula tortuosa?) as well as herbs (Fries, 1951, p. 119), which grew more closely together in the event of melioration in the climatic conditions and which prevailed in the pollen rain over far-transported pine pollen. If the non-arboreal pollens had been included in the total pollen sum, this circumstance would have been brought out still more clearly. The correctness of the above assumption is corroborated by the values of the pollen frequency in the analysed samples. As has already been mentioned, all samples had to be treated with hydrofluoric acid on account of their clay content. Even if the samples might for this reason be regarded as comparable with one another, this comparison would nevertheless scarcely be worth while, since it is very difficult to prepare the microscopical slides of equal

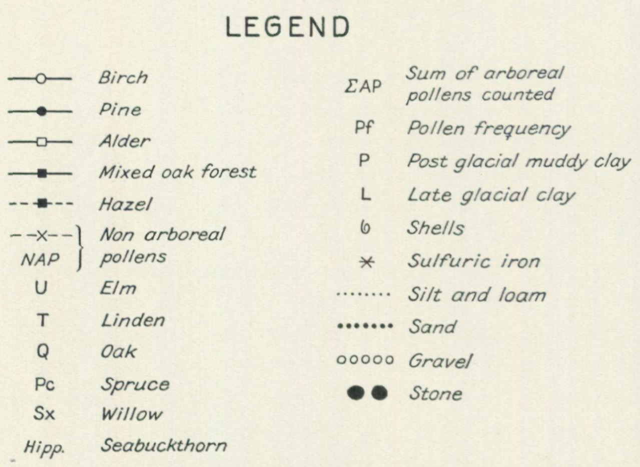
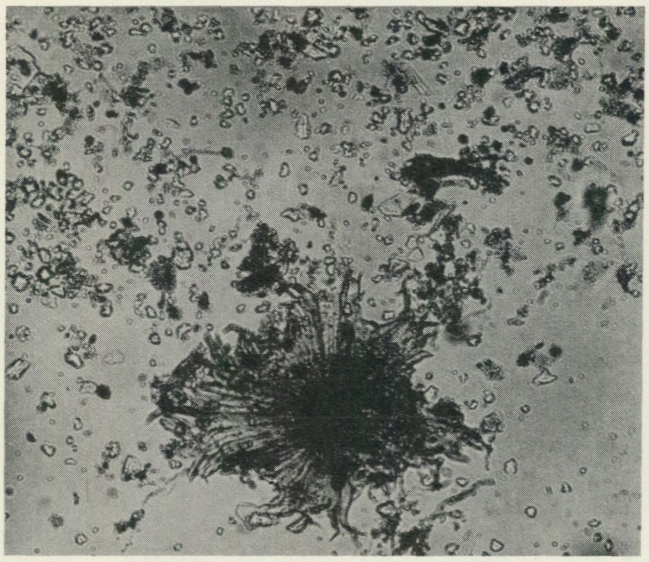
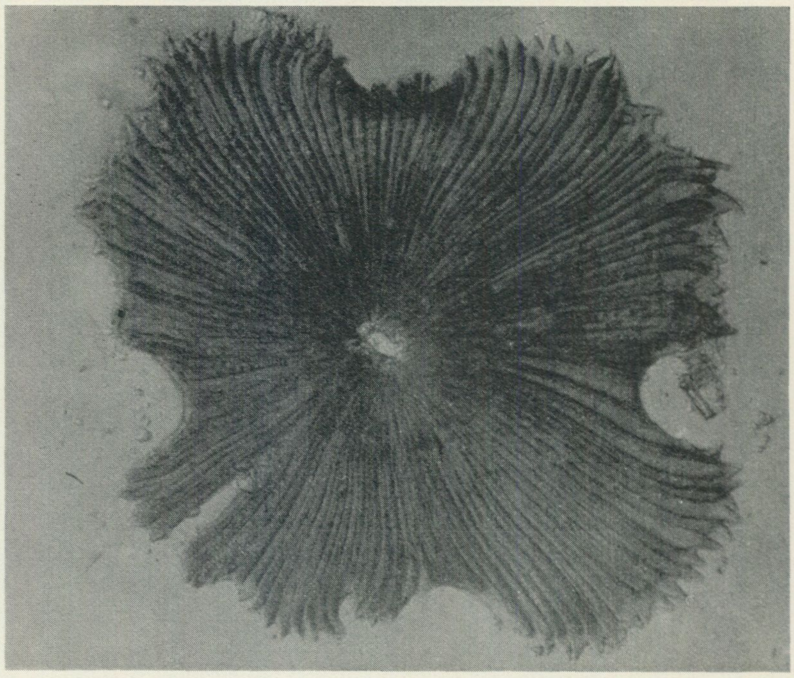


Fig. 3 a. Symbols used in Figs. 2, 3, and 6.



a.



b.

Fig. 4. Stellate hair of Hippophaë.
a. From E 14. Depth 35 m (145 ×).
b. From E 14. Depth 24 m (260 ×).

thickness. Furthermore, they may vary in degree of concentration. For all that, it is possible to form only an approximate idea of the pollen content of the sediments in its various parts. The values of the pollen frequency are higher at the Betula maximum in the period XI as well as at the outset of the period IX. The fact that the pollen frequency decreases again during the Postglacial period is surely due to the large quantity of relatively coarse organic detritus which was not withdrawn during the removal of clay and which has diluted the pollen.

The number of those types of pollen, in addition to grasses and Cyperaceae, which have been referred to non-arboreal pollens is comparatively small. They include Ericaceae (predominantly of the Vaccinium type), Chenopodiaceae, Artemisia, Caryophyllaceae, and several pollens which were not accurately determinable.

Moreover, it is to be noted that spores of ferns (mostly Polypodium) are fairly abundant throughout the whole series of strata, but their frequency in the Postglacial parts is slightly lower than in the Late Glacial parts. A few scattered spores of Sphagnum and Lycopodium have also been observed.

Only one Hippophaë pollen has been found (at a depth of 35 m), but stellate hairs have been observed at 21, 24, 25.5, 35 and 36 m. According to a check determination made by Professor E. Hulthén, these hairs also belong to Hippophaë, see Figs. 4 a and 4 b.

Single specimens or low percentages of Picea and Salix have been observed, primarily at depths below 20 m.

In contradistinction to the sediments at Gothenburg (Mohrén, 1945, p. 253), the Late Glacial sediments in the borehole E 14 contain only sporadic specimens of Hystrix, which has been systematically examined in this case together with the arboreal pollens, and has been calculated on their sum. The Hystrix curve, which is continuous in the Postglacial section, does not begin until a depth of 16 m, that is at the beginning of the alder curve, or at the time when, judging from the examination of diatoms, the discharge of fresh water from the basin of Lake Venern rapidly decreased and the hydrography of these regions began to be characterised by more halinous conditions. No picture was made of the Hystrix forms occurring in the borehole E 14, but it may be noted that by far the most frequent "varieties" of Hystrix are those represented in Figs. 5 a, 5 b, and 5 c, which relate to the borehole E 226. The forms a and b correspond to those which have been given by Fries (1951, p. 170). The former has a small number of robust spines, which are distinctly furcate at the ends. The diameter of the "body" itself in this case, just as in b and c, seems to be 40 to 50 microns. The type b has fine, almost capilliform spines, which were also found to be cleft at the ends when they were sufficiently magnified and when the aperture was

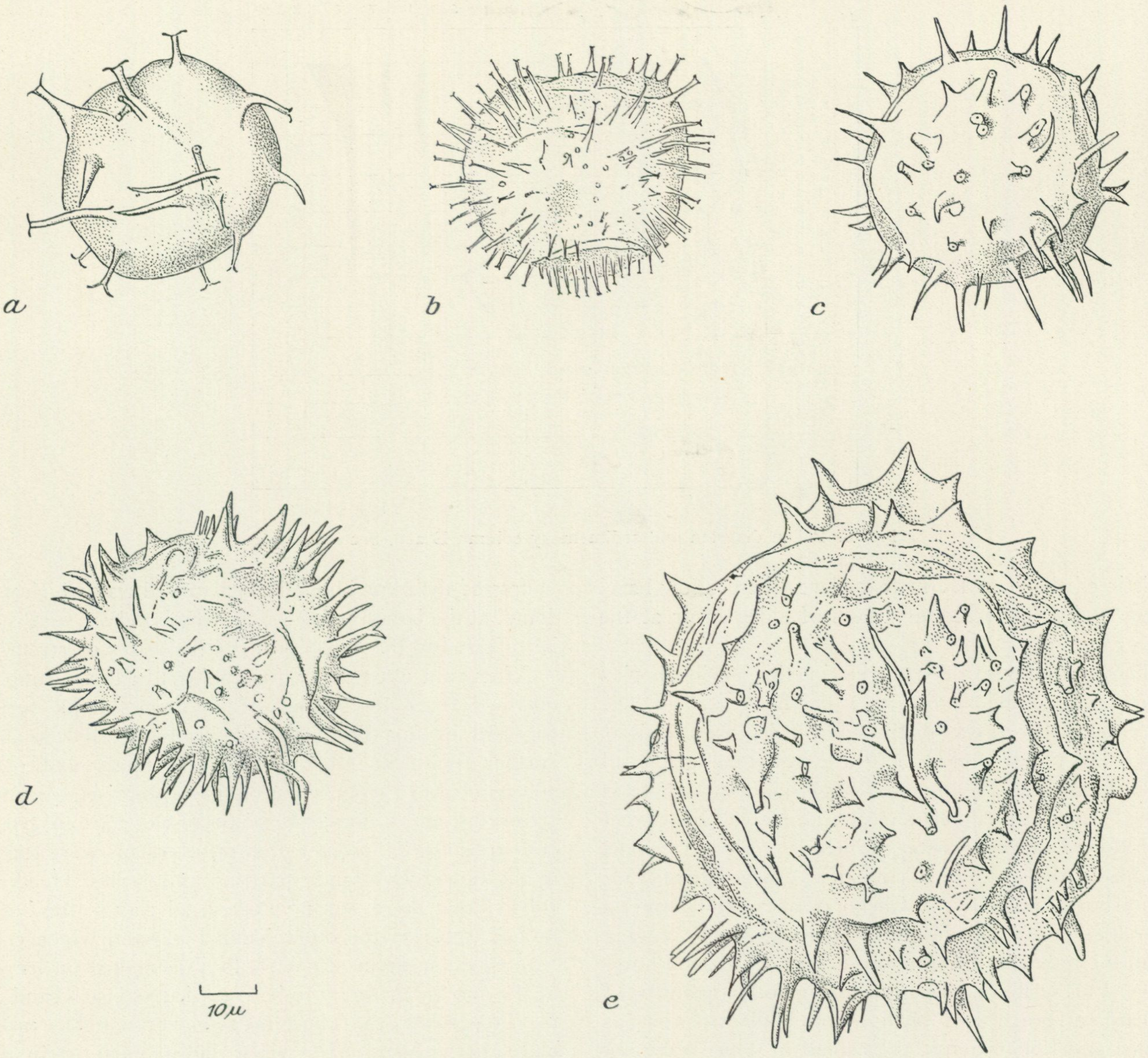


Fig. 5. Various types of Hystrix.

appropriately regulated. The details on the surface are difficult to decipher because large quantities of organic and inorganic detritus are often accumulated between the spines. The diameter, including the spines, is 55 to 60 microns.

In the borehole E 376, which represents the oldest parts of the series of strata (see below) and which contains only an extremely small number of pollen grains, a couple of different types were noted, which have not been observed in the other profiles and which may therefore be assumed to be rarer (Figs. 5 d—e).

It was not possible to find any answer to the question of the nature of Hystrix. Attempts were made to identify the types found in this place with some others, *e.g.* with the hystricoids represented by M. Lejeune-Carpenter (1937—1941), but they have not led to any result. However, we are inclined to agree with Fries, who states that Hystrix is an indicator of markedly halinous conditions and that it probably still exists on the west coast of Sweden.

The sample series E 226 is short in comparison with the series E 14; a sufficient quantity of pollen for a reliable analysis was obtained only in the range down to a depth of 9 m in a clay which was muddy in its uppermost part and which had a ferrous sulphide content increasing in a downward direction. The two lowermost samples, which originate from the depths 8.2 and 9.1 m, exhibit the markedly falling birch curve which is charac-

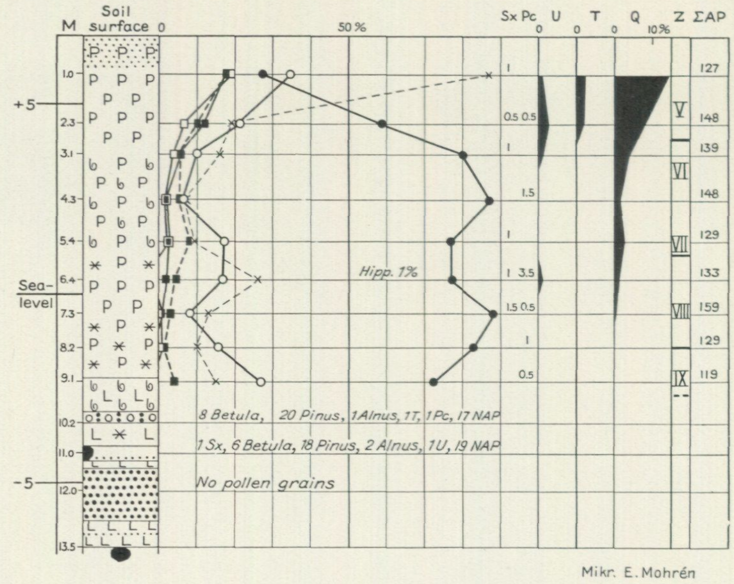


Fig. 6. Pollen diagram and sedimentary column E 226, Section + 966.

teristic of the zone IX in that place where a low hazel curve and a few scattered traces of alder occur at the same time.

The continuous alder curve in this series begins clearly and unmistakably at a depth of 5.4 m. The linden curve begins as distinctly at a depth as small as 2 m below the ground level, at the same time as a small alder maximum. The highest Postglacial limit (PG 1) is to be located at this pollen-analytical instant. This event is followed by regression, which is reflected in the sandiness of the sediment and in the large quantity of non-arboreal pollens, *e.g.* Chenopodiaceae and Armeria as well as great quantities of Gramineae, which, judging from the remnants of epidermis, originate from Phragmites. Furthermore, there is a considerable quantity of pollens of beach and shallow-water plants, such as Typha and Potamogeton, the pollens of which have not been included in the sum of non-arboreal pollens.

It seems that the sample from the levels 10 and 11 m should also be referred to the zone IX, although it contains very little pollen. The Betula frequency in this sample is approximately the same as in the preceding samples, *i.e.* 20 to 25 per cent. The frequency of non-arboreal pollens is strikingly high in relation to the sum of arboreal pollens. However, it is not certain where the lower boundary of the zone IX should be located.

The sand at a depth of 12 m contains practically no pollen grains whatever. After a substantial increase of concentration by mechanical and chemical methods, one single Pinus pollen was obtained from one microscopical slide.

The clay around the stone which stopped the sampler at a depth of 13.5 m seems to form part of the bottom varves of the same bluish-brown varved clay which was found at the bottom of the following borehole, and is to be referred to the oldest parts of the series of strata.

After vain attempts to find pollens in three samples obtained from the borehole E 376, the sample series collected in this borehole was not submitted to any further treatment. By that time, the total number of pollens obtained from 6 micro-slides comprised 4 Pinus, 1 Corylus, and 6 non-arboreal pollens of various types. It is to be noted, however, that these pollens were found in the upper, less sandy parts of this series. Hence it follows that there was no Postglacial clay in the borehole E 376. On the other hand, that sand which constituted the uppermost part, 3 to 4 decimetres in length of the core, is probably to be regarded as beach sand of the Postglacial sea. Thus, no sedimentation has taken place above a depth of 13 m, or the sediment has in any case been removed.

From this circumstance, among others, we may draw the conclusion that the quantity of secondary redeposited pollen in the Late Glacial parts of the strata is so insignificant that it cannot be of any importance in comparison with the pollen produced by the local vegetation or with the far-transported pollen. The term "redeposited" refers not only to that pollen which has been present in moraine or in the oldest Late Glacial series of strata and has been washed out of them, but also to pollen which has been deposited on, and embedded in, the land ice and which could be carried off by the water when the ice melted, and could be deposited at the same time as the sediments outside the ice border.

Some types of pollens and spores which were undoubtedly secondary have been found, but their number was extremely small. (Cf. Ross and Fries, 1950.)

Comparisons between the Pollen and the Foraminifer Diagrams.

Brotzen (1951, p. 62) has presented a stratigraphic scheme of the Quaternary sequence of strata at Surte as a diagram based on the boreholes E 14 and E 376, which are considered to be separated by a relatively small hiatus. He has divided the foraminiferal fauna into two sections, viz., late glacial and postglacial. The latter section is characterised by a fauna rich in species and with Streblus (Rotalia) beccari as a guide fossil. The late glacial section is subdivided into two zonal groups, both of which have Elphidium incertum and its variety Elphidium clavatum as their most important representatives. In the group A, which is the older of the two, Elphidium clavatum predominates in a high-arctic fauna where, for the rest, species and individuals are first rare (zone 1), but where individuals then become more abundant (zone 2). Finally, these zones are followed by the zone 3 with boreal elements.

The fauna in the group B is extremely abundant in individuals but deficient in species, and is dominated by the main form Elphidium incertum. In the lowermost part of this group the fauna is preponderantly arctic to artico-boreal (zone 4 a), whereas Lusitanian forms begin to occur in the upper parts (zone 4 b).

On the basis of the foraminifer content, Brotzen has located the boundaries of those periods which he regards as Postglacial (zone 5 and younger) and Late Glacial (zones 1 to 4 b) in the borehole E 14 at a boring depth of 16 m (level —14.6 m). This is the pollen-analytical level at which the alder curve sets in (VII—VIII). As has been mentioned above, this boundary in the borehole E 14 at Surte cannot be determined with absolute certainty so as to be accurate to one metre since the alder frequency is too low. Therefore, this boundary might be slightly shifted in an upward direction. If the diatoms from the sediments at Gothenburg are also taken into account in making this comparison, then it is found that a radical change in the hydrographical conditions took place precisely at that time. The forms occurring in cold fresh water disappear, and are replaced by a purely marine flora. It is probable that this change was caused by a decrease in the discharge of cold fresh water from the Baltic Sea through the river Svea älv and Lake Venern in combination with the general amelioration of the climate and the rise of the sea level. It is impossible to decide which of these factors has been preponderant in influence, but the available observations seem to indicate that the decrease in the discharge of cold fresh water has been the principal cause.

The period which is most interesting in this connection is that one represented by the sediments below a depth of 16 m. It is highly remarkable how little the foraminiferal fauna reflects the amelioration in climate which has been recorded by means of pollen analyses as early as in the zones VIII and IX. These zones seem as to the character of the foraminifera to be approximately equivalent to the zone X, the younger Dryas epoch, during which, according to the pollen analyses, the terminal moraines in Central Sweden were formed by an advance of the land ice sheet. On the other hand, if we consider the diatoms from Gothenburg, we find that the plankton flora in that place is greatly dominated in the whole zone IX by the clear-water and cold-water form Melosira islandica, var. helvetica down to the level which has been designated as the zonal boundary IX/X. This circumstance has been interpreted as an indication of a continuous discharge of fresh water floating as a layer at the surface of the Venern Bay above the salt water which was formed as a counter-current produced by this discharge.

The fresh water discharge was also ample during the zone X, but was now and then interrupted by salt water stages. The influence of the salt on the foraminiferal fauna appears to have been comparatively restricted and counteracted by the simultaneous cold. The molluscan fauna affords the same evidence as the foraminiferal fauna. The former is deficient both in species and in individuals, and contains specimens of Portlandia arctica at levels as high as 28 m. The deficiency of the marine fauna and flora in this period can certainly in part be attributed to the regression and the aggradation in the upper portion of the zone 4, which were inferred by Brotzen from a maximum of the shallow-water epiphyte Cibicides lobatula. The aggradation is also indicated in the sediments (cf. the field examination of the soil cores, p. 22, fig. 3) by the presence of fine sand and silt, by the occurrence of worm tubes, and remnants of vegetable matter, as well as by the abundant impregnation with ferrous sulphide. All this produces the impression of a shallow-water sediment.

The fact that boreal elements, *e.g.* Cassidulina crassa are distinctly present in the zone 3 is easy to interpret, if the Betula maximum around the levels 30 to 33 m is contemporaneous with the Allerödian period, zone XI. In this case, too, the warmer climate seems to have increased the supply of water produced by the melting of the land ice or possibly also to have caused a discharge of this water over the Central Swedish Sound, N for the Mount Billingen (before the advance of the ice to the terminal moraines),[1] which counteracted a strong influence of the salt water. In fact, we also at Gothenburg find a continuous curve of Melosira islandica showing high values. However, the foraminiferal fauna in zone 3 at Surte, which is richer than that in the zone 4,

[1] However, cfr. Caldenius 1944.

