Norges Geologiske Undersøkelse No. 212 **q**.

INTERNATIONAL GEOLOGICAL CONGRESS
XXI SESSION NORDEN 1960

MARINE CLAYS AND QUICK CLAY SLIDES IN SOUTH AND CENTRAL NORWAY

Guide to excursion no. C 13

by

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for the
INTERNATIONAL GEOLOGICAL CONGRESS
OSLO 1960

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Excursion no. C 13: Aug. 26th.–Aug. 31st., 1960.

Excursion leader:

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INTRODUCTION

Marine clays deposited during and after the waning of the last inland ice, form the subsoil of quite large areas of relatively densely populated land below the "marine limit". This is first of all the case in south-eastern Norway (Fig. 1.) and in the districts around the Trondheimsfjord. Except for the upper part of former fjord districts with large rivers in the upland, the water in which the clay was laid down, was saline.

The thickness of the clay sediments is often quite considerable, up to 80—100 m, and the present clay surface as much as 180—200 m above sea level in the most strongly uplifted districts. Physically the clays have readjusted themselves from the conditions of the sea bottom to the present land conditions and they are generally normally consolidated. Cases of slightly overconsolidated clay sediments are known.

Since the end of the 19th century the Norwegian clays have been studied by numerous scientists, among them were: Amund Helland, V. M. Goldschmidt and co-workers, K. O. Bjørlykke, Gunnar and Per Holmsen, and in the last decade the staff at the Norwegian Goetechnical Institute. Detailed list of literature referring to the works will not be given here, but from the literature listed it is possible to work backwards and see the importance of the pioneers.

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On the first day of the excursion (26th August) our party will travel by bus to the Bekkelaget area just SW of the centre of Oslo. From here on we continue in a northerly direction (40 km) making a few stops on the route before coming to the Ullensaker locality. Return to Oslo in the evening.

The second day (27th August) a visit to the Norwegian Geotechnical Institute is arranged. Here, L. Bjerrum, O. Eide and I. Th. Rosenqvist will give lectures on results of research carried out on Norwegian geotechnical problems. The afternoon is left free for sight-seeing, including a visit to the Viking Ship and Kontiki Museum.