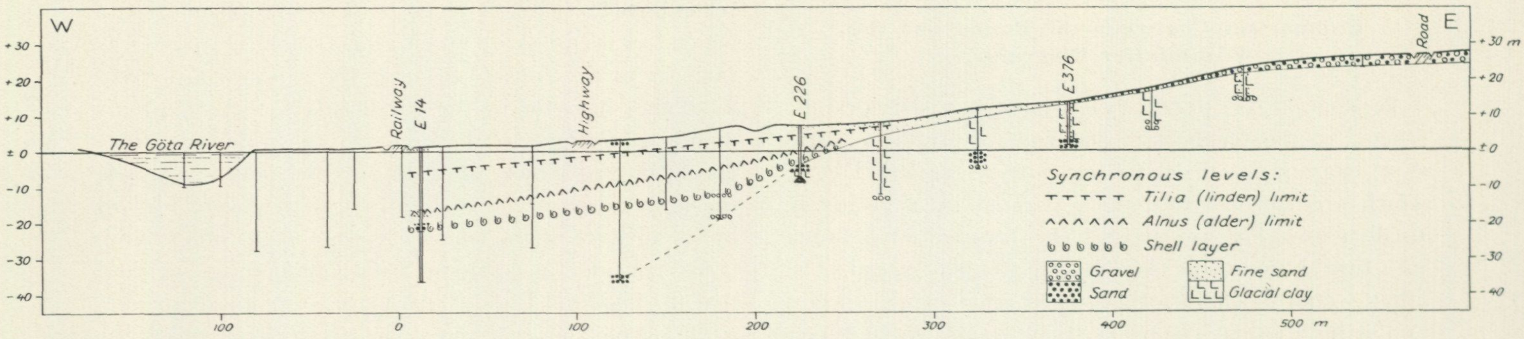


Fig. 7. Synchronous levels in Section + 966.

shows that the salt water had better possibilities of making its influence felt farther landwards in an eastern direction during this early stage, when the sea level was situated at a considerable height above the bottom at the Venern Bay. Thus, as has been pointed out by Mohrén (1951, Ref., p. 6), a molluscan fauna, rich in individuals, is found at Bromaden, 11 km south-west of Lidköping, a locality where a shell bearing clay is overlain by "moraine" and fluvioglacial gravel in the outermost row of the terminal moraines of Central Sweden. This fauna comprises Astarte borealis, Astarte elliptica, Astarte montagui, Mya truncata, Saxicava arctica, Neptunea despecta, and furthermore Balanus crenatus and Balanus porcatus. The statement (l. c. p. 6) that Zirphaea crispata and Balanus hameri have also been found there is incorrect.

As has been shown by the tentative pollen analyses, there is practically no pollen in the core from the borehole E 376. Consequently, these sediments cannot be compared with any parts of the sedimentary column of borehole E 14 other than those which have not been reached by the sampler. The sediments in the borehole E 376 must therefore belong to by far the oldest, high-arctic parts of the series of strata.

Those oldest parts of the core from the borehole E 226 which have been pollen analyzed, belong to the zone IX. However, Brotzen (p. 67) considers the lower boundary of his "Postglacial" zone 5 to be situated at a depth of 9 m in this borehole. This is not correct. Actually, this zone boundary, which approximately coincides with the pollen-analytical boundary VII/VIII, is situated at a depth of 5.4 m. Since Brotzen has not stated the reasons why he has located the boundary of the zone 4 at a depth of 10 m in this borehole, and since the pollen analysis does not afford any guidance in this case, it is not possible to decide, whether the location of these limits is justifiable. All the same, it seems hardly reasonable to assume that the pollen-free sand at a depth of 12 m is equivalent to the zone XI or to the zone 3 in the borehole E 14, which are comparatively rich in pollen. It is true that a small sand layer was observed at a depth of 32.1 m in E 14, but the thickness and the coarseness of the material in the borehole E 226 may be expected to require a stronger marking in the sediment which is only some 200 m distant. It appears more natural to correlate the sand layer at a depth of 12.2 m in the borehole E 226 with the sandy bottom layers in the borehole E 376. Since continued sampling in E 226 was prevented by a stone, it was impossible to find out whether the sand and the stone at the depth of 13.5 m were underlain by a clay layer of appreciable thickness.

Age and Parallelisation of Sand Strata.

Since the sand layers in this series of strata play an important part in the discussion of the cause and the course of the slide, these layers and their relative ages will be dealt with as follows.

At first we consider Section + 966. It is to be noted that in the whole Postglacial range, which reaches down to the zonal boundary VII/VIII, no real sand has been recorded except that which represents, on the soil surface in the east, the shallow-water facies during the regression of the sea from the Postglacial limit down to the present sea level. Similarly, in the zone VIII, in that case where it is well developed, nothing has been found but a small quantity of silt or thin silt layers.

On the other hand, the coarse material in the zone IX in the borehole E 14 is represented by clay with several diffuse layers of silt or clayey fine sand (see p. 11) and, between 23.20 m and 23.25 m, by medium sand with shell fragments. This sand stratum indicates shallow water and erosion, which increased the concentration of shells.

Owing to its pollen-analytical position at the base of the zone IX, the above-mentioned shell sand layer at a depth of 23.20 m in the borehole E 14 seems to be easy to correlate with a layer facially developed in the same way at the depth 9.90 to 10.15 m in the borehole E 226. As has been mentioned in the above, since the clay and the sand below 11 m in the borehole E 226 are almost completely free from pollen, it seems that they should be correlated with the bottom layers in the borehole E 376. In both boreholes put down at E 226 the sampler was stopped by stones. In consideration of the position of the borehole on the ground, these stones may be supposed to belong to the gravel deposit which is situated at the south-eastern corner of the sediment shelf.

In a borehole, put down at E 180 in this section by means of the Swedish sounding method, a sandy layer was also found in such a position that it may be assumed to be connected with the shell sand layers in the boreholes E 226 and E 14. However, no such layer has been found in the other boreholes made by sounding and situated farther towards the middle of the valley. This layer is either not present there or very weakly developed, so that it did not manifest itself in the boreholes, some of which were put down by means of a piston sampler.

Below the shell sand stratum at a depth of 23.5 m in the borehole E 14, no more or less pronounced sand layer or any other stratum of relatively clean and coarse material it met with until we reach the bottom of the borehole at a depth of 36.5 m, which appears to belong to the uppermost top part of the zone XII. It is possible that this sand layer has to be connected with the sand layers at the bottoms of the boreholes E 180 and E 125, but this question cannot be answered with certainty on the basis of our investigations.

It is obvious *a priori* that it will be much more difficult to follow and to correlate originally continuous sand layers in those parts of the series of strata which have been disturbed by the landslide. In the borehole W 137 (Section + 764) no sandy layers occur until we reach the lower parts of the greyish-blue muddy clay. For example, these layers are found at levels of 18.85 to 19.15, 19.60 to 19.73, and 22.00 m. In the borehole E 19 it is also necessary to pass through the whole greenish-grey Postglacial muddy clay as well as through the bluish-black muddy clay, which contains worm tubes and remnants of vegetable matter, until the first traces of fine sand are found between the levels 21.31 and 23.96 m. More or less distinct layers of fine sand occur at depths below 26.5 m, but none of them appears in the form of material mixed with shells.

In both these boreholes, the sand layers are far below those levels at which definite disturbances due to recent slides were detected (cf p. 19). The question whether the sand strata in Sections + 764 and + 966 are completely synchronous or not, cannot be answered with certainty.

Sandy layers in the borehole E 99 (Section + 660) occur at depths which are not greater than a few metres, but the stratigraphic disturbance caused in this place by the slide is so heavy that even the sand strata in the three boreholes 99 a, 99 b, and 99 c cannot be connected. For stratigraphic and faunistic reasons, the shell gravel layer about 17 m cannot be correlated with the shell sand at 23.5 m in E 14 and at 10 m in E 226. The altitude of the ground level at E 99 is about + 5 m and was about + 3 m before the slide. If we assume that the shell sand has not been disturbed by the slide, then its depth below the ground level would have been 15 m. This corresponds to an altitude of — 12 m above sea level. However, some traces of disturbances have been observed down to a depth of 20.30 m. Therefore, it is not certain that the sand has remained in its primary position.

In the borehole E 190 (Section + 660), with an altitude of the ground surface of + 4.90 m after the slide, the macrofossils found at a depth as small as 1.5 m below the ground level showed that these strata belonged to the Late Glacial period, and Portlandia arctica, which was found at a depth of 4 m, indicated high-glacial conditions. Consequently, the sand strata observed below that level, *e.g.* at 6.28, 12.10, 13.58 m, etc., must be older than those which were recorded in the sedimentary column in Section + 966 nearer to the centre of the valley.

Apart from the layer bearing shell sand, all those sand strata observed and dealt with in this investigation which are so recent that they might have played some part in the slide, judging from their position in the sedimentary column, seem to be so fine-sandy or mixed with clay, or else so little continuous that it is scarcely probable that an accidental artesian over-pressure could have been propagated along these strata towards the central parts of the valley. On the other hand, an artesian over-pressure might possibly have broken through around the outcrop of the Postglacial clay on the slope rising towards the sediment shelf. As has already been pointed out, peaty and muddy layers with a hygrophilous vegetation on the ground surface have been present in this place before the slide. Furthermore, it has been noted that some areas on this slope were difficult to plough on account of moisture. Consequently, it is possible that a landslide was initiated somewhere at the outcropping of the Postglacial clay.

4. Geotechnical Field and Laboratory Investigations.

By Rune Lundström.

Field Investigations.

The field investigations comprised sounding and soil sampling in four main sections at right angles to the railway line in the slide area. All sections extended from the river Göta älv, in the west, to the upper boundary of the slide area, in the east. The sections were marked in accordance with the length of the railway line, which is reckonned in the direction from Trollhättan to Gothenburg, and were denoted by the symbols km 464 + 560, km 464 + 660, km 464 + 764, and km 464 + 860, see Pl. I. Furthermore, the thickness of the soil strata was determined by sounding in the sections I, II and III, situated in that part of the slide area where the slope of the ground had been greatest before the slide and section IV situated in the northern part of the slide near the large bend of the highway. Moreover, sounding and soil sampling were carried out in a section, marked km 464 + 966, situated outside the slide area, in order to obtain geological and geotechnical data for comparisons with the conditions before the slide. The field investigations were partly entrusted to the Geotechnical Divisions of the Swedish State Railways. Soil cores in some boreholes were taken by representatives of the Royal Swedish Geotechnical Institute with aid of a soil sampler with metal foils. These samples were examined and determined by Dr. E. Mohrén at the Geological Survey of Sweden. The other soil cores, 45 mm in diameter, were taken by means of a piston sampler. The samples were sent in hermetically sealed containers by railway to the Laboratory of the Royal State Railway Board in Stockholm. About 1 700 samples were taken and tested in the laboratory. The soundings were made by means of a 19 mm sounding rod of the type of the Swedish State Railway. The purpose of sounding was to determine the thickness of the various soil strata and the situation of the firm bottom.

Laboratory Investigations.

Description of the Swedish Cone Test Method.

Most of the above-mentioned clay samples were tested according to the Swedish cone test. Since the testing procedure and the theoretical and experimental basis of this method can be presumed to be rather unknown outside Scandinavia, it seems to be suitable here shortly to describe the cone test method.

The Swedish cone test method was envolved by the Geotechnical Commission of the Swedish State Railways, 1914 to 1922, whose secretary, Mr. J. Olsson, of the Swedish State Railway Board was chiefly responsible for the development of this method. In the Swedish literature the method has been described in the final report of the above-cited commission, May 31st, 1922 (Stockholm).

The cone test procedure is made by means of a metal cone, the point of which is placed immediately above the surface of the sample and is then freely dropped into the sample. By measuring the depth of penetration of the cone, we obtain a relative "strength value" from which we can calculate the actual shear strength of the sample. The cone penetrometer is shown in Fig. 8.

In the experiments dealing with this method several cones, which varied in weight and in apex angle, were tested. Finally, a cone having a weight of 60 g and an apex angle of 60° was defined as a "standard cone". The tests under consideration were made not only with this standard cone, but also with 60° cones weighing 10, 30, 100, 200 and 300 g. The results of the tests carried out on various clays by means of the last-mentioned cones were plotted in diagrams exemplified in Fig. 9, where the abscissa expresses the depth of penetration, in millimetres, of the 60 g cone and the ordinate represents the depth of penetration, in millimetres, of all 60° cones. It is seen from Fig. 9 that the test results are

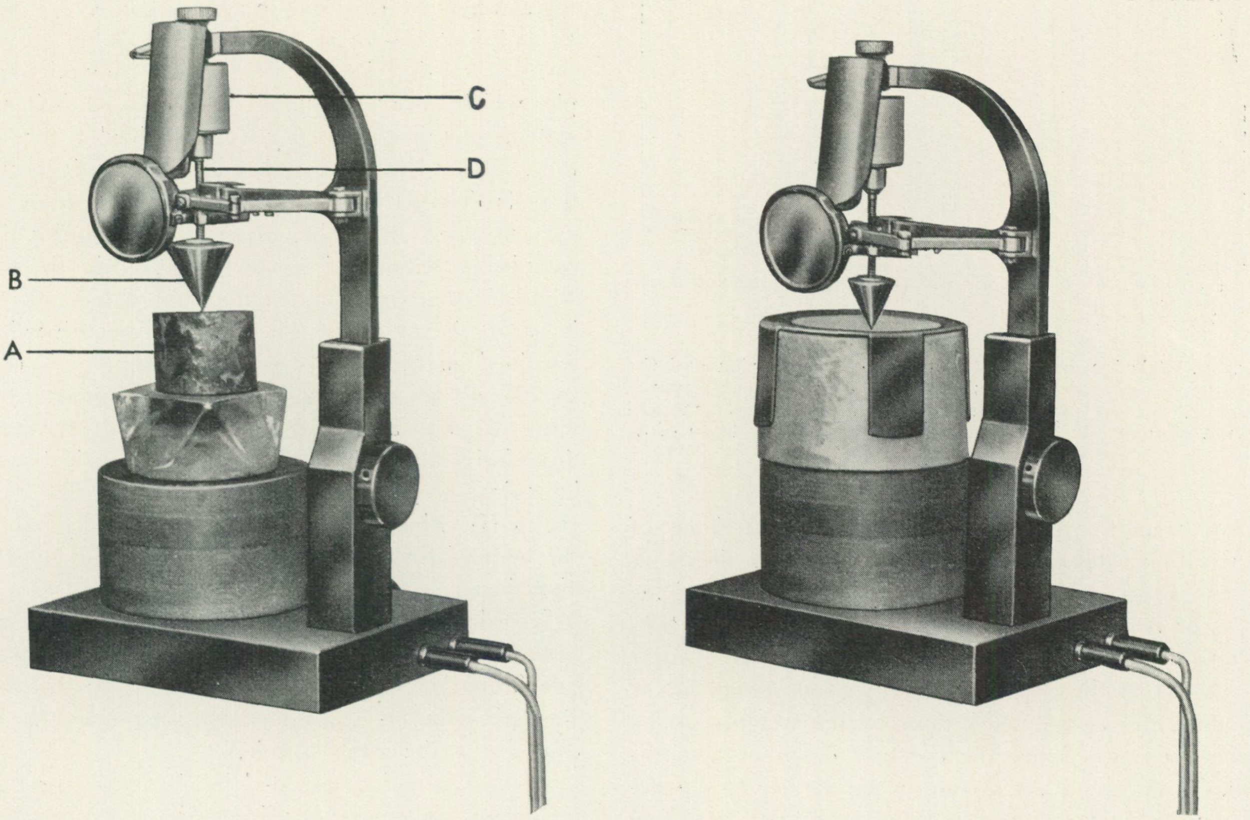


Fig. 8. The Swedish cone tester, *left* with undisturbed, *right* with remoulded sample. — A = clay sample, B = cone, C = magnetic hanging of the cone, D = scale for checking the sinking of the cone. Scale of cone tester abt. 1/3. (Photo S. Walther.)

closely grouped around the average value curves. If a line parallel to the axis of the ordinates is drawn so as to intersect the average value curves, then it follows that the ordinates of the points of intersection represent the depths of penetration of the respective cones in the same clay (clay-consistency). Consequently, if these values of the weight of cone and the depth of penetration are plotted in a diagram where the abscissa represents the weight of cone, in grammes, and the ordinate expresses the depth of penetration, in millimetres, then we obtain a curve which represents the relation between the depth of penetration and the weights of cone for the same consistency of the clay, for instance that one at which the depth of penetration of the 60 g, 60° cone is 10 mm. See fig. 10.

In cone tests, a loose consistency of the clay (a low

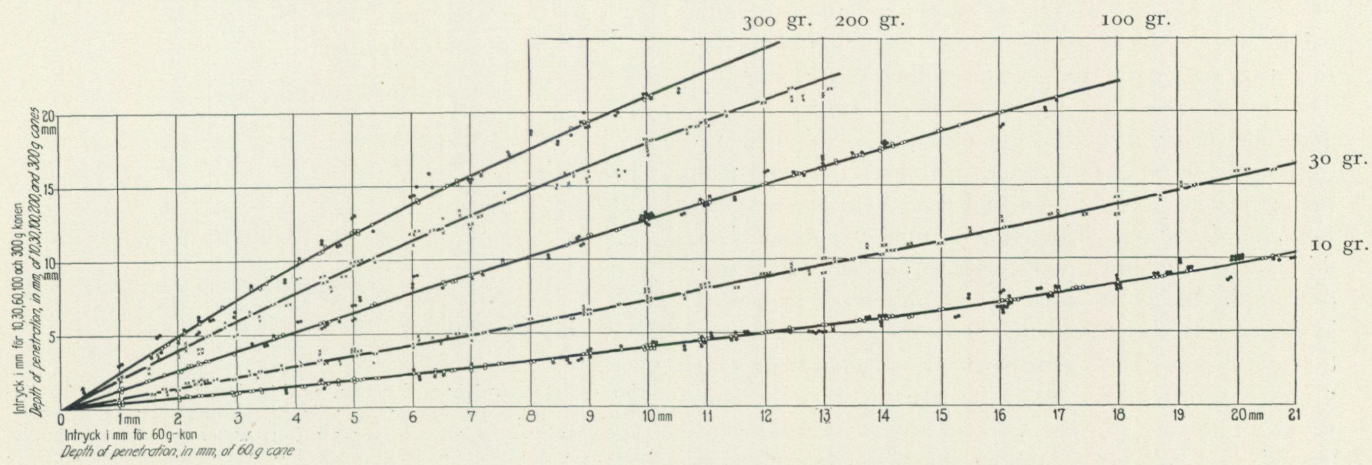


Fig. 9. Results of cone tests. The depth of penetration of 60° cones weighing (from below) 10, 30, 100, 200, and 300 g are resented as functions of the depths of penetration of the 60 g, 60° cone.

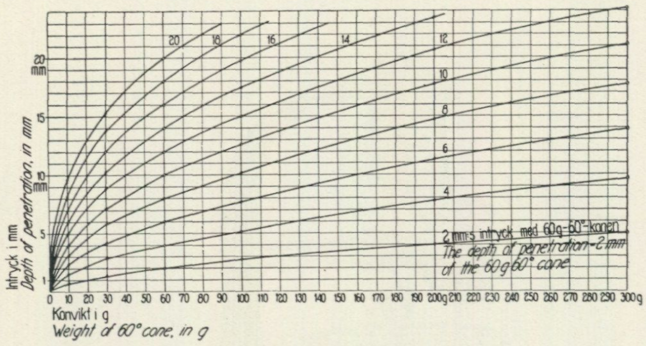


Fig. 10. Relation between the depth of penetration and the weight of a 60° cone in clays where the depth of penetration of the 60 g, 60° cone varies from 2 to 20 mm. Each curve is marked with a number which expresses the corresponding depth of a penetration of the 60 g 60° cone.

shear strength) results in a relatively great depth of penetration, whereas the depth of penetration decreases as the consistency of the clay becomes firmer. If the depts of penetration in different clays are equal, then it may be assumed that the consistencies (the shear strengths) of the clays are directly proportional to the amounts of external work done by the weights of the respective cones times the constant depth of penetration. On the above assumption, when the depth of penetration is constant, the consistencies of the clays are therefore directly proportional to the weights of each cone. If a line parallel to the axis of abscissae is drawn in the diagram shown in Fig. 10, then the abscissae of the points of intersection represent the weights of cones sought in accordance with the above at a constant depth of penetration.

If we examine the relations between the weights of cones determined by means of the latter method, then we find that these relations remain unchanged irrespective of comparatively great variations in the order of magnitude of the depth of penetration. By taking a definite basis as a point of departure the relations between the weights of cones, or the relative strength values were deduced at the constant depths of penetration 4, 7, 10, 13, 16, and 19 mm in the table of Fig. 11. The initial value (basic value) was put equal to 10 at that consistency of the clay for which the depth of penetration of the 60 g, 60° cone is 10 mm. It is seen that the agreement is very close and that there are no considerable deviations. The relative numbers obtained in this manner and the corresponding depths of penetration of the 60 g, 60° cone are graphically represented in Fig. 15. It was found that those depths of penetration of the 60 g, 60° cone wich are smaller than 3 to 5 mm or greater than 16 to 20 mm give less reliable values. For this reason, two additional curves were plotted, viz., one for a cone having a weight of 100 g and an apex angle of 30° and the other for a cone having a weight of 10 g and an apex angle of 60°. See fig. 15 and the tables p. 33.

The tests described in the above were made on samples which were undisturbed or as close to their natural state as possible when they were received in the laboratory. The relative strength value obtained from such tests is denoted by H_3. However, it was found to be very useful to determine the relative strength value on completely remoulded samples, that is, in those cases where further treatment of the sample does not reduce its strength any more. The relative strength value determined on completely remoulded samples is denoted by H_1. At an early stage in the development of cone tests, use was also made of the symbol H_2, denoting the relative strength value of partly disturbed samples, but this concept has now been abandoned. The ratio of H_3 to H_1, which is called "H ratio" or "H quotient", can be used for estimating the sensitivity of the clay to disturbances.

In order to determine the fineness of the clay further tests were made. The results of these tests are used for calculating the "relativ fineness" F from the relative strength value H_1 of a remoulded sample and the water contents of the same sample.

As has been demonstrated by A. Atterberg (1911), the water contents of a fine-grained clay are higher than that of a coarse-grained clay if both clays are equal in consistency.

If a certain definite consistency was adopted as a standard consistency, then each sample could be reduced to this consistency by addition or removal of water, and the water contents of the sample of standard consistency would therefore express the fineness of the sample. This method of testing is highly time-wasting. Furthermore, actual tests have proved this method to be unnecessary. In fact, these tests showed that, if the

Intrycksdjup 2,4,6,8,10,12,14,16,18 och 20 mm av 60 gr 60° konen
The depths of penetration 2,4,6,8,10,12,14,16,18 and 20 mm of the 60° 60 gr cone

Intrycksdjup 4,7,10,13,16 och 19 mm av 60° konen / *The depths of penetration 4,7,10,13,16 and 19 mm of 60° cones*	2 mm	4 mm	6 mm	8 mm	10 mm	12 mm	14 mm	16 mm	18 mm	20 mm
4	(200,00g) 200,00	(60,00g) 60,00	(26,50g) 26,50	(15,30g) 15,30	(10,00g) 10,00	—	—	—	—	—
7	—	(168,75g) 59,21	(83,00g) 29,12	(45,00g) 15,79	(28,50g) 10,00	(19,75g) 6,93	(14,00g) 4,91	(9,75g) 3,42	(7,00g) 2,46	(5,00g) 1,75
10	—	(320,50g) 53,42	(159,50g) 26,58	(95,50g) 15,92	(60,00g) 10,00	(39,75g) 6,63	(28,00g) 4,67	(20,10g) 3,35	(15,25g) 2,54	(10,95g) 1,83
13	—	—	(263,00g) 24,93	(158,00g) 14,98	(105,50g) 10,00	(72,75g) 6,90	(50,00g) 4,74	(36,50g) 3,46	(26,80g) 2,54	(20,10g) 1,91
16	—	—	—	(243,00g) 15,12	(160,75g) 10,00	(115,00g) 7,15	(82,60g) 5,14	(60,00g) 3,73	(44,25g) 2,75	(33,25g) 2,07
19	—	—	—	—	(234,50g) 10,00	(165,50g) 7,06	(122,00g) 5,20	(91,50g) 3,90	(68,75g) 2,93	(52,25g) 2,22
	A=200,00	A=57,54	A=26,78	A=15,42	A=10,00	A=6,93	A=4,93	A=3,57	A=2,64	A=1,95

Fig. 11. The weights of cones, within brackets, from the diagrams in fig. 10 and out of this calculated relative strength values at the depths of penetration which are shown in the table. — A = The average values of the relation at the corresponding depth of penetration of the 60 g 60° cone or the relative strength value H_3 of undisturbed samples.

Tables showing connections between the relative strength value (H_1 and H_3) and the depth of penetration (p) in mm of the 10 g—60°, 60 g—60° and 100 g—30° cone.

Depth of penetration (p) and H-value of the

10 g—60° cone.

p mm	*H*	*i* mm	*H*	*i* mm	*H*
		10.0	1.66	15.0	0.70
5.2	5.82	2	1.60	2	0.67
4	5.42	4	1.54	4	0.65
6	5.04	6	1.48	6	0.63
8	4.71	8	1.42	8	0.61
6.0	4.42	11.0	1.37	16.0	0.59
2	4.17	2	1.32	2	0.57
4	3.94	4	1.28	4	0.56
6	3.72	6	1.24	6	0.54
8	3.52	8	1.20	8	0.52
7.0	3.32	12.0	1.16	17.0	0.50
2	3.14	2	1.12	2	0.49
4	2.98	4	1.09	4	0.47
6	2.84	6	1.05	6	0.46
8	2.70	8	1.02	8	0.45
8.0	2.57	13.0	0.98	18.0	0.43
2	2.45	2	0.94	2	0.42
4	2.34	4	0.91	4	0.41
6	2.24	6	0.88	6	0.40
8	2.14	8	0.85	8	0.39
9.0	2.05	14.0	0.82	19.0	0.38
2	1.96	2	0.80	2	0.37
4	1.88	4	0.77	4	0.36
6	1.80	6	0.75	6	0.36
8	1.73	8	0.72	8	0.35
				20.0	0.34

60 g—60° cone.

p mm	*H*	*i* mm	*H*	*i* mm	*H*
5.0	36.9	10.0	10.00	15.0	4.2
2	34.4	2	9.60	2	4.05
4	32.2	4	9.25	4	3.95
6	30.4	6	8.90	6	3.80
8	28.4	8	8.55	8	3.70
6.0	26.7	11.0	8.25	16.0	3.60
2	25.1	2	7.95	2	3.50
4	23.5	4	7.65	4	3.40
6	22.1	6	7.40	6	3.30
8	20.7	8	7.15	8	3.20
7.0	19.6	12.0	6.95	17.0	3.10
2	18.6	2	6.70	2	3.02
4	17.8	4	6.45	4	2.94
6	16.9	6	6.25	6	2.86
8	16.2	8	6.05	8	2.78
8.0	15.4	13.0	5.85	18.0	2.72
2	14.7	2	5.65	2	2.65
4	14.0	4	5.50	4	2.58
6	13.4	6	5.30	6	2.52
8	12.8	8	5.10	8	2.46
9.0	12.2	14.0	4.95	19.0	2.40
2	11.7	2	4.80	2	2.34
4	11.3	4	4.65	4	2.27
6	10.8	6	4.50	6	2.20
8	10.4	8	4.35	8	2.14
				20.0	2.07

100 g—30° cone.

p mm	*H*	*i* mm	*H*
		7.0	104.0
		2	98.0
1.4	1 950	4	92.5
6	1 600	6	87.5
8	1 350	8	83.0
2.0	1 140	8.0	78.5
2	970	2	74.5
4	827	4	70.7
6	705	6	67.4
8	607	8	64.3
3.0	526	9.0	61.4
2	462	2	58.5
4	409	4	55.8
6	365	6	53.2
8	328	8	50.9
4.0	295	10.0	48.8
2	266	2	46.8
4	241	4	44.9
6	220	6	43.2
8	203	8	41.5
5.0	189	11.0	40.0
2	178	2	38.5
4	167	4	37.1
6	158	6	35.7
8	149	8	34.4
6.0	140	12.0	33.2
2	132	2	32.1
4	124	4	31.0
6	117	6	30.0
8	110	8	29.0

60 g – 60° and 100 g—30° cone.

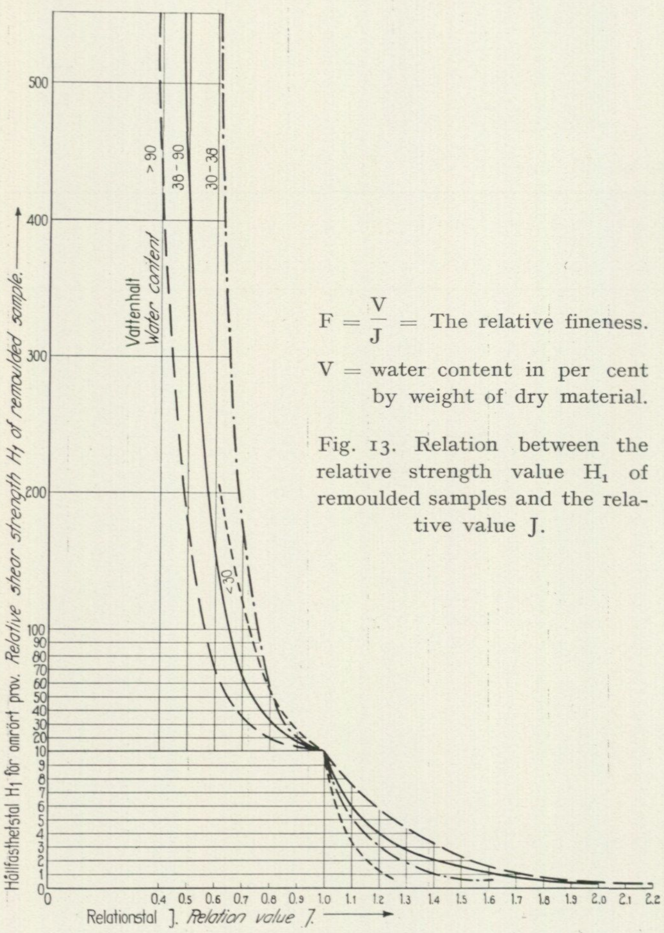
Penetration of the 100 g—30° cone	Penetration of the 60 g—60° cone in mm																		
	4.9	4.8	4.7	4.6	4.5	4.4	4.3	4.2	4.1	4.0	3.9	3.8	3.7	3.6	3.5	3.4	3.3	3.2	3.1
6.0										99.1	105	110	115	120	124	128	132	135	138
2									89.2	94.9	100	105	109	114	118	122	125	128	130
4								80.7	85.8	90.9	95.5	100	104	108	112	115	118	121	123
6								78.0	82.8	87.4	91.7	95.6	99.6	103	106	109	112	114	116
8							71.1	75.5	79.8	84.0	87.9	91.6	95.3	98.5	101	104	106	108	109
7.0						63.9	69.1	73.2	77.0	80.8	84.5	88.0	91.3	94.1	96.7	99.1	101	102	
2					57.7	62.5	67.1	70.9	74.3	78.0	81.2	84.6	87.5	90.0	92.2	94.2	96.0	97.1	
4				52.5	56.7	61.2	65.3	68.9	71.9	75.5	78.4	81.5	84.1	86.4	88.2	90.2	91.7		
6			47.9	51.8	55.7	59.9	63.6	67.0	69.8	73.1	75.7	78.6	80.9	83.0	84.6	86.6			
8			47.4	51.1	54.8	58.6	61.9	65.1	67.8	70.8	73.2	75.9	77.9	79.8	81.3				
8.0		43.7	46.9	50.4	53.9	57.4	60.4	63.3	65.9	68.6	70.9	73.3	75.1	76.9					
2	39.8	43.4	46.4	49.8	53.0	56.2	58.9	61.7	64.1	66.6	68.7	70.8	72.7	74.0					
4	39.6	43.1	46.0	49.1	52.2	55.1	57.6	60.2	62.4	64.7	66.7	68.5	70.2						
6	39.5	42.8	45.6	48.5	51.4	54.0	56.4	58.7	60.9	63.0	64.8	66.5							
8	39.3	42.4	45.1	48.0	50.7	53.0	55.3	57.4	59.4	61.3	63.0								
9.0	39.2	42.1	44.7	47.4	49.9	52.1	54.2	56.2	57.9	59.8									
2	39.0	41.9	44.3	46.9	49.1	51.3	53.1	55.0	56.6										
4	38.9	41.6	44.0	46.3	48.5	50.5	52.2	53.8	55.3										
6	38.8	41.4	43.6	45.9	47.9	49.6	51.4	52.8											
8	38.6	41.1	43.3	45.4	47.3	49.0	50.5												
10.0	38.5	40.9	43.0	45.0	46.8	48.4													
2	38.4	40.7	42.7	44.6	46.3														
4	38.3	40.5	42.4	44.2															
6	38.2	40.3	42.1																
8	38.2	40.1																	
11.0	38.1	39.9																	
2	38.0																		
4	37.9																		

When the depth of penetration of the 60 g—60° cone is greater then 4.9 mm only use the values for this cone. When the depth of penetration of the 60 g—60° and the 100 g—30° cone gives a H_1-value which should be greater then those in the table only use the depth of penetration of the 100 g—30° cone.

Relativa hållfasthetstal H_1. Relative strength value	Group 1		Group 2			Group 3													Group 4	
	Sample 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
0.46	35.8 1.26	—	—	59.0 1.69	56.5 1.53	—	93.7 2.08	—	86.8 1.75	122.0 2.10	117.5 2.02	—	122.0 2.0	—	—	150.0 1.99	—	—	223.6 2.24	245.6 2.11
0.98	34.9 1.22	36.0 1.23	43.6 1.44	50.8 1.46	51.2 1.38	—	76.3 1.69	—	78.0 1.57	100.0 1.72	98.5 1.69	100.3 1.65	101.0 1.65	119.2 1.66	—	121.0 1.61	—	—	181.0 1.82	193.6 1.66
2.02	33.5 1.18	32.9 1.12	39.7 1.31	44.0 1.26	46.6 1.26	—	65.6 1.45	—	67.3 1.35	82.5 1.42	80.0 1.37	84.9 1.40	85.3 1.39	102.3 1.43	—	103.4 1.38	—	—	159.6 1.60	173.5 1.49
4.82	30.8 1.08	30.8 1.05	34.1 1.12	38.7 1.11	41.1 1.11	43.5 1.14	53.8 1.19	55.6 1.20	55.8 1.12	68.2 1.17	67.1 1.15	72.8 1.20	71.5 1.17	84.4 1.18	84.5 1.13	86.0 1.14	82.8 1.10	91.7 1.10	127.6 1.28	145.2 1.25
10.0	28.4 1.00	29.3 1.00	30.3 1.00	34.9 1.00	37.0 1.00	38.0 1.00	45.1 1.00	46.5 1.00	49.7 1.00	58.1 1.00	58.3 1.00	60.9 1.00	61.2 1.00	71.6 1.00	74.6 1.00	75.2 1.00	75.4 1.00	83.3 1.00	99.7 1.00	116.2 1.00
20.3	25.8 0.91	27.5 0.94	27.4 0.90	31.4 0.90	33.8 0.91	33.5 0.88	39.6 0.88	39.7 0.85	44.1 0.89	51.0 0.88	51.4 0.88	51.4 0.84	49.9 0.82	62.1 0.87	65.8 0.88	66.1 0.88	65.4 0.87	73.6 0.88	80.7 0.81	87.4 0.75
31.1	24.5 0.86	26.1 0.89	25.6 0.84	29.6 0.85	31.9 0.86	30.8 0.81	36.6 0.81	36.9 0.79	41.2 0.83	47.5 0.82	47.7 0.82	47.9 0.79	45.9 0.75	56.4 0.79	63.0 0.85	60.5 0.81	58.6 0.78	68.8 0.83	73.7 0.74	79.5 0.68
65.3	21.7 0.76	23.4 0.80	23.8 0.79	27.3 0.78	29.3 0.79	26.7 0.70	32.0 0.71	33.4 0.72	37.7 0.76	41.4 0.71	40.4 0.69	40.9 0.67	40.4 0.66	48.9 0.68	57.0 0.76	51.5 0.69	49.5 0.66	59.7 0.72	62.7 0.63	68.4 0.59
131.2	17.8 0.63	22.0 0.75	—	25.0 0.72	27.2 0.74	24.[illegible] 0.65	27.7 0.61	30.1 0.65	33.9 0.68	36.6 0.63	35.4 0.61	36.0 0.59	35.8 0.58	43.2 0.60	—	45.2 0.60	44.7 0.59	—	54.3 0.54	60.1 0.52
202	15.1 0.53	20.4 0.70	—	23.4 0.67	25.6 0.69	22.0 0.58	25.6 0.57	28.3 0.61	30.1 0.61	33.5 0.58	32.4 0.56	33.8 0.56	33.2 0.54	39.6 0.55	—	40.0 0.53	42.1 0.56	—	49.6 0.50	54.2 0.47
380	—	—	—	21.1 0.61	24.4 0.66	—	24.0 0.53	—	—	31.5 0.54	28.4 0.49	30.8 0.51	29.9 0.49	36.0 0.50	—	36.4 0.48	—	—	42.5 0.43	46.7 0.40
460	—	—	—	20.5 0.59	24.1 0.65	—	23.5 0.52	—	—	30.8 0.53	27.5 0.47	29.2 0.48	29.0 0.47	34.8 0.49	—	35.6 0.47	—	—	40.1 0.40	45.1 0.39
650	—	—	—	19.7 0.56	23.5 0.64	—	22.1 0.49	—	—	29.5 0.51	25.9 0.44	—	—	32.6 0.46	—	34.6 0.46	—	—	39.9 0.40	43.7 0.38

Fig. 12. The variation of the water content with H_1 in 20 different soil samples and the calculated ratios between the water contents. The water content is expressed relatively to dry weight, and is found to the left in each column.

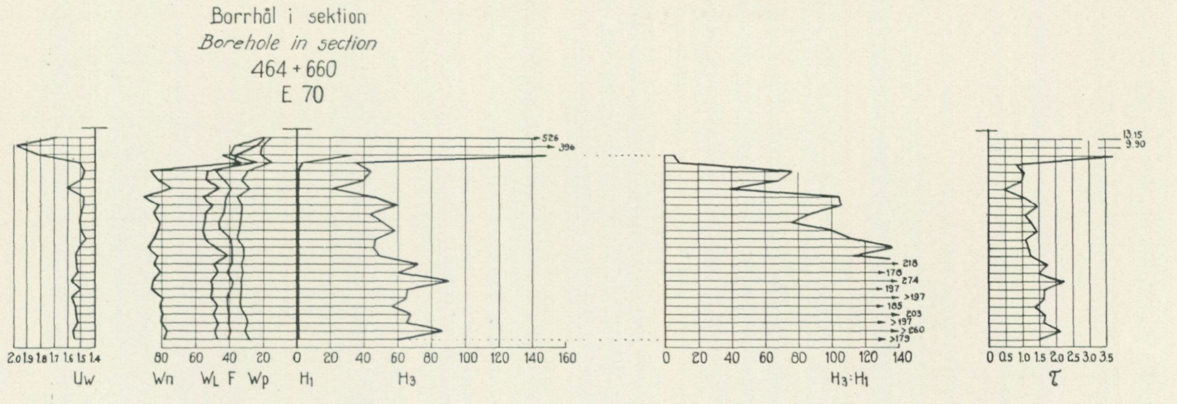
water contents are expressed in per cent by weight of dry material, the water contents V_1, V_2, V_3 etc. of different samples having the relative strength value H_1 are directly proportional within certain definite limits to the water contents V'_1, V'_2, V'_3, etc., of different samples having the relative strength value H'_1. $V_1 : V_2 : V_3$, etc., $= V'_1 : V'_2 : V'_3$, etc. Hence it follows $V_1 : V'_1 = V_2 : V'_2 = V_3 : V'_3$, etc., that is to say, the water contents of different clays vary with the relative strength number in approximately the same manner. The basic value of the relative strength value (consistency) H_1 was put equal to $H_1 = 10$, and all relative values of the water contents were put equal to 1.00 at this value of H_1. The results of the tests are tabulated in Fig. 12, where the numbers on the left side of each column express the water contents in per cent by weight of dry material, while the numbers on the right side represent the relative values. The results are not closely in agreement, and some values deviate from the mean value to a considerable extent. In view of this, the samples were divided into four groups, so that the deviation in each group was reduced to a minimum. The samples were grouped in such a manner that the limits of the water contents in per cent by weight of dry material at a relative strength value $H_1 = 10$ are < 30 per cent, 30 to 38 per cent, 38 to 90 per cent, and > 90 per cent. The results obtained in this way are graphically represented in Fig. 13, where the abscissa expresses the relative value J and the ordinate the relative strength value H_1. It may be inferred from the test results shown in the above tables that any arbitrary concistency (relative strength value) can be used as a basis. As mentioned above, the relative strength value $H_1 = 10$ was taken as a basis, and the water contents corresponding to this value and expressed in per cent by weight of dry material represent the relative fineness of the soil sample. In other words, the relative fineness F gives the quantity of water in per cent by weight of dry material, which is bound in a soil sample when the sample, after complete remoulding, has a consistency which corresponds to the relative strength value $H_1 = 10$. Accordingly, the relative fineness F can be calculated from the formula $F = \frac{V}{J}$.



$F = \frac{V}{J}$ = The relative fineness.

V = water content in per cent by weight of dry material.

Fig. 13. Relation between the relative strength value H_1 of remoulded samples and the relative value J.



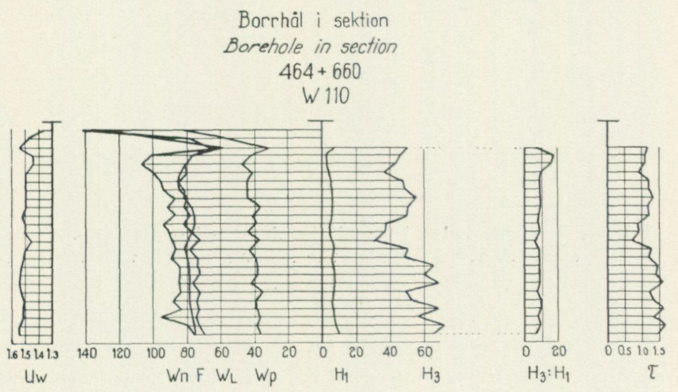


Fig. 14. The results of laboratory tests of soil samples from boreholes W 110 and E 70 in section 464 + 660.