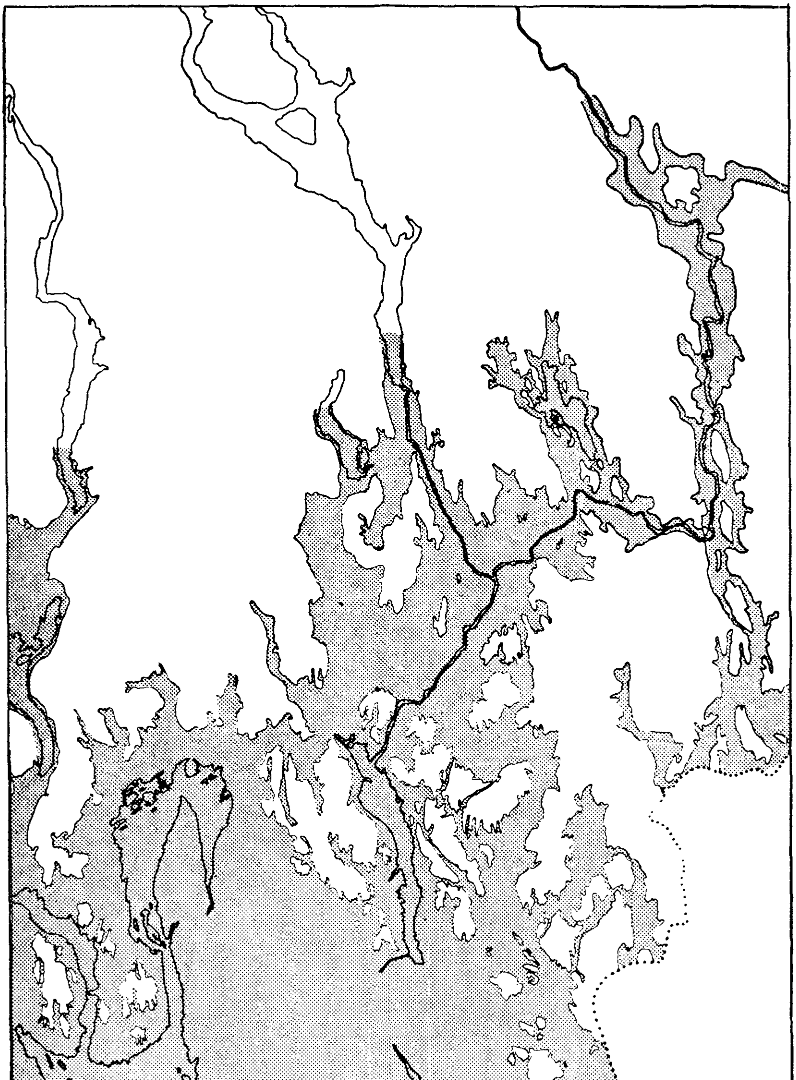


Fig. 1. Map of the districts around and north of Oslo. Shading shows the area submerged by the sea after the recession of the ice. (After G. Holmsen 1946.) Approximate scale: 1 cm = 10 km.

The third day (28th August) travel by bus to the Kongsvinger locality 80 km NE of Oslo. Return to Oslo in order to take the night-train to Trondheim.

The 4th day (29th August) allows a study of the Trondheim district, Hummelvik to the east, and the Orkdalsfjord area to the west. Visit to the cathedral and the Technical University.

The 5th day (30th August) we take the bus north-eastwards along the Trondheimsfjord to the Verdal locality and from there on to the town of Namsos—where we will stop overnight. The town is situated 125 km (as the crowflies) N of Trondheim.

The subject to be studied on the 6th (final) day (31st August) is the prehistoric and recent slides sites of Namdalen. From there, return by bus to Trondheim, arriving in the late afternoon.

All the localities which are to be visited have been recently investigated in connection with slide disasters.

After a general introductory statement on "marine-clays" and "slides in natural slopes", an account of those localities to be visited will be given.

MARINE CLAYS

The clay minerals are mostly of illitic and chloritic character. These minerals probably originated mainly from mechanical weathering of rock-forming minerals modified by subsequent chemical alteration. In the Trondheim area and Northern-Norway chloritic minerals are more common than in South-eastern-Norway. This is in agreement with the abundance of green schists and gabbroic rocks in the first mentioned areas. Although the bedrock which furnished the material for the clay minerals to a certain extent determined the mineralogy of the sediments, the clay fraction of the deposits, however, does not just represent rock-flour. Important chemical alterations have taken place before the deposition. A great part even of the finest fraction is, however, made up of non-clay (inactive) minerals such as quartz and feldspars. The sediments originally had a water-phase identical to the water-phase in the ocean-water and the active minerals, mainly the illites, had adsorbed the cations characteristic for ocean-water in equilibrium concentrations. Erosion has to a certain extent unloaded the sediments, but generally not by more than a few tenths of metres. They are thus to be designated as normally consolidated or slightly overconsolidated sediments.

In the upper two to four metres, which have been influenced by the atmosphere, the clays have partly dried out and partly undergone chemical weathering processes. These weathering processes, subsequent to the deposition, have to a certain extent changed chloritic or illitic minerals into montmorillonitic minerals. The upper crust of the clay sediments are found to have higher activities and higher base exchange capacities than the deeper strata. This is no primary feature, but a result of weathering. The upper crust, which is so characteristic in the Scandinavian clays, may be fairly stiff. The shear strength may be several times higher than in the underlying clay. In spite of this, the water content is not always lower in the upper crust. It may even be higher at certain levels. Deeper strata are much less influenced by the secondary weathering processes, but even they have undergone certain chemical alterations since deposition.

The change in mineralogy due to the secondary weathering in postglacial time has been dealt with extensively by J. Moum and I. Th. Rosenqvist.

If we examine the present salt content of the pore-water in a clay sample, we will most often find values varying from a few grams per litre up to 25 grams. Rarely values below one gram per litre are found, and also rarely more than 25—35 grams, which must have represented the original salinity of the pore-water during sedimentation. Thus, we see that a considerable reduction in the salinity has taken place since the deposition of the sediments. It is also easy to ascertain that the reduction in salinity has been highest in slopes and in clay deposits in a higher situation, thus mainly where major hydraulic gradients in the ground-water are to be expected, and the possibility of leaching is thus greater. In clay deposits of this type we have most of the slides characteristic of the Scandinavian clay sediments.

In order to illustrate this, it is necessary to refer to the physical properties of marine clays of non-expanding minerals as function of the salinity in the pore-water. *A decrease in the salinity will generally influence the plasticity.* In soil mechanics "plasticity" denotes the extent of the field where mixtures of minerals and water have plastic properties. Below a certain water-content the consistency of the water-clay mixture is considered brittle and above a certain water-content the mixtures are considered as semi-liquids. The difference in percentual water-content between these two limits is called *the plastic index.* A change in salinity of marine illitic clay will normally influence the plastic index. A reduction in salt reduces the upper limit (the liquid limit), whereas the lower limit (the plasticity limit) is kept fairly unchanged. (Fig. 2.) Another property of the clays which is highly influenced by a change in salinity is the *sensitivity.* (Fig. 2.) The sensitivity is defined as the ratio between the shear strength of a clay in an undisturbed and in a completely remoulded state. The sensitivity for a normal clay where the salt content of the pore-water is the same as during deposition, will mostly vary between 3 and 6. Marine clays in which the salt has been leached out, may have sensitivity values well above 100, i.e. the remoulded clays have less than 1 % of their strength left. Such clays are called *quick clays.* Thus, we see that a normal clay sedimented in salt water may be changed into a highly sensitive quick clay when the salt-water is leached out of the pores and replaced by the same amount of fresh water. The Norwegian clays differ from soils in many other countries by the fact that they were originally laid down in highly saline water and which, due to the land uplift, has been leached out and replaced by fresch water. The leaching has caused the following changes in normal deposits: (1) The shear strengt in undisturbed state is somewhat reduced, (2) The plasticity is reduced. (3) The sensitivity is highly increased.

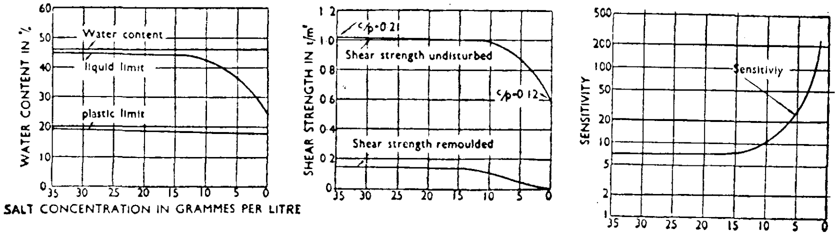


Fig. 2. Variation of mechanical parameters in Norwegian clays as function of salt concentration.

The Pleistocene clays of Norway may be divided in five genetically different groups, viz.:

The boulder clays. These clays and in some cases possibly inter-glacial clays have often borne very thick ice masses. They have very high shear strength values and low water-contents, corresponding to their high degree of overconsolidation.

The normal marine clays. In these sediments the shear strength increases with depth, dependent upon their activity and the effective overburden. The increase may correspond to 0,20 to 0,40 times the effective consolidation pressure.

The leached marine clays. Dependent upon the activity of the mineral phase and the degree of leaching, the shear strength increases with depth. The increase may correspond to about 0,1 to 0,2 times the effective consolidation pressure.

The weathered clays. In the post-glacial weathered clays the shear strength may be high, though never as high as in the boulder clays proper. The activity is normally higher than in the unaltered sedimented clays.