The division of the samples into four groups in the determination of the relative fineness was performed for two reasons, viz., first in order to facilitate the calculation of the relative fineness, and second, in order to classify the samples roughly according to four types of soils: fine sand, silt, clay, and organic mud (gyttja). The relative fineness of mineral soils in Sweden is seldom higher than 80 to 90. If the relative fineness exceeds these values, then the soil is generally mixed with organic matter. As a rule, it may be stated that the relative fineness decreases as the soil becomes more coarse-grained. However, it has so far proved impossible to demonstrate a relation between the relative fineness and the grain fractions occurring in the sample. The relative fineness is thus a relative coefficient of the same order as Atterbergs's consistency limits which are known as the liquid limit and the plastic limit. In order to bring the relative fineness into approximate relation with the liquid limit and the plastic limit, some samples were taken at Surte in Section 464 + 660 in two boreholes. One of them (W 110) passed through typical "Gothenburg clay", which is homogeneous and fat, and which is mostly found in an area west of the highway. The other borehole (E 70) traversed typical quick clay which occurs east of the highway. The results of the laboratory tests made on these samples are shown in Fig. 14. As is seen from these diagrams, the values of the relative fineness F lie in the middle between the liquid limit W_L and the plastic limit W_P of the quick clay, while the F and W_L curves of the "Gothenburg clay" are practically coincident.

The testing method described in the above gives relative strength values (H_1 and H_3). Formulae for converting the relative strength number H_3 to the shear strength, in tons per m², have been deduced from laboratory tests as well as from measurements and comparisons with observations made on actual landslides, with the load-bearing capacity of piles, etc. For comparatively coarse Norwegian clays, Mr. Skaven-Haug, of the Norwegian State Railways, has found the relation

$$\frac{H_3}{32 + 0.073\,H_3}$$

tons per m². For the fat "Gothenburg clay", the relation $\tau = \frac{H_3}{40 + 0.055\,H_3}$ tons per m² has been determined by experiments. However, the mean value $\tau = \frac{H_3}{36 + 0.064\,H_3}$ tons per m² seems to be that value which is best suited to the most common Swedish clays. It is to be noted that when the above formula is applied to these clays, the value of denominator shall not be less than 40.

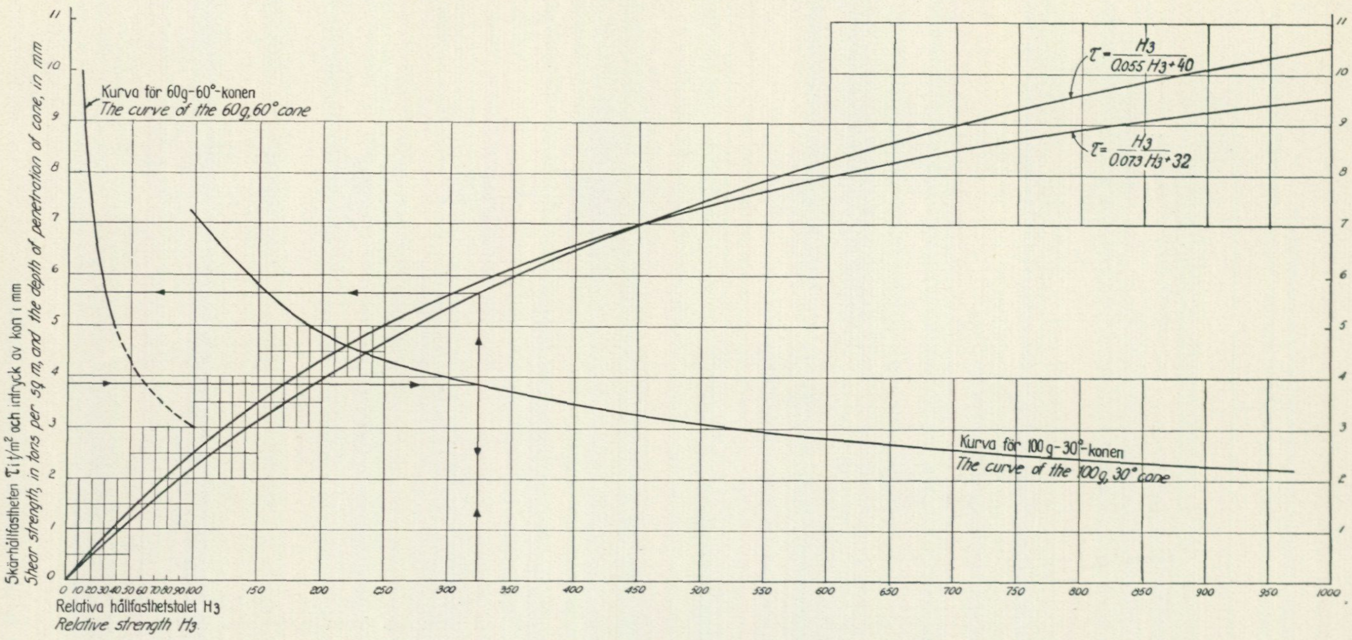


Fig. 15. Diagram showing the connection between the relative strength value H_3 and the depth of penetration of the 60 g 60° cone and the 100 g 30° cone and between the relative strength value H_3 and the shear strength τ in tons/m².

The relation between the relative strength number H_3 and the shear strength is graphically represented in Fig. 15. The Royal Swedish Geotechnical Institute (Jacobson, 1954) has carried out tests in order to compare shear strength test made by means of various methods. These comparative tests have shown that the results obtained from cone tests are reliable when the depth of sampling does not exceed about 15 m below the ground level. When the samples are taken at still greater depths, the values of the shear strength obtained from cone tests are probably slightly too low. The purely theoretical values of the shear strength which are mathematically deduced from cone test results are in fairly close agreement with experimental values.

The Swedish cone test method offers the advantage of enabling rapid determination of the shear strength of undisturbed or remoulded samples and the relative fineness for estimating the character of the sample. For instance, 15 to 20 samples can be tested, and the test results can be utilised for deducing the values required for practical use by one person during a normal working day (7 to 8 hours).

5. Morphology and Geology of the Slide Area.

By Carl Caldenius.

Morphology of the Slide Area.

The aerial photographs taken immediately after the slide (see Pl. A) are extraordinarily good general pictures of the slide area. They indicate the configuration and the character of the slide elements. It was easy to distinguish four groups of slide elements (see also the map in Pl. 2).

1. Most of the slide elements or remnants of slide elements in the innermost part of the slide area were narrow and long-extended. Grass-covered plots of ground surface were on them well preserved only here and there and within a width of utmost about two metres. Some slide elements had the shape of sharp, thin clay ridges. Some other slide elements were crushed and twisted into a chaotic muddle of variform, sharp-edged or smooth-levelled clay blocks. Those slide elements which were less injured than the others were crescent-shaped. They were convex in the direction of slide movement, and were grouped in separate "streamlines" or rows.

2. At an increasing distance from the inner part of the slide area, the slide elements became broader, the greensward was undisturbed almost everywhere, and the length of the slide elements was so great that the rows of grain shocks in the southern half of the slide area, which had originally been regular, remained approximately in their former positions. Though bent and broken, they were nevertheless so little displaced that they were easy to follow from one slide element to another. Slide elements of this type were also prevalent between the houses above the highway in the central and northern parts of the slide area, that is, in a belt which extended nearly across the whole slide cavity. The crescent-shaped cracks between the slide elements were slightly convex towards the river. Their outward direction was most marked in the northern half of the slide cavity. Towards the northern boundary of the slide area, the slide elements were shortened and conformally curved along this boundary. Towards the southern boundary of the slide area, they were S-shaped. In both these cases, the deformation of the slide elements was presumably due to the resistance to the movement of the sliding masses in the boundary zones of the slide. Furthermore, the slide elements were separated by radial rows of cracks into slide element belts, which were irregularly displaced with reference to one another. The greatest changes in their relative positions were met with in the northern third of the slide cavity.

3. Outside, to the west of that part of the slide cavity described in the above, there were two slide elements which were entirely different from the others in their order of magnitude and in their appearance in other respects. They extended across the whole slide cavity, their width varied from 50 to 70 m, and their surfaces were even or slightly undulating. The boundary between them was marked by a crack in the shape of an arc, convex towards the river and slightly depressed in the middle. On the whole, the external edges of the outer slide element were conformal with this crack. The external edge of the inner slide element was indented by radial and tangential cracks, forming particularly severe cuts in its northern part. Again, the southern portion of the outer slide element was cleft into large pieces, wedgelikely displaced. The northern part of this slide element was covered by clay blocks forming a wide crescent-shaped mound, the northern branch of which bent outwards in the direction of the northern boundary of the slide cavity, and the southern branch bent inwards in the direction of an east-west row of cracks, which broke not only through the inner slide element, but also through the slide elements lying on the inside and belonging to the group 2. On the whole, both these slide elements sloped towards the river, and the difference in level between them formed a steplike ledge,

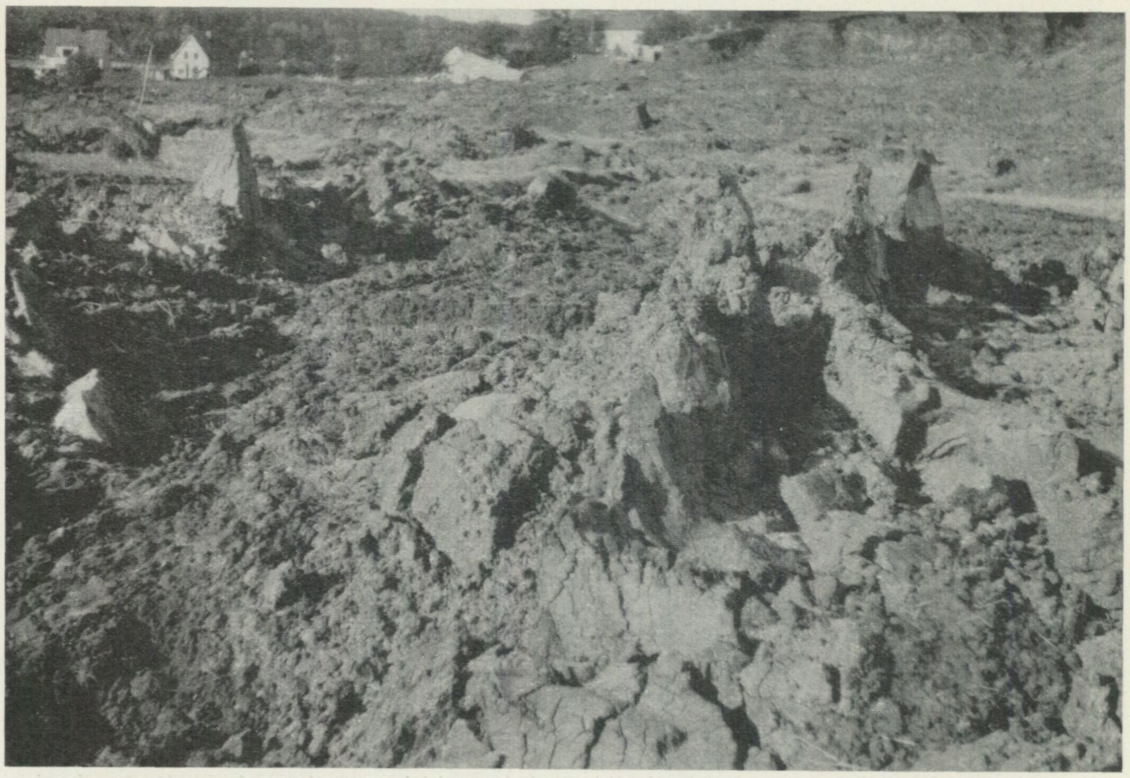


Fig. 16. Clay ridges forming the remnants of slide elements, which were further disintegrated by shearing in the course of the slide. This photograph was taken in the central portion of the local slide area in the eastern part of the main slide cavity. (Photograph by R. Lundström.)

about 2 m in height in the southern part. The north portion of this ledge was hidden under the large clay block mound. Close to it the station house had sunk into a depression, formed by the crack. South of the station house, a thick bank of clay blocks had also been thrown out on the outer slide element.

4. In the outermost part of the slide area, the slide elements were pushed out into the river and shoved up. The had the shape of narrow ribs or sharp clay ridges, concentricly situated with the large slide element on their inner side. The were surrounded by belts of clay blocks of all sizes thrown together in heaps.

5. At the north side of the slide cavity, a large slide element, about 60 m in length and slightly less in width, came between the slide element groups 1 and 2 described in the above. The greensward was well preserved, and the surface of this slide element was furrowed with smooth radial waves. The edges were severely indented by cracks, which were most pronounced in the transverse direction of the slide.

6. After the movements released in connection with the slide had ceased, several smaller, secondary slides and ravines were produced on the steep slopes along the eastern boundary of the slide cavity.

The configuration, the shape, and the size of the slide elements at Surte, just as the cracks running in an east-west direction and the crescent-shaped clay blocks mounds, give indications of some features in the development of the slide. Furthermore, reliable measurements for determining the magnitudes and the directions of the changes in the positions of various slide elements were obtained by comparing the cartographic data on the situation of houses, roads, and the railway line before and after the slide. A map with contour lines at intervals of 1 m had been drawn to a scale of 1 : 2 000 before the slide, and the slide area was mapped photogrammetrically almost immediately after the catastrophe itself. It was found from a comparison of these maps that, in the central part of the slide area, the edge of the river bank was pushed some 35 m into the river, the houses on the inner large slide element mentioned under Point 3 in the above were displaced 50 to 70 m towards the river, and the houses situated between the thinner slide elements were displaced in the same direction about 90 m in the outer part and as much as about 150 m in the inner part. Hence it follows that the sliding earth masses were forced together or deformed to a progressively increasing extent in the direction of the latter slide elements. This was indicated, for instance, by the overthrusts of very soft clay over dry crust clay which were observed in several places and which sometimes gave rise to folds

Fig. 17. Slide elements in southern part of the local slide area, which were not appreciably deformed by shearing in the course of the slide. The grass-covered surfaces of these slide elements are inclined in a direction opposite to that of the slide movement. The gravel pit at the esker delta, close to the south-eastern corner of the small valley, is visible in the background, behind the slide cavity. (Photograph by R. Lundström.)

in the greensward held together by grass roots. In the soil cores extracted from boreholes, the planes of overthrust manifested themselves in the form of zones of more or less deformed clay, which often proved capable of being closely correlated with outcropping slide surfaces. The circumstance that the slide elements have been forced together more and more towards the inner boundary of the slide seems to show that the slide elements, such as they appeared after the slide, were in essence those which had been separated from the edge of the slide during the retrogressive phase in the development of the slide, and that they have not ben produced by folding or any other secondary subdivision of larger slide elements. However, sharp, scored clay ridges, indicated that the slide elements have frequently been cleft along those ridges and these separating parts of the slide elements have sunk into the widening fissures formed between the original elements, during the slide movement. When it was attempted to localise the places of origin of the narrow slide elements in the groups 1 and 2 as well as that of the broad slide element in the group 5, it was found that these places were situated in the higher part of the ground, which was separated from the valley flat extending along the river by the highway as an approximate boundary, while this valley flat was broken up into the two large slide elements referred to the group 3. An examination of the boundary between the portions of the ground which had been depressed and elevated by the slide showed that this boundary approximately coincided with the former foot of the slope forming a transition to the higher part of the ground. In other words, this boundary was located slightly closer towards the interior between the narrow slide elements in the group 2, and was situated in a section of the original configuration of the ground surface which was important from a statical point of view.

From the interviews with the eye-witnesses of the slide as well as from the displacements and from the new positions of the houses it may be inferred that the slide movements resembled wave motion with smooth, relatively slow transitions from one phase of movement to another. For instance, some of the displaced houses formed large angles with the horizontal plane, and one of the larger houses was overturned, but none of the persons present in the interior was seriously injured. One of the houses, the station house, was found to be close to the fissure between the two large slide elements in the group 3. In spite of the fact that this house was almost completely surrounded by clay

Fig. 18. Cracks passing along and across the highway at the south-eastern corner of the first large slide element in the valley flat. (Photograph by R. Lundström.)

masses, having been pressed upwards it had not been subjected to any substantial deformations, although open cracks gaped in its surroundings both in the longitudinal and in the transverse direction of the slide.

Geology of the Slide Area, with Special Reference to the Distribution of Relative Fineness of Clay.

In order to throw light on the geological background of the slide, several sections and diagrams have been drawn on the basis of the results obtained from soundings, from the examination of soil cores taken by means of a piston sampler and a sampler with metal foils, as well as from laboratory tests. The position of the firm bottom is represented in Pl. 2 by the full-line curves, which show that the firm bottom rises from a level of about — 35 m at the highway to a level of about + 10 m at the eastern boundary of the slide area, and that there is a comparatively flat shelf between levels of — 15 and — 5 m approximately in the middle between the highway and the eastern boundary of the slide cavity.

The firm bottom is directly overlain by a sand stratum, which forms a tonguelike projection extending towards the north from the southern boundary of the slide area, precisely within the limits of the abovementioned flat shelf of the firm bottom, and then deviates towards the west in the form of a sheet, about 2 m in thickness, which reaches down to the highway. This sand stratum is represented in Pl. 2 by dash-line curves, which indicate the thickness at intervals of 2 m.

In Pls. 3 and 4 the values of the relative fineness (F) obtained from Sections 464 + 966, 464 + 764, and 464 + 660 are compiled and registered, with curves of equal values of relative fineness. For Section 464 + 966, situated immediately outside the slide cavity, the relative strength values (H_3) are represented in a similar manner. Consequently, that series of strata which must have existed in an undisturbed state in the slide area may be expected to be represented in the last-mentioned section. Furthermore, this section may be considered to be roughly representative of the consistency of the various strata.

By examining the curves of relative fineness obtained from this section (Pl. 3), it is easily found that the strata situated above the highway generally increase in coarseness as the depth and the distance from the highway become greater. On the other hand, the values of relative fineness obtained from the strata below the highway are extremely uniform and indicate the same fineness down to a level of — 35 m, that is, the maximum depth of soil sampling in the borehole E 14. At depths greater than 3 m, the values of relative

Fig. 19. Aerial photograph of the slide cavity seen from the west. The valley flat was divided by the slide into broad slide elements with level surfaces, which are clearly visible in front of the highway. The positions of the houses are vertical or nearly vertical, and the rows of grain shocks are almost intact, in spite of the movements of these slide elements. The displaced railway line is in the foreground, on the right. The railway station house, which has sunk into the crack between two large slide elements, is in the foreground, on the left. The slide elements originating from the initial stage of the slide are seen behind the highway (where the larger houses are situated). The large slide element denoted as No. 5 and other slide elements originating from the secondary, retrogressive stages of the slide are visible behind the above-mentioned initial slide elements.
(Photograph by F 9.) Godkänd av Försvarstaben 11/3 1955.

fineness vary from 60 to 70. At smaller depths, they are even higher, from 80 to 90, owing to the higher mud content of the superficial strata. In the borehole E 150, some 40 m east of the highway, the values of the relative fineness vary from 60 to 70 only so far as the depth is not greater than 6 m. Then they become still smaller, so that they vary from 50 to 60 in the depth range from 6 to 11 m. As the depth increases, the relative fineness continues to decrease, and is generally comprised within the limits from 30 to 40. Marine clay often combines these lower values of the relative fineness with a property which manifests itself in the fact that the mineral texture is easily broken down under mechanical stress. The clay becomes yielding, and is then known as "quick clay". A reliable expression of the quickness of clay is the ratio of the relative strength numbers H_3 and H_1. The boundary between quick clay and other clays is in general not sharply defined. P. Holmsen (Holmsen, 1946) has defined quick clay as a clay having an H_3/H_1 ratio greater than 50. In the present investigation, however, the limit value of the H_3/H_1 ratio for quick clay was put equal to 75, since this value is on the safe side as regards quick clay. In the borehole E 150 the clay situated at depths below 12 m is markedly quick. If we examine the other boreholes in the same section, then we find that the relative fineness is mainly above 70 in the borehole E 226, generally below 60 in the borehole E 271, generally below 50 in the borehole E 325, and generally below 40 in the borehole E 376. The clay in these boreholes progressively increases in grain size, but it is not a quick clay, with the exception of a thin layer at a depth of 5.5 m in the borehole E 376. The increase in the general coarseness of the clay — the material is well stratified in alternate layers of clay, silt, and fine sand — is connected with the rising level of the firm

Fig. 20. Aerial photograph of the slide cavity seen from the east. The large slide element denoted as No. 5, in the north-eastern part of the slide cavity, is seen in the foreground, on the right. Those houses which are more or less inclined indicate the slide elements originating from the initial stage of the slide, which are visible behind the slide element No. 5. The valley flat was divided by the slide into two broad slide elements, which are situated outside the above-mentioned portions of the slide cavity. These slide elements are still partly covered with water from the river. The wide bow-shaped group of slide elements caused by the rise of the river bottom is seen in the area adjacent to the river. (Photograph by F 9.) Godkänd av Försvarsstaben 11/3 1955.

bottom, so that the strata of glacial clay which are deposited more and more proximally are raised towards the ground surface, on a level with, and higher than the more recent clay strata in the lower parts of the section. This is clearly indicated by the line drawn in the section on the basis of the examination of microfossils to represent the discordance which was produced during the regression of the sea level before the Post-Glacial transgression, and which is partly marked by shell-bearing clayey gravel and sand. This line cuts both through quick clay and through non-quick clay. Hence it follows that this property of the clay is not inseparably associated with a definite clay stratum, but is attributable to other conditions influencing the clay mass. The strata are in concordance with the undulations of the firm bottom.