The remoulded, reconsolidated clays. Clay material which has been remoulded by land-slides and subsequently consolidated without ever having been completely disintegrated and sedimented mineral by mineral will have certain characteristic properties. The shear strength increases with depth, corresponding to about 0,5 to 0,6 times the effective consolidation pressure. Lumps of weathered crust and other surface material may be found enclosed together with uncompletely remoulded parts of the original sediments. The shear strength may thus be very variable in such deposits, see Fig. 3.

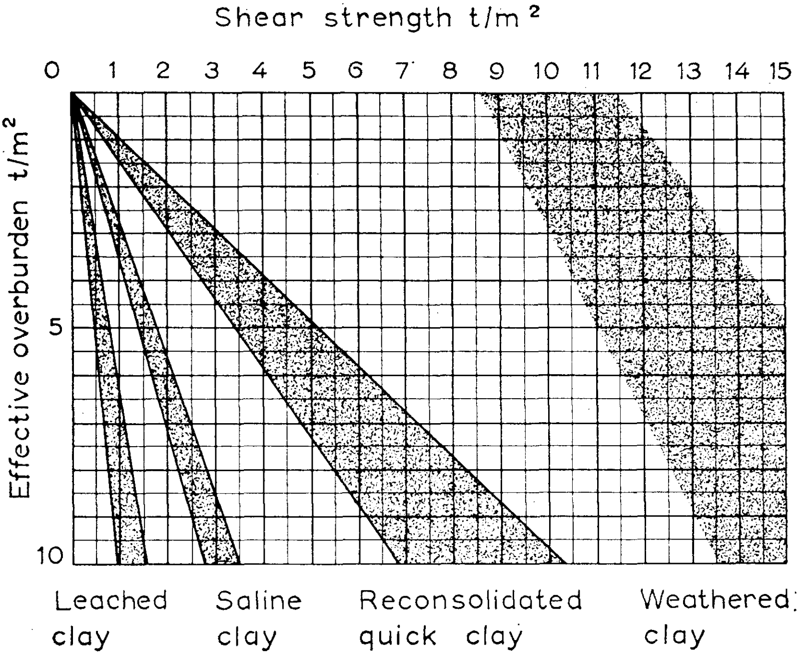


Fig. 3.

SLIDES IN NATURAL SLOPES

Nearly every year land-sides involving more than 100 000 cu.m of soil take place in Norway. In some cases only, insignificant external moments influencing the factor of safety can be traced. In many cases no such external factors can be referred to. Slopes which have been stable for hundreds and thousands of years may one day slide out and cause large damages. Only when the ground is frozen (February), the slide frequency is at a marked minimum. Fig. 4. As we have seen in the previous chapter, natural geological processes, viz. the leaching, will change the properties of a soil and reduce the natural factors of safety defined as the ratio strength/stress, in the less favourable potential sliding surface. When the clay sediments rise above sea-level their stability depends upon the shear strength mainly in the deeper parts of the slopes. In many cases the factor of safety must have been close to unity. As soon as the clay rose above sea-level, evaporation of water from the surface caused the upper part of the clay to consolidate. Subsequently weathering processes and leaching processes have continuously taken place. The weathering tends to increase the shear strength and increase the factor of safety. At the same time leaching processes in the deeper parts decrease the shear strength, thus rendering the slopes less stable. These two processes determine the long-term stability of a slope. The stability of many slopes depends upon which of these two processes will be the dominating one. The fact that February is the month with a minimum of slides, shows us the importance of the strength of the upper crust. Whether this is strengthened by frost or weathering is in itself un-important.

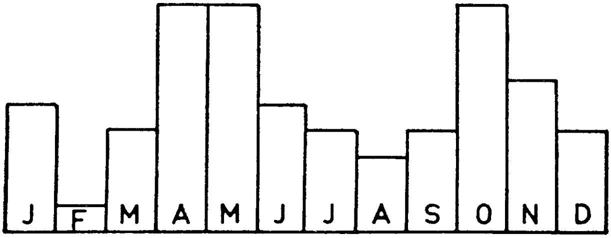


Fig. 4. The monthly frequence of clay slides, based on 63 major slides in the 20th century.

Most of the quick clay slides have many features in common. As an example of the most common type of land slides we may take a slide at Ullensaker 1953, see p. 13. The result was that the slide formed a larger cauldron with a diameter of about 200 metres behind the initial cut, which formed the bottleneck, and from this bottleneck a liquid mush of clay with high velocity floated out. The characteristic feature of this and similar slides is that the clay during sliding transforms the fairly solid material into a liquid, without any addition of water.

In other clay slides the amount of clay of the quick clay type is not so high, but the stiffer material may flow upon a thin layer of quick clay. This was the case for instance by the slide in Namdalen, which took place in April, 1959, see p. 22. In this type of clay-slide and in several others there has been no general remoulding. Only in a thin sliding-zone has the quick clay turned liquid, whereas the upper part, which may either consist of sand, gravels and silts, or of unaltered clays, may move as a solid body upon the lubricating layer of remoulded quick-clay.

AREAL DESCRIPTIONS

The Bekkelaget area, and its slide site.

In the southern part of Oslo a clay slide took place on the morning of October 7th 1953. Fig. 5. The railway line and the road which form Oslo's chief communication with the south and east side of the Oslofjord slid out for a distance of one hundred metres, together with the adjacent lower natural slope. 4 people lost their lives. Although the slide took place within a very short time, about one minute, several buildings in the affected area followed the moving monolitic clay body downwards 18 m without being damadged.

The most outstanding feature in the geology of the Bekkelaget area is formed by the bedrock. The steep rock slope, running approximately in north-south direction represents one of the main fault zones of the Oslo area, formed during Permian times. The bedrock of the lowland to the west is made up of Cambro-Silurian sediments. To the east Precambrian gneisses form the bedrock. On top of the Cambro-Silurian slates and limestones, are found glacial and postglacial clay sediments down to depths of about 25 m. These clays were deposited in highly saline water, as ascertained by micro and macro fossils. The present pore water of the clays shows, however, very low salinities, from 0.2 gram to a few grams per liter, even below sea water level. In general the slide site is characterised by an upper drying crust, mainly influenced by weathering processes. The thickness of this weathered crust increases from the sea shore towards the east, indicating that its thickness is a function of the time the clay has been above sea level. In average the weathered crust shows a thickness of 2 to 2.5 m. Below this crust proper there is a zone of partly weathered clay, and under this a very soft quick-clay, with sensitivity values of the order of 100. The activity of the clay minerals is extremely low, 0.20—0.30. The liquid limit is mostly well below the natural water content. The glacial clays forming the undermost part of the profile may contain some sand. The postglacial clays are normally free from sand.

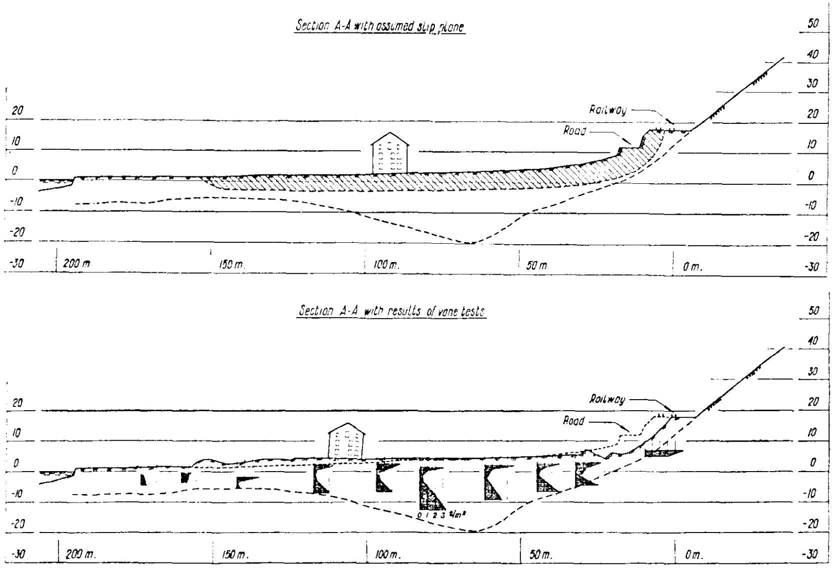


Fig. 5. Cross section through the Bekkelaget slide. In the lower figure shear strength values of the clay profiles are shown diagrammatically.