The curves of relative fineness (Pl. 4) for the two borehole sections in the slide area, viz., 464 + 764, approximately at the centre of this area, and 464 + 660, in its northern half, show an entirely different distribution of the clay strata. This difference is due to two causes. First, of course, the positions of the strata were disturbed by the slide. Second, it is probable that the original extent of the coarser, silty clay was greater than in Section 464 + 966. The most conspicuous feature is the nearly vertical boundary between the values of the relative fineness below 40 and the higher values approximately at E 140 in Section 464 + 764 and approximately at E 40 in Section 464 + 660. This boundary was established in both these sections by means of boreholes situated at a distance of 20 m from each other, and was found to reach down at least to a level of — 25 m in the former section. This boundary may probably be interpreted as a consequence of an extremely violent overthrust caused by the slide. The boundary in question is roughly coincident with the position of the initial slide element in Section 464 + 764, but is situated between the secondary slide elements, outside the initial slide elements, in Section 464 + 760.

Further upwards in the slide area, the curves of relative fineness are approximately horizontal in both these sections, but the curves in Section 464 + 966, outside the slide area, have a certain tendency to follow the slope of the ground towards the river, whereas the curves in the two sections situated in the slide area repeatedly tend in the opposite direction, probably owing to the overthrusts to which the clay slide elements were subjected.

Further outwards in the slide area and in the region of higher relative fineness, the curves of relative fineness in Sections 464+ 660 and 464 + 764 have a comparatively marked wavy shape in contradistinction to those in Section 464 + 966, which exhibit a fairly uniform slope towards the river, *i.e.* towards the central part of the valley at the river Göta älv. Unfortunately, the sampling in Section 464 + 966 was not continued right down to the river, so that no definite statements can be made regarding the shape of the curves of relative fineness in that part of this section which is nearest to the river. Since the material becomes increasingly muddy in that direction, as has been found in the two sections within the slide area, where samples have been taken all the way down to the river, it is probable that the strata continued to be inclined towards the river. On the other hand, in the raised slide element complexes of the two sections situated in the slide area, the strata generally slope in the opposite direction, *i.e.* away from the river.

In spite of repeated supplementary boreholes, it is obvious that the data derived from the boreholes are not exhaustive enough to serve as a basis for fixing even the approximate boundaries of the slide elements into which the ground was broken up during the slide. Nevertheless, these data give a realiable general picture of the great extent of quick clay in the interior part of the slide area, where it was localised in the regions of the initial slide and the retrogressive slide faces. Furthermore, these data give clear indications concerning the magnitude of the overthrusts which were caused by the slide. Moreover, since they show that the position of the strata has on the whole been turned to a dip against the movement of the slide, these data have demonstrated that the supposed folding of the clay (Jacobson 1952) in the progressive part of the slide cavity is scarcely probable. It is more likely that the slide developed with elements pressed out as wedges in this part of the slide area. The latter assumption is in agreement with the picture of the course of the slide formed on the basis of the configuration of the slide elements.

6. Ground Water and Erosion Due to Ground Water. Precipitation during the Period from May to September in the Years 1900 to 1950.

By Carl Caldenius.

Ground Water.

It has been stated that several cracks had been observed a few days before the slide at a distance of about 40 m from the highway and at a level of 6 to 7 m in the lower part of the slope between the lower and the higher sediment plane in the north-western portion of the slide area. These cracks (Pl. 2) appeared immediately above a site on which piles were being driven for the foundation of a building to be erected. Early in the morning, two days before the slide, it was noted that these cracks discharged water which was grey-coloured by fine-grained sediments. The rate of discharge was so high that the yard of the lot No. 2 : 1, which was situated some 60 m farther in a north-western direction, was flooded with water, which rose to a height of about 15 cm above the level of the yard plane. The flow of water ceased about noon of the same day on which it began. Unfortunately, the cracks have not been measured, but if their length had been in any way sensational, this would undoubtedly have been noticed by those members of the resident population who inspected them while the water was flowing and who interpreted it as the issue of a "new spring". Since these cracks were formed in the region of the initial slide element or in the immediate vicinity of this region, their formation must have been connected with the release of the slide (see Chapter 8, which deals with the causes of the slide).

The buildings in the slide area, which exclusively consisted of dwelling houses of the single-family or multi-family type, were concentrated in the north-western portion of this area, where they had gradually climbed higher and higher on the steeper slope, and had spread both northwards along this slope and eastwards on the higher ground level (see Pl. 2). At the same time, the water supply to these houses was ensured by sinking a progressively increasing number of wells, including 11 tube wells, which were driven down to depths varying from 12 to 29 m below the ground level in the area east of the highway, and which varied in yield from 70 to 1 000 litres per hour and well. In other words, all these wells reached down to the sandy bottom strata on the moraine, and the water consumption was so great that not inconsiderable quantities of water were drawn from these strata. The yields of the wells which were less deep was in general irregular and not satisfactory. For instance, the estates Nos. 26, 28, 29, and 30 had tube wells, about 5 to 6 m in depth, which did not yield any water; the estate No. 27 had three tube wells, 20 m in depth, which yielded little or no water; the estate No. 25 had a tube well, 25 m in depth, which yielded water copiously; the estate No. 7 had a tube well, 20 m in depth, which yielded some water; and the estates Nos. 5, 6, and 10 had tube wells, about 20 m in depth, which yielded little or no water. The estates where the yield of their own wells was insufficient were supplied with water from the well of the estate No. 25. The estates situated west of the highway were likewise supplied with water from the last-mentioned well, since their own wells — one of which was sunk down to a depth as great as 45 m — did not yield any water. An exception in this respect was the estate No. 12, the well of which supplied water to four families. The well of the estate No. 25 yielded artesian water, and an artesian source, which discharged a thin rill of water, was situated immediately south of the estate No. 29. It proved impossible to collect information on the origin of this source. It is possible that it came into existence during earth boring.

The ground water in the sandy bottom strata was submitted to such a high pressure that the water was forced upwards to the ground surface at a level of about + 16.0 m.

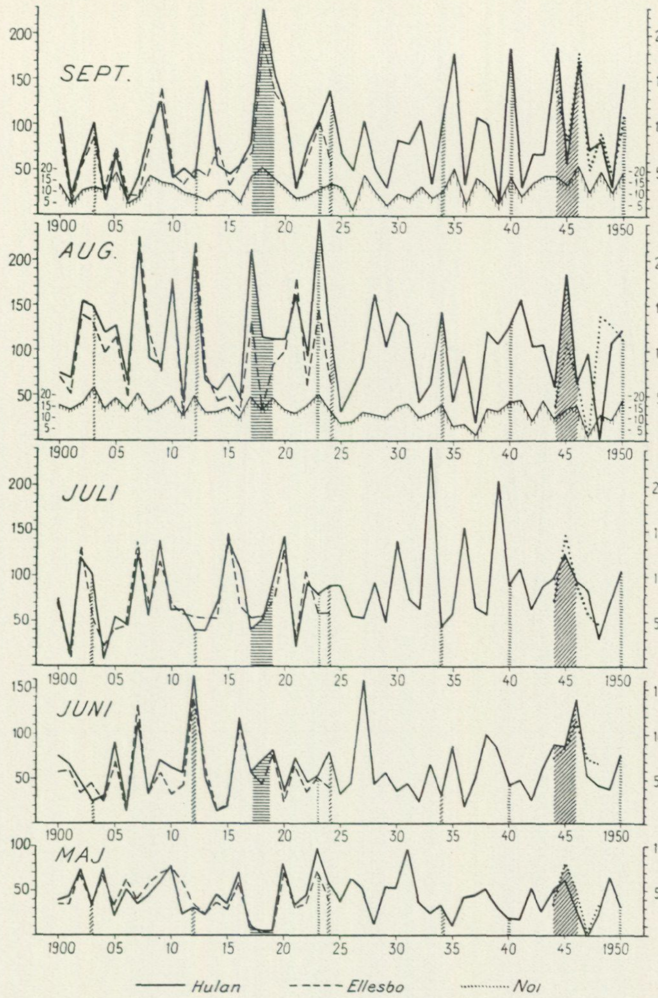


Fig. 21. Precipitation in mm during May—September at Hulan, 13 km SE of Surte, at Ellesbo, 1.5 km W, and Nol, 10 km N of Surte, for the years 1900—1950 at Hulan, 1900—1924 at Ellesbo and 1944—1950 at Nol. Years with greater precipitation are marked with hatched lines. —

Erosion Due to Ground Water.

Since the ground-water-bearing sand strata were bared by the slide at the foot of the eastern scarp of the slide cavity, local cuts were produced in this place at a very early stage, and these cuts were propagated in the scarp along the depressions in the bed strata. In the north-eastern half of the slide cavity this secondary erosion was so rapid that it caused ravine-like clefts. The retrogressive erosion in these ravines was not to be prevented until the removal of sand and fine sand particles from the foot of the scarp was rendered impossible by facing it with an inverted filter made of sand, gravel, and crushed stone.

Precipitation during the Period from May to September in the Years 1900 to 1950.

Precipitation is of interest in estimating the causes of the slide. In order to find out whether precipitation might be supposed to have had any influence on the slide, the mean monthly values of the amount of precipitation for May, June, July, August, and September were plotted in a diagram (Fig. 21) covering the years during which observations of precipitation had been made at weather stations in the neighbourhood of the slide. In the years 1900 to 1950, a continuous series of observations has been made only at Hulan, in the valley of the river Säveån, about 13 km south-west of Surte, whereas the observations made at the two nearest weather stations, Ellesbo and Nol, in the valley of the river Göta älv, at respective distances from Surte 1.3 and 10 km, extend only over a smaller number of years, viz., from 1900 to 1924 at Ellesbo and from 1944 to 1950 at Nol. All the same, a comparison of the amounts of precipitation observed at these three weather stations shows so close an agreement that the precipitation diagram based on the records from Hulan may be

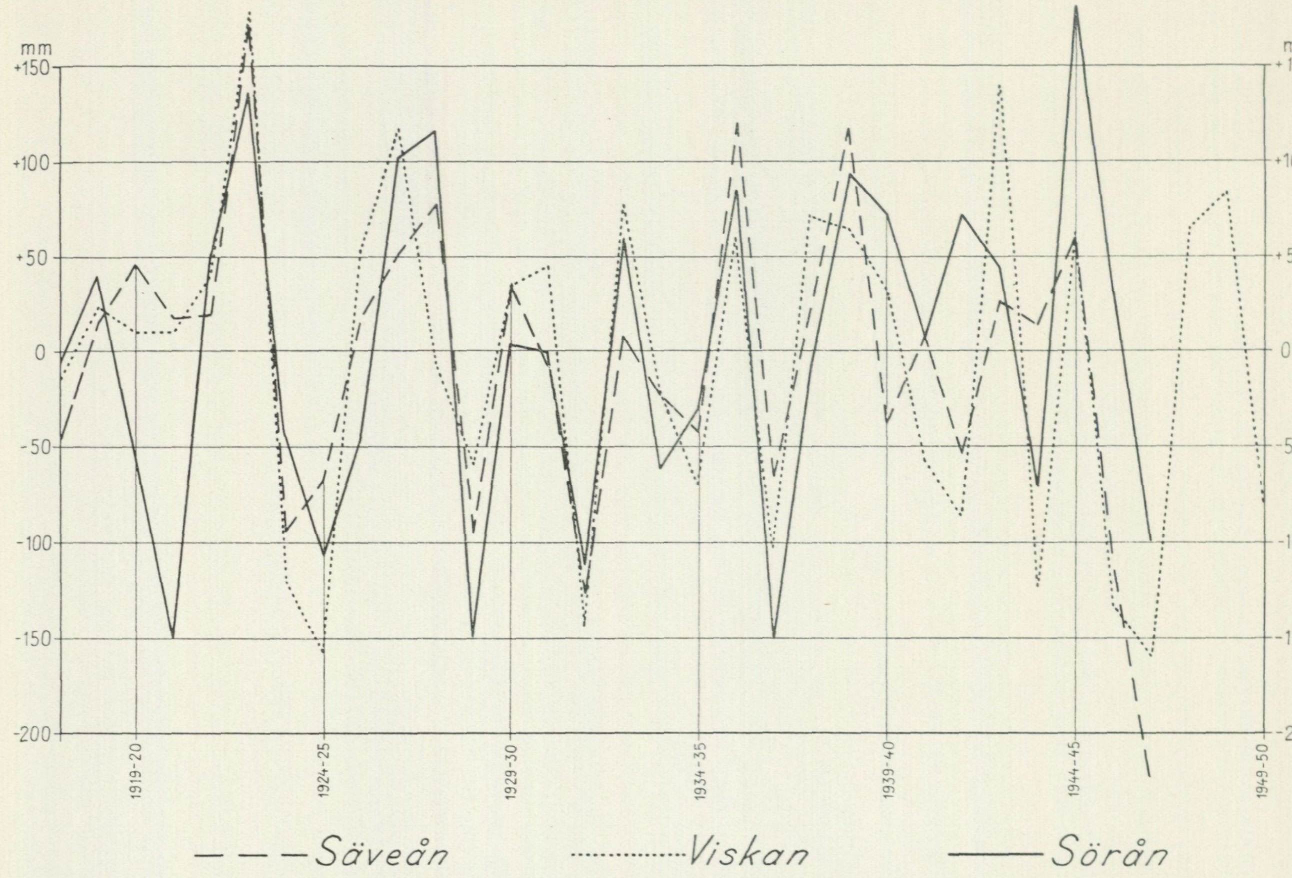


Fig. 22. Storage of groundwater in mm during 1917—1947 in the basins of the Rivers Säveån, Sörån and Viskan (table 10, F. Bergsten, 1950). In the basin of the River Viskan even during 1948—1950.

regarded as representative of the variations in precipitation at Surte during the whole period under consideration. It is clearly seen from the diagrams in Fig. 21 that the amount of precipitation in the year 1950, when the slide occurred, was smaller than in former years. This statement applies to the total amount of precipitation during the five-month period in question as well as to the amount that has fallen during anyone of these months. The precipitation during the period from May to September 1950 was not by any means exceptional. It was greater in the years 1918, 1923, 1945, and 1946, while it was approximately equal in the years 1903, 1912, 1924, 1934, and 1940.

Mr. Folke Bergsten, State Hydrologist, has made an attempt to calculate that part of the amount of precipitation which had been stored as ground water during the period from 1917 to 1947 in the drainage basins of the rivers Säveån, Viskan, and Sörån (Province of Småland). The results of his calculations show that this storage exhibits variations which are closely in agreement with one another (see Fig. 22). The available primary data on the valley of the river Göta älv are not sufficient for similar calculations, but since this valley belongs to the same precipitation region as those mentioned in the above, it seems justifiable to assume that the quantity of precipitation stored in this valley was subject to analogous variations. At our request, Bergsten has kindly continued his calculations to 1950 inclusive, but they were practicable only for the valley of the river Viskan. Their results indicate a marked decrease in the quantity of ground water stored during the period from 1949 to 1950.

7. Course of the Slide (Mechanics of the Slide).

By Rune Lundström.

In general a slide starts from an initial area where the soil is overstrained for some reason or another, with the result that the area of ground in question is rendered unstable. On both sides of the initial slide, reckonned in the direction of the slide movement, the reckonned in the direction of the slide movement, the ground. Therefore, the slide often develops in two phases, viz., first, a retrogressive phase, which comprises repeated smaller slides, and second, a progressive phase, which is characterised by overthrusts and by failure in shear strength of the ground situated immediately in front of the initial slide element. The overthrusts can produce an overload on the ground to such an extent that the ultimate stresses in the soil are exceeded, and this causes further slides. However, this type of slide development is not very common. The retrogressive phase is frequently characterised by oblique slide elements sloping in a direction which is opposite to that of the slide movement and by clay ridges, see Fig. 16. On the other hand, the slide elements formed during the progressive phase are more or less irregular in respect of their direction of slope, but this direction often coincides with that of the slide movement.

Initial Slide and Retrogressive Phase.

In Surte several typical slide phases could be observed and the initial slide took probably place in the north-eastern part of the slide area, where the ground had been steepest before the slide. Its upper boundary is likely situated between the houses Nos. 27, 29 and 28, 30. In this respect the results here presented agree with those which have been published previously (Jakobson, 1952).

The lower boundary of the initial slide area is on a level with the houses Nos. 11, 7, and 13 according to the calculations of stability which are described in Chapter 8, "Causes of the Slide". The extent of the initial slide in a south direction is rather difficult to determine, but, judging from the large fissures in the direction of slide movement, it seems probable that this slide approximately covered the area marked red in Pl. 1. Alternatively, it may be imagined that the steeper slope in the north part of the initial slide area was set in motion first, and that the ground in the south part of this area began to slide a short time later. The upper (eastern) slope formed by the initial slide was excessively steep, and this caused further slides. The retrogressive phase of the slide was successively developed in this manner until it reached the final upper boundary of the slide cavity, where continued development was arrested by layers of coarser and firmer soil. By examining the eastern part of the slide area in Pl. A, it is found that the retrogressive phase of the slide exhibits three marked longitudinal troughs. An area, which is indicated by yellow colour in Pl. 2 stands out in the south-eastern part of the slide cavity. The sand underlying the clay in this area varies from 4 to 10 m in thickness, and the clay was comparatively coarse-grained. This part of a slightly coarser soil layer was probably carried away by the slide at a relatively late stage, and had a retarding effect on the adjacent areas. This is also indicated by the changes in the positions of the rows of grain shocks. Before the slide, these rows had been at right angles or parallel to the furrows ploughed in the neighbouring field. After the slide, the change in angle of the rows of grain shocks situated west of the above-mentioned area of ground was relatively small, whereas the corresponding change in angle in the area lying south-east of the houses Nos. 26, 29, and 28 was very great — up to 30 degrees. Furthermore, it is to be noted in this connection that the slide element which is clearly visible in the north-eastern part of the slide area originated from a smaller slide which occurred a few days later than the large slide.

Progressive Phase.

Since the slip zone in the initial slide area developed in quick clay, the retarding effect produced on the earth masses which were set in motion was very slight, and the kinetic energy acting on the areas in front of the initial slide element was considerable. The areas of ground in front of the initial slide element were progressively folded and partly disintegrated. Overthrusts occurred in the dry crust, and, owing to the resistance offered by the clay layers around and below the highway, down to the river, the clay masses were heaped up in this area, with the result that the ground level was raised. The pushing forces due to the sliding clay masses were greatest in the north-western area, or it is also possible that the passive resistance in this area, where the greatest displacements below the highway took place, was lower than in the surroundings. Relatively small counteracting forces were developed in the quickish clay which was found west of the highway (see Section IV in Fig. 29). Pl. A clearly shows the unsymmetrical movement, the northward bulge of the boundary of the slide cavity immediately below the highway, and the completely disintegrated area of ground situated west of the house No. 17. At the same time as the slide was retrogressing, it was also coming nearer and nearer to the river. Finally, the load due to the rise of the ground level immediately above the river and the pushing forces which acted at right angles to the river became too great, with the result that the earth masses slid down into the river and raised the level of the river bottom. In the area situated immediately east of the river we find three bodies of water framed in cracks. It is clearly seen from Pl. A that the depressions occupied by the bodies of water at the centre and in the north have been filled up with the clay masses which slid from an area north-west of the house No. 17. It is therefore probable that the disintegrated area of ground referred to in the above has been developed in the last stage of the slide, after the earth masses had been pushed into the river.

8. Causes of the Slide.

By Rune Lundström.

In the reconstruction of such an extensive slide as that at Surte, some of the considerations presented must, of course, be partly based on assumptions and probabilities which are not completely verifiable. Many valuable indications which might have contributed to the explanation of the slide were erased on account of the vast extent of the slide and the numerous phases in its development. The reflections on the causes of the slide offered in what follows are based on topographic maps made before the slide, on the extensive soil investigations described in the above, on interviews with eye-witnesses, and on observations made in the field after the slide.

A. Previous Theories of the Surte Slide.

If we study the appearance of the land before the slide, we find that the only place where a slide could be possible was the area of comparatively steeply sloping ground east of the highway. The slide did certainly not start in the valley flat near the river, first, because the stability of the soil in this place is quite sufficient to preclude slides, and second, because the witnesses were unanimous on that point. Furthermore, the water level in the river Göta älv was not low at the instant of the slide. This is seen from the water level diagram in Fig. 23, reproducing observations made at a point situated about two kilometres south of the slide area. On the question where the slide began, there is complete unanimity but different answers have been given to the question how it was possible that the slide developed all the way down to the river over an area of practically horizontal ground, which was up to 350 m in length and about 450 m in width. Moreover, divergent opinions are held on the causes of the slide.

According to the theory put forward by Mr. B. Ja-

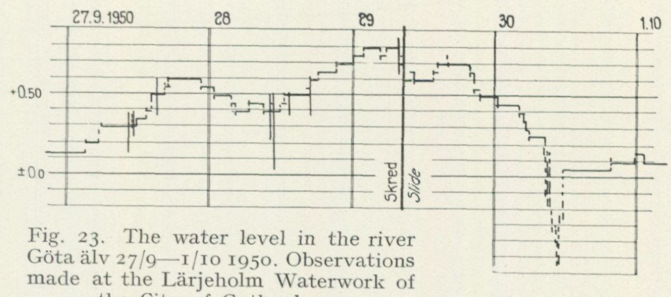


Fig. 23. The water level in the river Göta älv 27/9—1/10 1950. Observations made at the Lärjeholm Waterwork of the City of Gothenburg.

kobson (1952), the slide developed along a single slip surface, which was originally formed in the area of steeply sloping ground east of the highway, and was progressively propagated all the way down to the river. He supposed that this slip surface was in the main formed right down to the river along an assumed weaker clay zone, which was influenced by the artesian pressure. However, there are several facts which may be considered to be at variance with this representation of the development of the slide. A week clay zone with very low shear-strength, constituting the necessary condition for a slide in a single slip surface down to the river, has not been possible to demonstrate. The witness No. IX stated that "the highway and all the ground west of it appeared to be at rest, while the houses east of the highway were moving down towards the river". From this statement it may be inferred that an initial slide of the type described in Chapter 7, "Course of the Slide (Mechanics of the Slide)", was the first movement in the course of the whole slide. Furthermore, it seems probable that the movement of the area of flat ground near the river developed in the form of a rotational slip, judging from the depressions in the ground which were filled with water in this area, and from the oblique series of strata close to the river (cf. Pls. 2, 3, and 4).

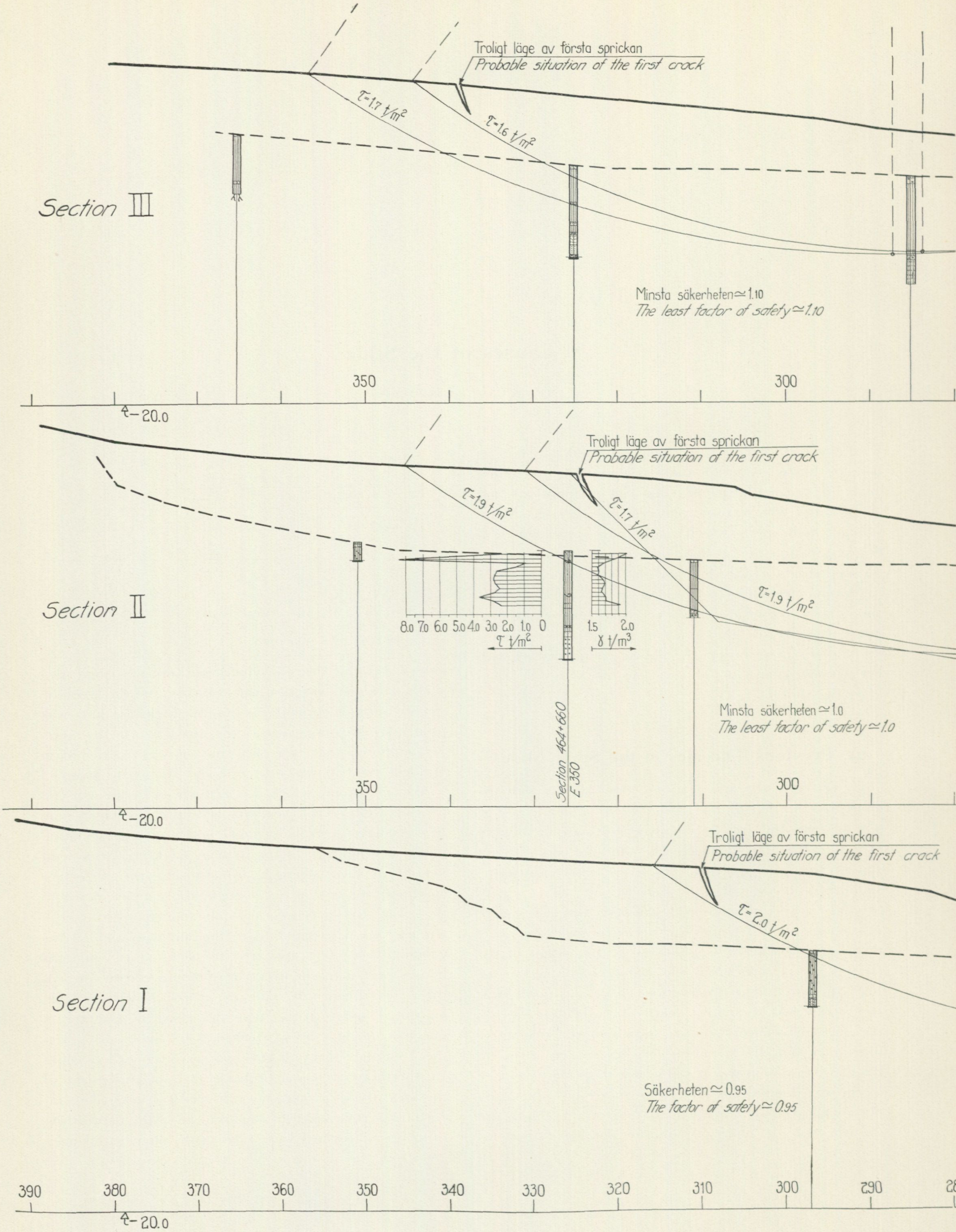
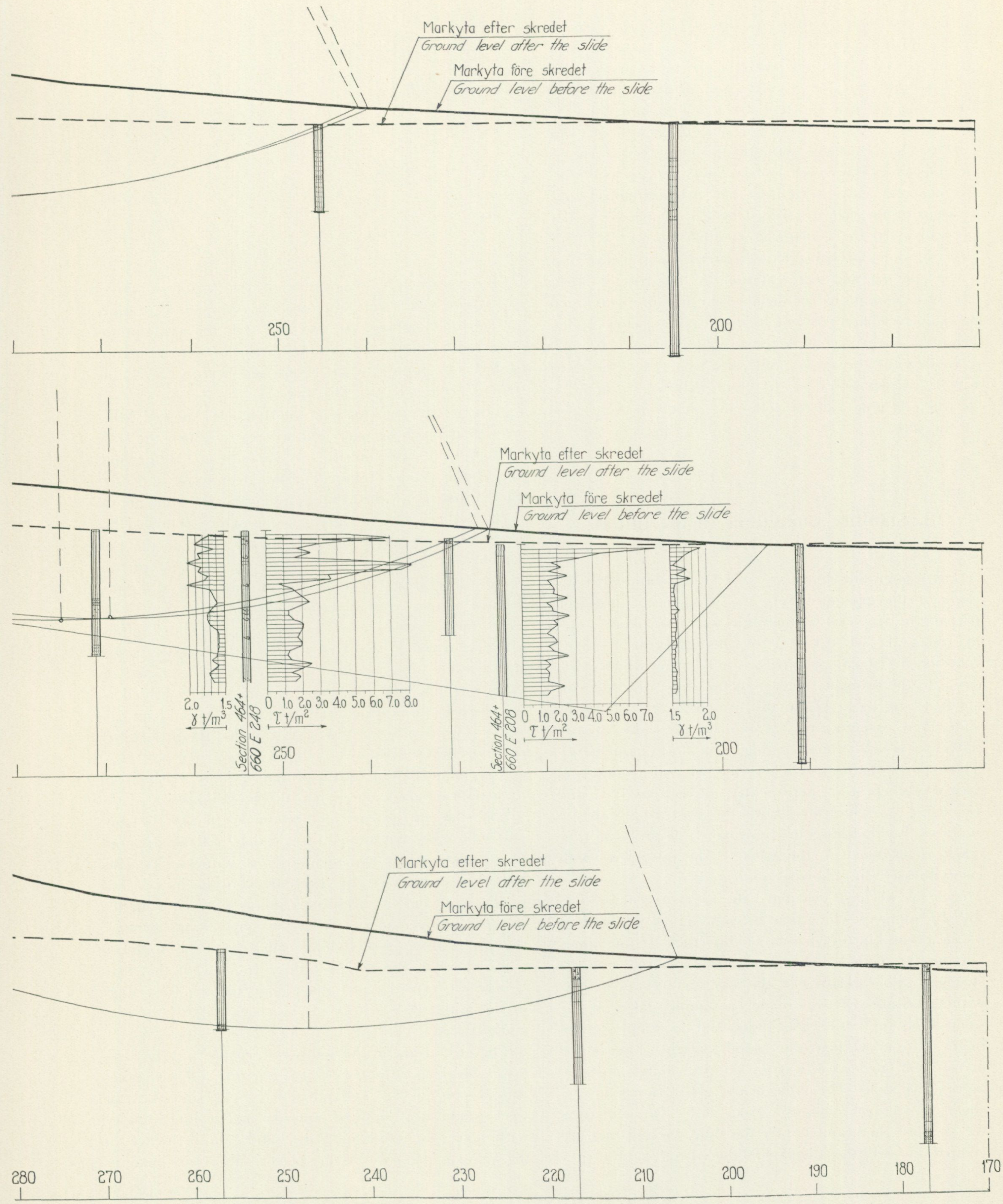


Fig. 24. The sections I, II, and III with slip surfaces,



shear strength diagrams, and factors of safety.

In a discussion with B. Jakobson (Löfquist, 1952), B. Löfquist considered that the artesian pressure in a presumed sand stratum would have been sufficiently high to reduce the forces of friction in this sand stratum to a value which would have been low enough to create the necessary conditions for a slide along a single slip surface in accordance with the principle put forward by Jakobson. However, it has not been possible to demonstrate with certainty that a continuous sand stratum of the type presumed by Löfquist had existed in reality. In the geological examination we can find that old slides probably have occurred, which have disturbed the original sedimentation. As regards the other necessary conditions for the artesian pressure, reference is made to Chapter 6 and to the remarks below under heading "Influence of Artesian Pressure".

In view of the above, and considering that the slide can be explained in a different manner, it appears desirable to point out the following views on the causes of the slide.

B. Stability Conditions in the Initial Slide Area.

The topographic map (cf. also Pl. 1) shows that the slope of the ground before the slide in the northern part of the area east of the highway varied from 1 : 5.5 to 1 : 9.5. If we calculate in this case the requisite cohesion in circular-cylindrical slip surfaces which reach down to the probable bottom of the slide at a depth of about 15 to 18 m below the ground level before the slide, then, assuming the factor of safety to be equal to unity, we obtain values ranging from 1.6 to 2.0 tons/m². Those parts of this area where the original ground surface was steepest are represented in Sections I, II and III in Fig. 24, which also shows the most dangerous slip surfaces. Furthermore, the position of the probable first crack, determined on the basis of the interviews with eye-witnesses, is likewise indicated in each section. Moreover, we have calculated the requisite cohesion in the slip surfaces which tend to come out to the surface of the ground in the vicinity of this crack. If the values obtained from these calculations are compared with the strength values relating to the slip surfaces as well as with the results of tests made on samples taken at the same levels in Section 464 + 966 and on samples taken in the slide area, then it is found that the slope in the above-mentioned area was in all probability unstable before the slide. The table below gives values of the shearing strength obtained from tests. In estimating the stability conditions before the slide, these values are comparable with the calculated values 1.6 to 2.0 tons/m².

Section	Borehole	Depth below Ground Level m	Shearing Strength tons/m²
464 + 966	E 226	1.5 to 12	Increase from 1.3 to 2.3
464 + 966	E 150	3 to 15	Increase from 1.1 to 1.9
464 + 660	E 250	12.5	1.3
		15	1.9
464 + 660	E 208	13.5	1.4
		15	2.3
464 + 660	E 100	13	1.4
		15	1.5

To calculate the magnitude of the factor of safety is extremely difficult since the clay samples were more or less disintegrated by the slide. On the assumptions referred to in the above, the factor of safety against slides was found to be comprised within the limits from 0.80 to 1.10 (cf. also Fig. 24).

The observations made in the slide area showed, however, that, in those parts of the area in which the slide bottom had come out to the surface of the ground, the slide did not follow circular-cylindrical slip surfaces. Instead of this, the slide had largely, but not as a rule, taken place along slip zones which followed the natural stratification. In some places, east of the line which was assumed as an eastern boundary of the initial slide area, the slide bottom had even a slightly convex shape, as may be seen from Fig. 25. However, the observed convex parts of the slide bottom were situated in the area of the retrogressive phase of the slide. The results of the calculations based on circular-cylindrical slip surfaces may be regarded as an evidence indicating that the ground was in an unstable condition before the slide and that the probability of a slide was great.

The plane extent of the initial slide is marked out by a red boundary line in Pl. 1. The boundaries of the initial slide in the east and in the north may be considered to be determined in a fairly reliable manner by calculations, by statements of eye-witnesses, and by field investigations. The boundaries of the initial slide in the west and in the south cannot be fixed with the same accuracy. Judging from the slope of the ground, the probability of a slide is smaller in the southern part, where the ground is flatter. In view of this fact, it may be deemed justifiable to confine the first stage of the initial slide within the northern half of the red-marked area.

The clay strata in the south-eastern part of the slide area, which is situated in the vicinity of the esker delta visible in Fig. 25, and in which thick sand strata were found at a depth of some 10 m, are intermingled with layers of sand and fine sand. An influence of the artesian pressure in this place is therefore imagin-

Fig. 25. The bottom surface conforming to the stratification in the retrogressiv face of the north-eastern area of the main slide cavity. The esker delta with the gravel pit is visible in the background in a south-eastern direction. (Photograph by R. Lundström.)

able. We have reasons to suppose that the first stage of the initial slide took place in the northern half of the red-marked area, and that the southern half of this area, which was probably also nearly unstable, was started by forces due to the first slide element. However, it may be assumed that the difference in time between the phases of the initial slide was not great.

C. Influence of Artesian Pressure.

Prior to the slide, artesian water has been found at two points in that part of the slide area which was situated east of the highway before the slide. As has been mentioned in the above, Jakobson and Löfquist considered the influence of the artesian pressure to be the primary factor in releasing the slide and in causing its development down to the river.

An artesian pressure on a thin impermeable stratum can theoretically become so high that it lifts the overlying soil. In that case the vertical force acting on that stratum in which the artesian pressure is developed becomes equal to zero, and no friction can be produced in such a stratum. Consequently, in the absence of other counteracting forces, a slide takes place if the water-bearing stratum is inclined. The relation between the magnitude of the artesian pressure, expressed in metres above the ground level, and the shear strength in sand layers situated at depths of 10, 15, and 20 m below the ground level is graphically represented in Fig. 26, in which the angle of friction is assumed to be 20, 25, and 30 degrees.

The artesian water pressure at Surte has not been measured before the slide, but is seems scarcely probable that this pressure was sufficiently high to cause "zero friction". According to estimates based on boreholes and on observations made in the field, the slip surface was situated at a depth of about 15 to 18 m below the ground level in the upper parts of the slide area. If "zero friction" had occurred, this would imply that the artesian water pressure would have reached some 11 m above the ground level, and this value seems to be much too high. If the pressure amounts to about 6 m above the ground level — a value that is also high — then the remaining pressures at depths of 15 and 18 m are about 3.2 and 5.1 tons/m^2, respectively. If the angle of friction is assumed to be 25 degrees, the respective values of the shear strength are 1.5 and 2.4 tons/m^2. If these values are compared with the cohesion existing in the clay strata at comparable levels outside and within the slide area, then they are found to be equal in the order of magnitude. Furthermore, a comparison of plane and circular-cylindrical slip surfaces measuring up to 100

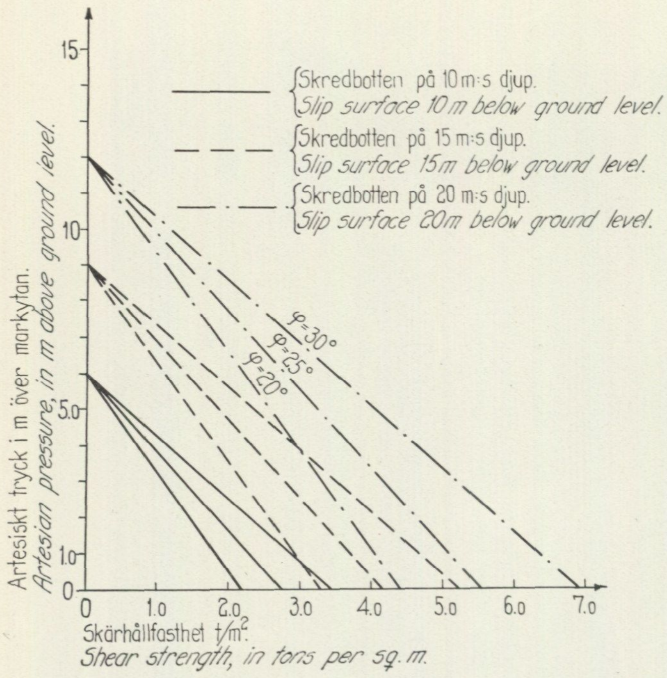


Fig. 26. The relations between the magnitude of the artesian pressure, expressed in metres above the ground level and the shear strength in sand layers situated at depths of 10, 15, and 20 m below the ground level, when the angle of friction = 20, 25, and 30°. $\gamma \sim 1.65$ tons/m³.

or 150 m in length and situated at depths of 15 to 18 m shows that the circular-cylindrical slip surfaces give a greater requisite cohesion than the plane slip surfaces under the ground conditions in the northwestern part of the slide area. Thus, the natural conditions do not afford any direct evidence in support of the assumption that the artesian pressure has reduced the forces of friction, with the result that a plane slip surface, which extends farther in a western direction than the circular-cylindrical slip surface, would have been more dangerous than the circular slip surface.

It is seen from Pl. 2 that a tongue of sand extends below the low plain west of the highway at a depth of 25 to 30 m, and it is therefore imaginable that an artesian pressure has existed in this place but it is not possible that a pressure of the magnitude exemplified in the above has had a harmful influence on the strength. Again, it is not probable that an artesian pressure over the whole slide area has existed in layers situated at a depth of 20 m or less in the area between the highway and the river. For this reason, the movement of the sliding earth masses along a single slip surface down to the river seems to be very unlikely. Considering those pressures which so far have been measured in the valley of the river Göta älv, it may be assumed that the forces of friction exceed the values of the cohesion in clay at the artesian pressures occurring at a depth of 20 m or more.

Since large quantities of water were drawn from those wells which yielded water, it appears probable that the artesian pressure which influenced the soil strata in the areas of comparatively steeply sloping ground east of the highway was reduced in comparison with that pressure which had existed before the erection of houses in the slide area. Therefore, if the artesian pressure alone is taken into account, the stability conditions have been improved in the course of years.

In addition to the above remarks on the artesian pressure, it is to be noted that the water level in Lake Surte, which is situated at a level of + 98 m and which may be imagined to constitute a pressure tank, has formerly been much higher, as may be seen from Fig. 27. The amounts of rainfall, which were observed by the Surte Glassworks, have also formerly been exceeded, judging from the records published by the Hydrological and Meteorological Institute of Sweden (see Chapter 6). Consequently, it is not very probable that the artesian pressure was exceptionally high at the time when the slide occurred.

As may be inferred from the above, it is not self-evident that the slide developed along those soil strata in which the strength of the clay or the forces of friction in a sand stratum (if any) were reduced by the artesian pressure. On the other hand, it seems to be highly probable that the initial slide developed along approximately circular-cylindrical slip surfaces.

D. Effect of Dynamic Forces.

How, then, was it possible that the sliding masses moved all the way down to the river? In order to form a more accurate idea of the possibilities of this movement, it seems advisable to give a short retrospect of

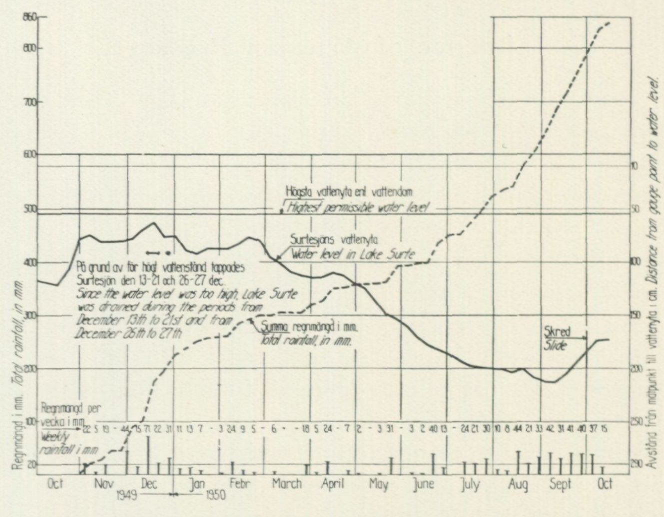


Fig. 27. Diagram showing the variations of the water level in Lake Surte and the rainfall in Surte during the year 1950 just before the slide. — The diagrams are based on observations made by Surte Glasswork.

the clay strata which covered the area of ground in question before the slide.

Practically the whole area east of the highway as well as a small area west of the highway, around the wedge-shaped sand layer extending over the highway in a western direction, was covered before the slide by quick clay, which was characterised by high values of the H_3/H_1 ratio. This clay was therefore very sensitive to disturbances. West of the highway, the clay was very loose, and its shear strength varied from about 0.8 to 1.7 tons/m^2 down to a depth of 10 to 15 m. The upper layer of dry crust clay was thin, and its thickness seldom exceeded 1 m.

In Chapter 7, which deals with the course of the slide, it has been pointed out that the kinetic energy of the clay masses affected by the initial slide itself was very great. The volume of these masses was estimated at 3×10^5 m^3. This corresponds to a weight of 5×10^5 tons. The maximum velocity of these masses was about 1.5 m/sec. Consequently, the kinetic energy of the masses was 0.51×10^5 ton-metres. The retarding effect in the slip zone itself can be eliminated, since the H_3/H_1 ratios of the quick clay are as high as 100 to 300, that is to say, the shear strength of the clay in the remoulded state is equal to zero. Accordingly, all retarding forces which acted on the masses involved in the initial slide were probably produced in an area in front (west) of the initial slide.

Thus, only the area west of the initial slide played a passive part in the slide, and had a counteracting effect. In view of the low shear strength of the clay, it appears natural that the passive area of ground successively failed in slide elements and that the slide developed in this manner down to the river.

Let us assume that the initial slide displaced an area of ground 200×300 m^2 in size, which seems very probable considering the main crack zones. The calculated average shear strength of the clay at a depth of 15 m is 1.7 tons/m^2. Furthermore, we assume that the shear strength of the clay decreases linearly to 20 per cent of its initial value during a displacement of 0.1 m and that the masses of the displaced area and the initial slide got such a low slide velocity as 0.3 m/sec alternatively 0.5 m/sec after the displacement mentioned above. Under these assumptions we find that the amount of work done in displacing the masses 0.1 m is $0.23 \cdot 10^5$ ton-metres alternatively $0.37 \cdot 10^5$ ton-metres. In these calculations we have taken account of the passive earth pressure down to a depth of 15 m and the effect of forces of cohesion in lateral walls. The calculated values of work done in displacing the masses 0.1 m is smaller than the previous value of the kinetic energy due to the initial slide but of the same order of magnitude.

When studying the main crack zones it seems justifiable to suppose that the initial slide first displaced the area of quick clay between the initial slide area and highway and that the movements of the soil masses were then propagated further through the quick clay area down to the railway line. In consideration of that assumption and the fact that the area of ground in question failed in shear in a large number of slide surfaces, with the result that overthrust of the dry crust were produced and the clay was crushed in some zones, it can be said that the kinetic energy of the initial slide was not enough to produce any further development of the slide than down to about the railway.

On the same assumptions as in the above a similar calculation is made for a slip area 350×400 m^2, which extends all the way down to the river. The slide bottom is assumed to be situated at a depth of 20 m in conformity with the hypotheses concerning the course of the slide which has been published earlier. The calculated average shear strength of the clay at a depth of 20 m is 2.5 tons/m^2. Then it is found that the requisite amount of work is $0.55 \cdot 10^5$ ton-metres alternatively $0.91 \cdot 10^5$ ton-metres. These values are greater than the energy of the initial slide and it seems not probable that the effect of the initial slide reached all the way down to the river.

If we now consider the earth masses which were involved in the retrogressive phase of the slide up to the final boundary of the slide cavity, we find that these masses were on the whole equal both in volume and in energy content to those studied in the above. It seems probable that the effect of these masses was propagated without any appreciable losses through the quick clay area down to the areas situated between the highway and the river. On the assumption that the initial slide has influenced and displaced the above-mentioned area extending down to the railway line, there remains an area which reaches down to the river and which varies from 100 to 150 m in width. It is obvious that the area between the highway and the railway line had a retarding effect, since the clay in this area is not quickish, if we except a small part of the area in question. In spite of this, it appears highly probable that the kinetic energy supplied to the subsequent slide was sufficient to bring about a further development of the slide in a western direction and down to the river bank. Owing to the rise of the ground surface and to the action of pushing forces, the river bank was subjected to an overload. This caused a relatively large rotational slip, with the result that the earth masses slid out into the river, raised the river bottom, and blocked the river channel. The necessary conditions for the movement of the slide into the river are represented in Fig. 28, which permits a comparison of the overload applied to the river bank owing to a rise of the ground level and a pushing

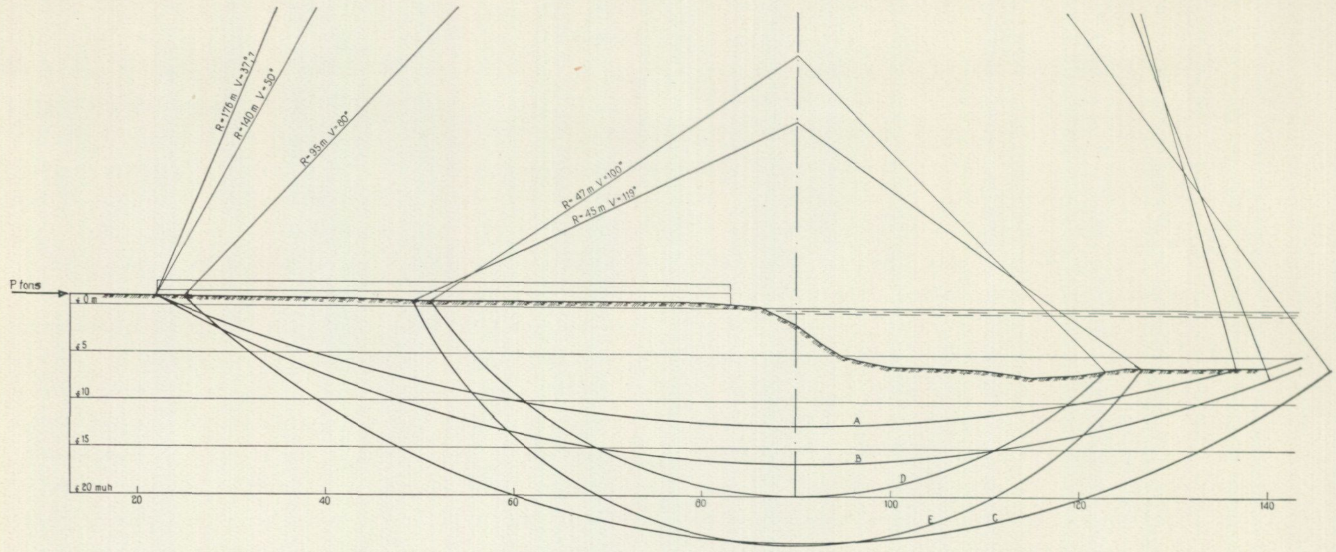


Fig. 28 a. Slip surfaces and stability conditions at the river bank.

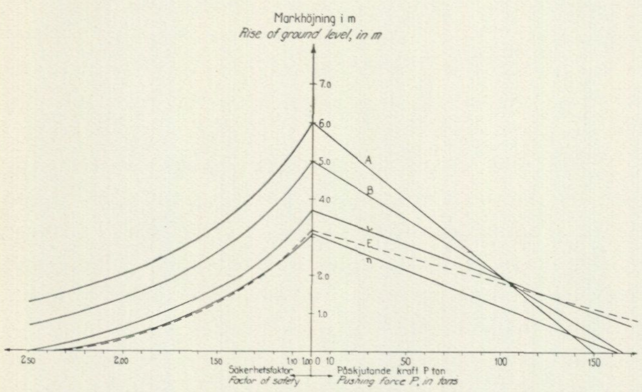


Fig. 28 b.

Influence exerted by the rise of the ground level near the river bank on the stability of five slip surfaces (A, B, C, D, and E).

Relation between the rise of the ground level near the river bank and the pushing force P in the dry crust clay, when the factor of safety = 1.00.

force regarded as causes of the slide. As may be seen from the diagrams shown in Fig. 28, the values of the pushing forces at the slip surfaces C, D, and E, with an overload of 2.5 m, and the respective pushing forces of 32, 42, and 69 tons/m are reasonable in their order of magnitude.

Thus it appears that the bottom of the slide near the river was situated at a depth of about 20 m. The depth to which the clay masses were affected has presumably varied within wide limits between the slide which moved into the river and the initial slide. For instance, it seems that the slide has not reached deeper than about 15 m west of the highway in its displaced position after the slide. In the active part of the slide, that is, in the initial slide area and in the subsequent slide area of the retrogressive phase, the slide bottom was situated at a depth of about 15 to 18 m below the original ground level.

Judging from the ocular examination of the sample-cores we can find that the deepest slide zone is found at some higher levels than those mentioned above. The probability that the slide has developed after a single slip surface all the way down to the river is very little, if the slip surface is situated at such a shallow depth as 10—12 m under the original ground surface in agreement with the geological examination. When the depth to the slide bottom is little, the slide mass probably will break in slide elements in accordance with the theories represented in chapter 7 and 8.

If the slide at Surte is regarded in the manner described in the above, it is possible to explain its final unsymmetrical shape, with the marked bulge in a north-western direction and the large zone of fissures, which extends from the station house in an upward direction towards the houses Nos. 16 and 5, the latter being split in two. Another feature of the unsymmetrical picture, which has already been mentioned, is the area of completely disintegrated ground west and north-west of the house No. 17. As may be seen most clearly from fig. A and Pl. 2, an explanation of these unsymmetrical configuration is probably to be found in the fact that the quick clay extended farther in a western direction in this part of the slide area along the previously mentioned wedgelike sand layer which reached over the highway and half-way down to the railway line. In those slip zones which were formed in the quick clay area, there was little resistance, and the amounts of kinetic energy due to the sliding earth masses east of the highway were therefore propagated

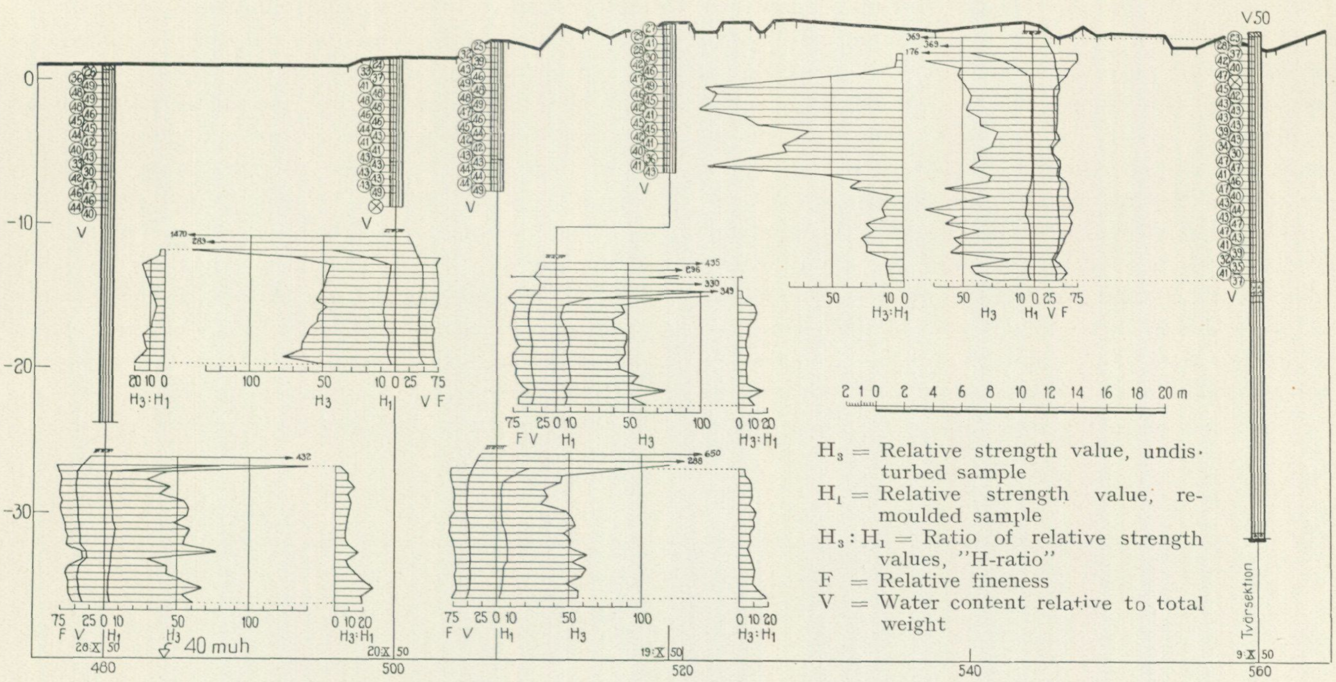


Fig. 29. Results of borings in section IV.

farther westwards than in the south-western part of the area in question. In order to investigate the soil conditions in the north-western area between the highway and the railway line, boreholes were put down in Section IV (see Fig. 29 and Pl. 1). Quickish clay was found only in a single borehole, at km 464 + 560, whereas the clay in all other boreholes was of the type known as "Gothenburg clay". Distinct overthrusts of the dry crust were observed in the borehole at km 464 + 519. This confirms the above representation of the mechanics of the slide. Furthermore, attention is directed to the terrace-shaped elevations in the area of ground between km 464 + 480 and km 464 + 510 outside the slide cavity, which are clearly visible in Fig. 30. They decrease in height as the distance from the slide cavity becomes greater, and must obviously consist of incipient slide elements. In principle, the observations described in the above seem to indicate that it was possible for the large slide to move forwards along slip surfaces which were successively formed and which raised the ground in the areas situated in front of them.

Several arguments can of course be adduced against the theory advanced in the above. For instance, it may be objected that the maximum velocity of the sliding masses has never reached 1.5 m/sec, and that the kinetic energy of the pushing masses was therefore considerably smaller than that assumed in the above. Eye-witnesses have stated that the duration of the slide was about 3 minutes. The initial slide itself lasted 60 seconds at most, *i.e.* one-third of the total duration. Approximately the same time was probably required for the downward movement of the main part of the earth masses situated east of the initial slide area to the eastern boundary of the incipient slide. Since the observed displacement of the earth masses in the areas east of the initial slide was 80 to 140 m, and since the time required for this displacement was 60 seconds, it follows that the velocity of these masses was of the order of 1.5 m/sec. However, it is likely that the velocity of the masses involved in the retrogressive subsequent slides was still higher because the retarding forces acting in front of these masses were considerably smaller than those in the initial slide.

E. Immediate Cause of the Slide on September 29th, 1950.

What, then, was the immediate cause of the slide on September 29th, 1950? In general, slides are caused by cuts due to erosion in watercourses, by excavation, or by excessively high fills on loose subsoil. None of these factors is to be regarded as a cause of the slide at Surte. Since the slide was initiated in the eastern part of the area, we have to exclude erosion in the river from the number of possible causes of the slide. No large excavations or fill constructions were in progress when the slide occurred. It is obvious that the houses erected in the slide area and the terraces built up around them in the course of several years have reduced the stability, but these works may be considered to be of minor importance in comparison with the earth masses involved in the slide. Finally, as has been pointed out in the above, there is no reason to suppose that the artesian pressure in the slide has been higher than before.

At the time when the slide occurred, a foundation was being constructed for the house No. 32 in the slide area (see Pl. 1), and timber piles, about 15 m in length, had been driven down to the firm bottom some days before the slide. This pilework was not completed at the instant of the slide. By studying the foundations of the other houses in the slide area, it is found that all these houses rested on slab foundations, without any piles. Consequently, it was the first time that piles were driven in the slide area, and this circumstance was the only new factor that has been added to the conditions which existed immediately before the slide. Is it possible, then, that this piling was the cause which released the slide? As may be seen from Pl. 1, the site on which the piles were driven was situated within that area of steeply sloping ground in which the slide was initiated. Considering that the above-mentioned area of ground was unstable, and that it was comprised within the quick clay area, it seems justifiable to assume that the shock waves and the vibrations produced in the soil by piling might have caused the release of the slide.

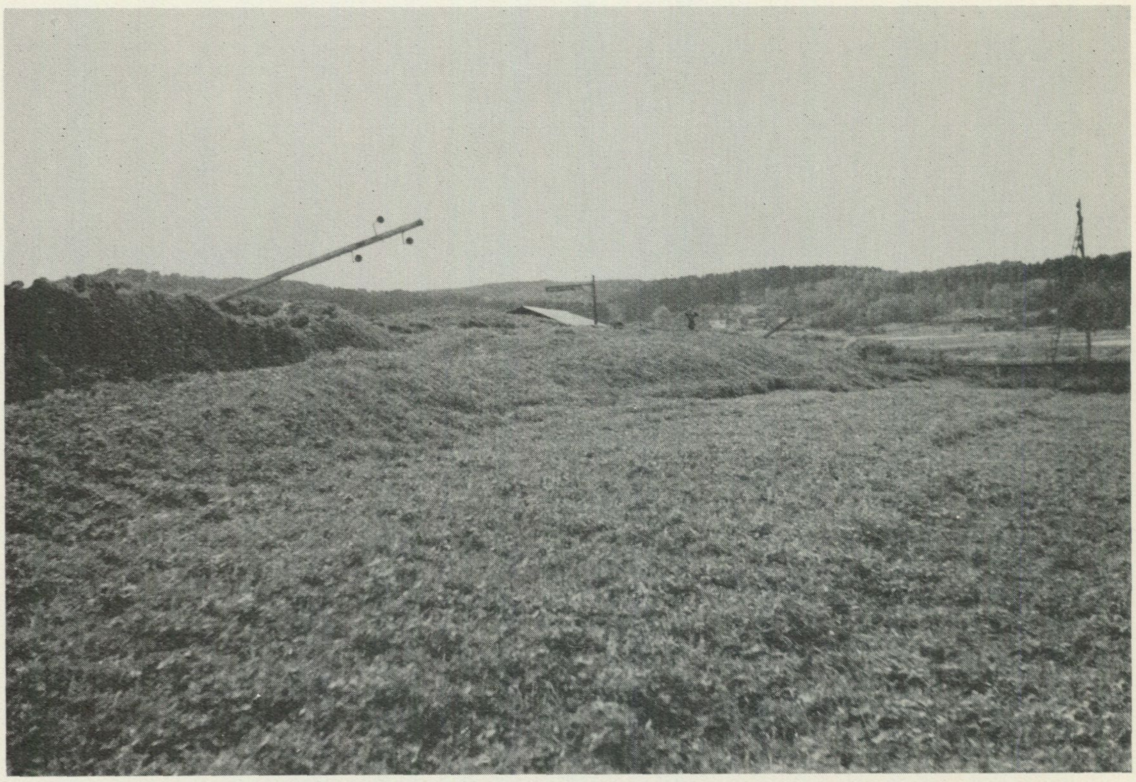


Fig. 30. Terrace-shaped elevations at the northern, bulged boundary of the slide. Section IV is situated at right angle to the terraces and at about the tilted post. (Photo by R. Lundström.)

9. Geotechnical Problems in Reconstruction of Trafficways.

By Bror Fellenius.

All river, railway, and highway traffic at Surte was blocked by the slide. One of the most important tasks to be accomplished was therefore to reopen the obstructed trafficways. The reconstruction works required for this purpose gave rise to several interesting geotechnical problems. Some of these problems are dealt with in what follows.

The plans for the reconstruction of the railway line and the highway were roughly drawn up as early as on the next day after the slide. These plans were based on a visual inspection of the slide area and on certain results obtained from the first boreholes. Both the highway and the railway line were situated in the lower part of the slide area. On the whole, a reconstruction of these trafficways in their original positions did not involve any change in the stability conditions. The dredging operations required for reopening the canal to traffic might impair the stability, but this impairment could always be counteracted by excavation in the lower part of the slide area. It was therefore considered to be quite obvious that the highway and the railway line could be reconstructed in their original positions in the plan. As regards their positions in the profile, it is to be noted that the ground level at the highway after the slide was only 1 to 1.5 m higher than before the slide. The highway was situated approximately at the boundary between that part of the slide area which had been subjected to downward vertical displacements and that part which had undergone upward vertical displacements. The railway line, on the other hand, was situated in that part of the slide area which had been submitted to considerable upward vertical displacements. The ground level in this place after the slide was 4.0 m higher than before the slide. It was estimated that the area, the stability of which was primarily affected by dredging in the canal extended all the way to the railway line at a distance of about 100 m from the canal. The highway, at a distance of about 200 m from the canal, was situated outside this area. Therefore, it was possible to reconstruct the highway at a level which roughly coincided with the ground surface after the slide. On the other hand, since it was probable that excavation would be required in an area situated immediately west of the railway line, it was considered that this line should be reconstructed at a low level, preferably the same level as before the slide. In that case the track would have to be laid in a clay cut which was in some places more than 4 m in depth. Since the ballast of the railway had to be at least 1 m in thickness, so as to ensure appropriate pressure distribution, it would therefore be necessary to remove the clay in some places to a depth of up to 5 m below the ground level after the slide. This was deemed to be scarcely practicable as the clay was partly remoulded by the slide, and was severely fissured, but it was decided to start excavation so as to use the original level of the railway line as a point of departure, and then to proceed by aid of experience.

It was not possible to begin the reconstruction of the canal until the arrival of the dredgers. It took a few days to convey them to the site, and this delay was utilised for extremely intense soil investigations in this part of the slide area as it was hoped that the stability conditions might be elucidated before dredging was started.

Since the highway, the railway line, and the canal were under the authority of the Swedish State Board of Roads and Waterways, the Swedish State Railways, and the Swedish State Power Board, respectively, it was necessary to appoint a Joint Committee for the reconstruction of these trafficways. The members of this committee were Mr. Westerberg, of the State Power Board, Mr. Sandström, of the State Railways, and Mr. Börjesson, of the Board of Roads and Waterways, so that all common interests were co-ordinated. On account of its neutral situation in the slide area, the highway was the least interesting object from the standpoint of soil mechanics, whereas the co-operation of the representatives of the State Power Board and the State Railway in the Joint Committee was most interesting from this point of view.

The reconstruction of the highway and the railway line was rapidly set on foot, and was conducted in three shifts day and night. Use was made of power shovels and tractors. All power shovels had to operate on special timber bed frames, which the shovels themselves picked up and carried along as they advanced. At first, the excavation required for the reconstruction of the railway line was slow. The excavated material had to be tipped at a distance of at least 20 m from the edge of the cut in order to prevent local slides. It was soon found that much time would be saved if it were possible to lay the railway track at a higher level.

The soil investigations were soon carried forward so far as to enable rough estimates of the stability conditions in the slide area west of the railway line. It was found that a reduction in load by excavation in this area was necessary before the canal was dredged to its full depth. This excavation would extend all the way up to the railway line. If the railway line were not located at a sufficiently low level, the stability of this line would therefore be inadequate. However, the excavation would be only so deep that it would be possible to raise the track about 1 m above its original level without running any risks. In that case, in view of the danger of local slides, the lower part of the trench for the track would be excavated in smaller lengths, and would be immediately filled with gravel. In the meantime, the superintendents of the works, who wished that the traffic should be resumed as soon as possible, decided to raise the line 1 m higher, so that the new track was to be laid 2 m above its original level. Consequently, the requisite depth of excavation was reduced, and it was possible to increase the rate of reconstruction. From the standpoint of soil mechanics, this implied that the stability of the area of ground below the railway line would not be adequate. The Joint Committee had discussed the possibility of moving the canal in a western direction in order to improve the stability conditions and to reduce the depth of excavation in the vicinity of the railway line. It was pointed out, however, that this relocation of the canal was not desirable for several reasons, *e.g.* from a navigational point of view. It was impossible to estimate the average shear strength of the clay on the basis of the results obtained from the tests of the soil samples taken in the slide area, because the clay was heavily fissured and partly remoulded. Therefore, the values of the shear strength observed in the laboratory tests were too high. It has long been known that this phenomenon occurs in clays of this type when they are damaged by a slide.

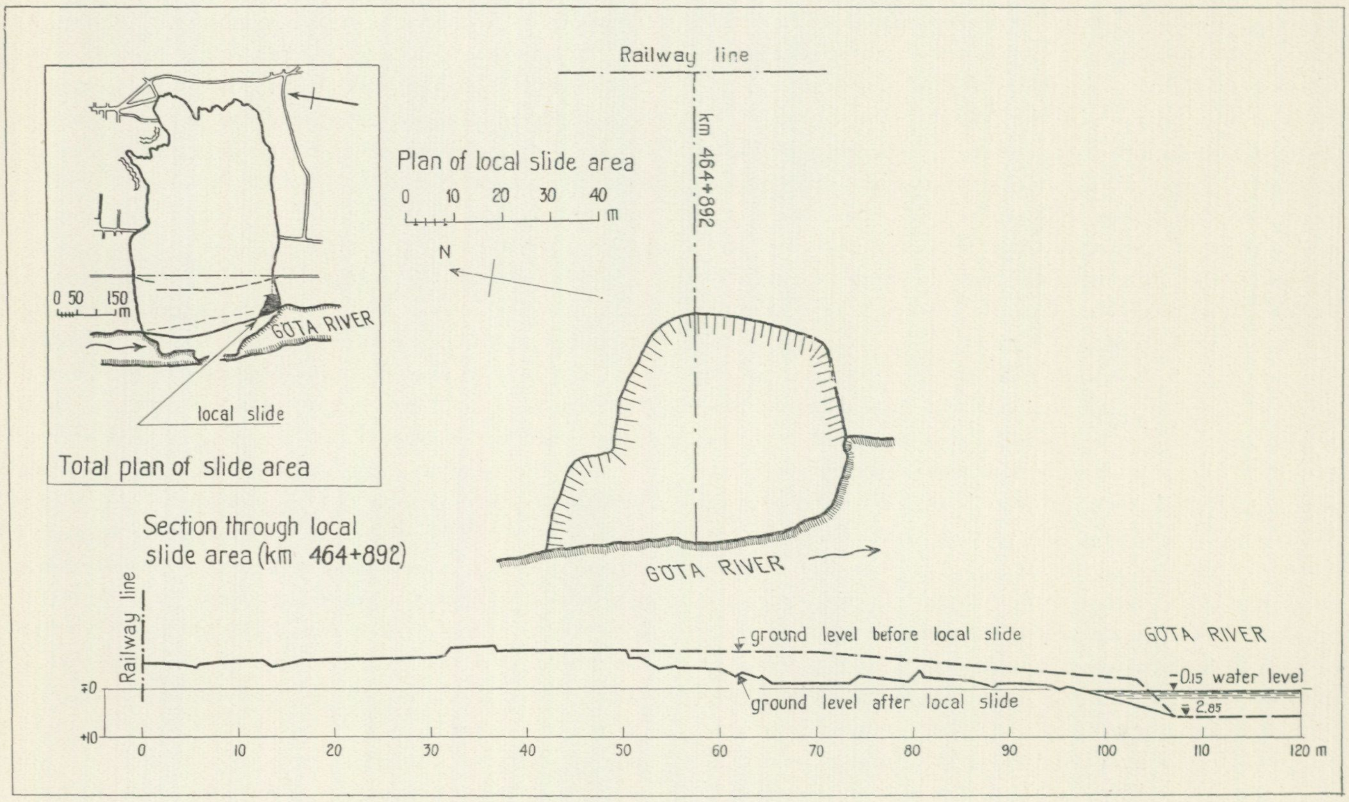


Fig. 31. Plan and vertical section of the local slide which occurred in the course of dredging on October 20th and 21st, 1950.

A local slide, about 50 m in length and 50 m in width, took place in the southern part of the slide area in the course of dredging. The situation of this slide is shown in Fig. 31. The local slide occurred while the river was being dredged to a level of —2.85 m, and developed slowly as the dredging continued. Owing to this slide, the earth masses which rose from the river bottom were dredged away as the level of the river bottom became higher. A few days before the local slide, a cross section had been levelled close to the future site of the slide. A section passing through this slide was levelled after the slide (see Fig. 31). The data obtained in this manner enabled a fairly accurate calculation of the average shear strength of the clay. According to the laboratory tests, the shear strength of the clay in the upper clay strata was about 1.2 tons/m^2, while a calculation of stability based on this "key slide" showed the actual shear strength to be as low as 0.7 tons/m^2. Owing to this slide, it was therefore possible to make a more reliable calculation of that average shear stress which produced failure in a circular-cylindrical slip surface in the clay masses in the lower part of the slide area, which were disintegrated by cracking and to a certain degree remoulded. On the basis of this value of the shear stress, it was found that a considerable excavation would be necessary between the railway line and the canal. Since the railway line, the embankment of which was practically completed at that time, had been raised 2 m above its original level, there remained no other economical solution than to move the canal in a western direction. The calculations showed that the stability of the area in question would be adequate if the canal were moved 35 m westwards and if the areas close to the canal bank and near the railway line were appropriately excavated. Since it was important to ensure that these stability problems should be solved as satisfactorily as possible, the Swedish Board of State Railways appointed a committee of experts, which consisted of Mr. John Olsson, Former Head, Geotechnical Department, Swedish State Railways, Mr. Hjalmar Granholm, Professor of Structural Engineering, Chalmers Institute of Technology, Gothenburg, and the Author, to report on the stability conditions. On the whole, this committee arrived at the same conclusion as that one mentioned in the above, *i.e.* that it would be necessary to excavate the canal bank and the area on both sides of the railway line after moving the canal 35 m westwards. In that case, the excavation near the railway line would be only so deep as not to impair the stability of the railway embankment. As it was uncertain whether and to what extent the clay was weakened by fissures and other disturbances, it was considered advisable to base the calculations on a factor of safety of 1.3 referred to the value of the ultimate shear strength obtained from the "key slide", *i.e.* the above-mentioned local slide. This value was 0.7 tons/m^2. In other words, the allowable shear strength used in the calculations was assumed to be $\frac{0.7}{1.3} = 0.54$ tons/m^2. Dredging and excavating operations were then carried on in accordance with this principle, and were completed without causing any unforeseen slide movements.

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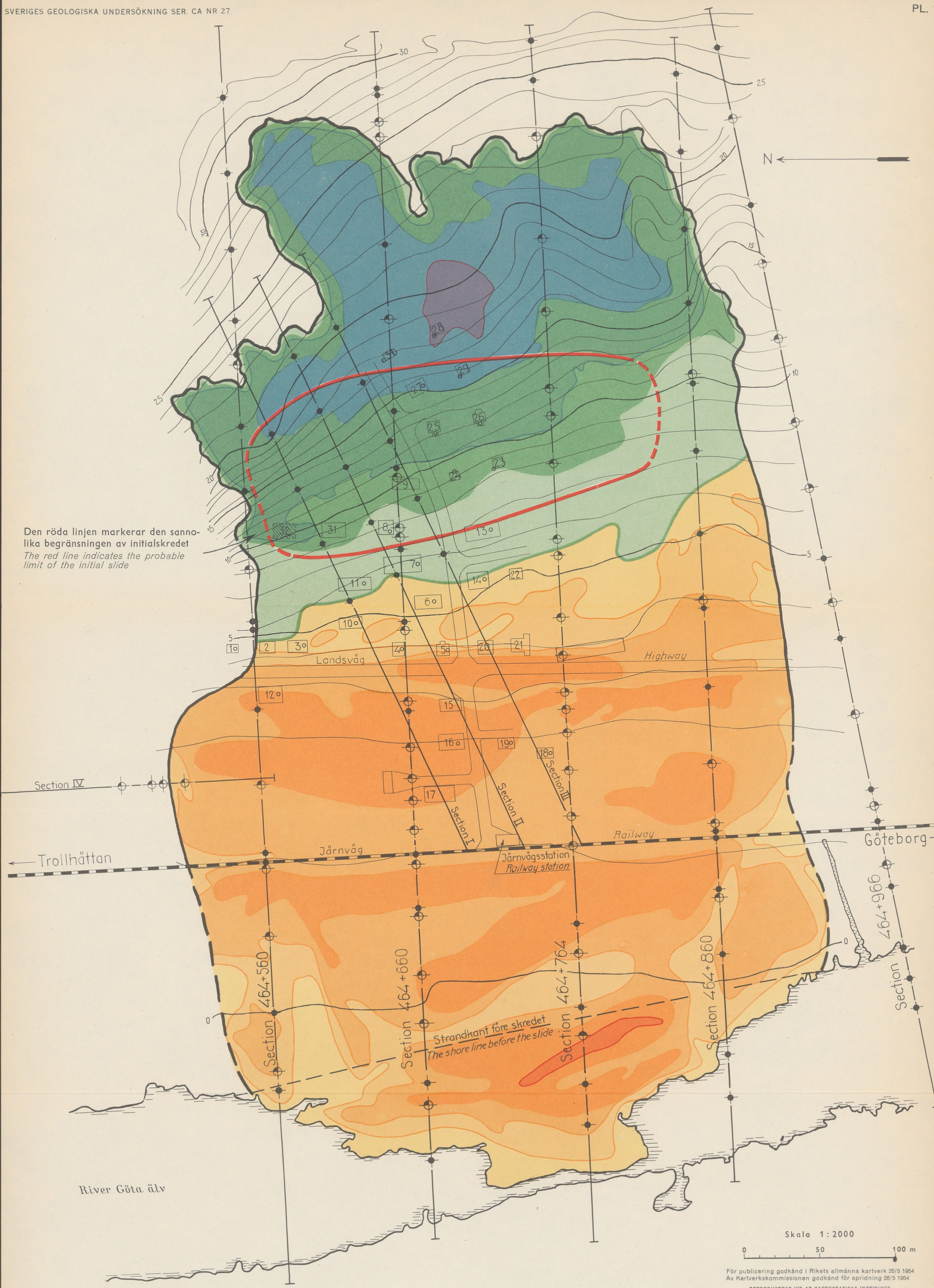


För publicering godkänd i Rikets allmänna kartverk 26/5 1954
Av Kartverkskommissionen godkänd för spridning 26/5 1954
REPRODUCERAD VID AB KARTOGRAFISKA INSTITUTET
ESSELTE AB. STOCKHOLM 1954

Av skredet höjt område
Area elevated by the slide

- 0 — 1 meter
- 1 — 2 "
- 2 — 3 "
- 3 — 4 "
- 4 — 5 "

Av skredet sänkt område
Area lowered by the slide

- 0 — 2 meter
- 2 — 4 "
- 4 — 8 "
- 8 — 10 "
- 10 — 12 "

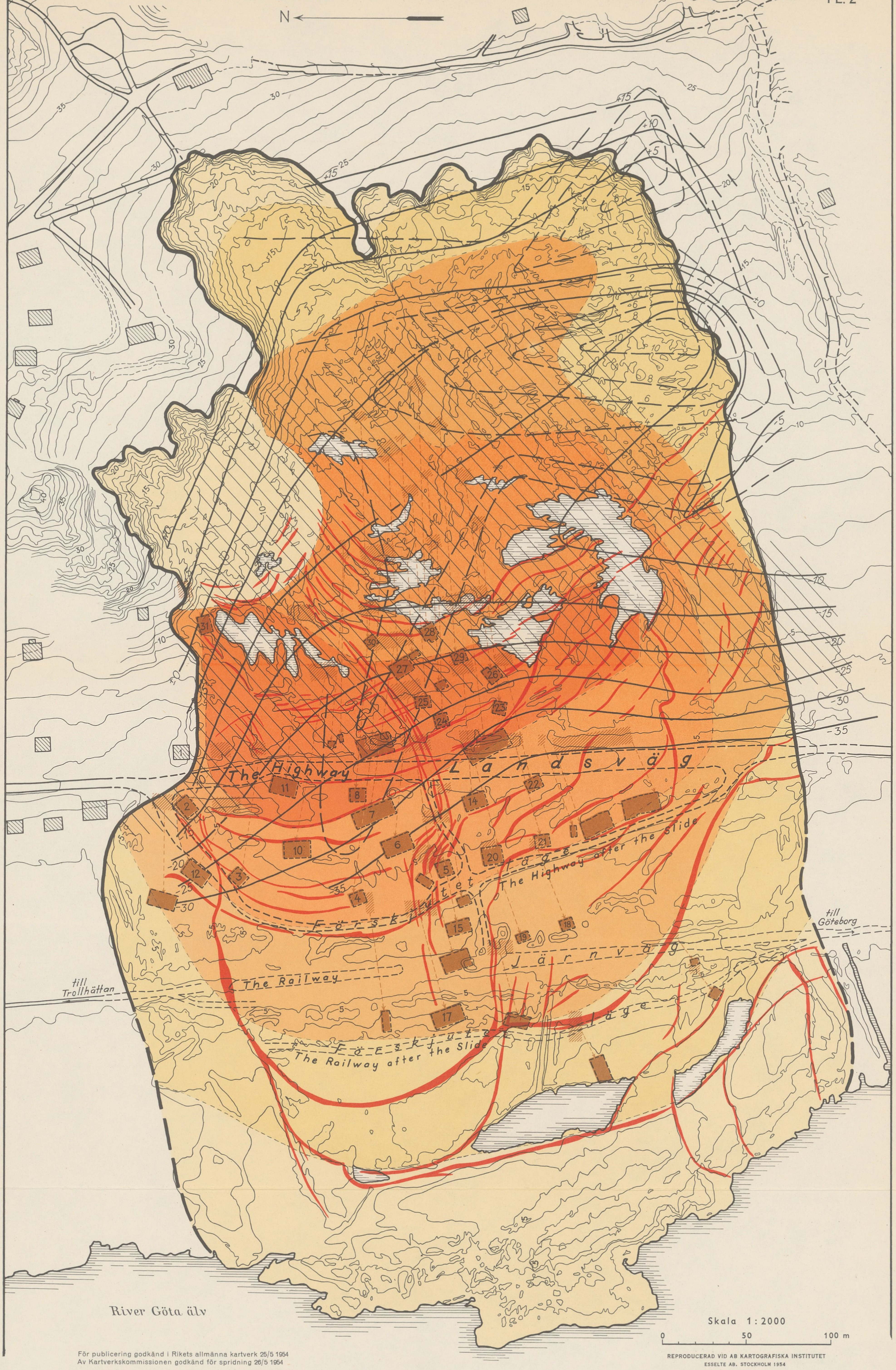
De olika färgerna ange djupet under respektive höjden över markytan före skredet
The different colours indicate the depth below or height above the surface level before the slide

- **Sondborrhål** — *Soundboring*
- **Provtagningshål, kolvborr** — *Borehole for taking samples with piston sampler*
- **Provtagningshål, foliekärnborr** — *Borehole for taking continuous cores by means of sampler with metal foils*
- 10 / 5 **Nivåkurvor i m för markytan före skredet** — *Contour lines in metres of the surface level before the slide*
- 3 ∘ **Hus med grävd eller borrad brunn** — *House with well, dug or bored*

SKREDÄRRET VID SURTE

THE SLIDE SCAR AT SURTE

Kartan sammanställd av R. Lundström på basis av fotogrammetriska mätningar 13 dagar efter skredet den 29 september 1950
Map compiled by R. Lundström and based on photogrammetric levellings 13 days after the slide, 29th September 1950



För publicering godkänd i Rikets allmänna kartverk 25/5 1954
Av Kartverkskommissionen godkänd för spridning 26/5 1954

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Initialskredskollor
Initial slide blocks

Skredskollor, 2:dra skredfasen, framåt- och tillbakagripande
Slide blocks, 2nd slide phase, displacement spreading forward and backwards

Skredskollor, 3:dje skredfasen, framåt- och tillbakagripande
Slide blocks, 3rd slide phase, displacement spreading forward and backwards

Skredskollor, 4:de skredfasen, framåt- och tillbakagripande
Slide blocks, 4th slide phase, displacement spreading forward and backwards

Skredskollor, 5:te skredfasen, framåt- och tillbakagripande
Slide blocks, 5th slide phase, displacement spreading forward and backwards

Sprickzoner, mera betydande
Main crack zones

Sand, senglacial, proximal; mäktighetskurvor
Late glacial sand; thickness curves in metres

Fasta bottnen, höjdkurvor
Firm bottom of moraine and rock, contour lines in metres

Nivåkurvor i m för markytan
Contour lines in metres of the surface level

Område för kvicklera, berört av skredet
Area of quick clay, touched by the slide

Hus i ursprungligt läge
House, original situation

Hus i förskjutet läge
House, displaced situation

SKREDÄRRET VID SURTE

THE SLIDE SCAR AT SURTE

Kartan sammanställd av Carl Caldenius och R. Lundström på basis av fotogrammetriska mätningar 13 dagar efter skredet den 29 september 1950

Map compiled by Carl Caldenius and R. Lundström and based on photogrammetric levellings 13 days after the slide. 29th September 1950

REPRODUCERAD VID AB KARTOGRAFISKA INSTITUTET
ESSELTE AB. STOCKHOLM 1954

DEL AV SEKTION SÖDER OM SKREDÄRRET VID SURTE. Sammanställd av C. Caldenius

PART OF SECTION OUTSIDE THE DISPLACED AREA AT SURTE AND ALONG ITS SOUTH BORDER. Compiled by C. Caldenius

Stratigrafien åskådliggjord genom kurvor över relativa hållfasthetstal H_3, finlekstal F och hållfasthetstalskvoten $H_3:H_1$

Stratigraphy of undisturbed layers illustrated by curves of equal relative strength H_3, of equal relative fineness F and of equal strength value ratio $H_3:H_1$

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DELAR AV SEKTIONER GENOM SKREDET VID SURTE. Sammanställda av C. Caldenius

PARTS OF SECTIONS THROUGH THE DISPLACED AREA AT SURTE. Compiled by C. Caldenius

Lagerstörningar åskådliggjorda genom kurvor över finlekstal F och hållfasthetstalskvoten $H_3:H_1$. Överskjutningssprickor

Disturbed layers illustrated by curves of equal relative fineness F and of equal strength value ratio $H_3:H_1$. Main cracks showing overthrusts

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