The land slide took place along a shear plane parallel to the ground surface. As can be seen from the fig. 5 the inclination is very gentle, only a few degrees. Pore water measurements after the slide gave values very close to the weight of the overlaying clay (Fig. 6). Thus the effective stresses must be very close to zero. Stability calculations by φ_0 analysis gave factors of safety close to unity. This slide can not be classified as an entirely natural catastrophy. The influence of human activity must take part of the blame, as the road and the railway embankment in the upper part of the area added to the shearing stresses. The reduction of salinity, however, during the time since the deposition, must have reduced the shear strength of the clay to about 60 % of the original value. This extensive leaching in the clay sediment so close to the sea shore is most probably due to ground water pressure in the brecciated rock along the fault line between the Cambro-Silurian shales and the Precambrian gneisses. As the permeability parallel to the layering of the clay is higher than the vertical permeability, the water pressure at the end of the sediment series will be a more effective leaching agent than is normal in clay water.

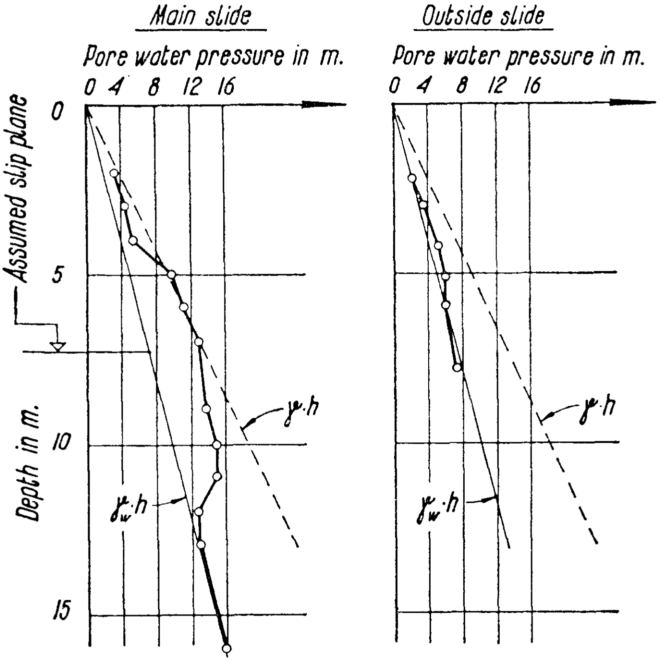


Fig. 6. Pore water measurements. Bekkelaget slide.

The district between Oslo and Ullensaker.

From Bekkelaget the excursion continues northeastwards, passing the area between the Oslo valley and the Romerike valley. This pass with an attitude about 160 metres above sea level is only thinly covered by marine sediments. The land was here only submerged by sea-water for a very short period after the retreat of the land ice. On the eastern side of the pass, at Høybråten, clay and silt sediments cover the bedrock up to 15 m thickness. These sediments prove, however, in many cases to be "varved", and thus showing features very much different from those found in the clays on the western side. Varved sediments have not been found in the Oslo valley at all, and they are normally not found in the Romerike valley neither. In some places, as for instance at Høybråten, the conditions for sedimentation must, however, have been different for a fairly long period after the retreat of the land ice. We had here brackish water in a bay of the ancient Romerike fjord.

Coming down from this site to the *Lillestrøm* area, we have a plain formed of recent deposits of silty material carried out with the rivers Vorma and Glomma together with Nitedalselven. These deposits are filling up the valley to great depths, forming a plain partly covered with peat bogs. On the sides of the plain older clay-sediments are found at higher altitudes than the younger silty material. These older coarse marine clays or clay silts have partly been transformed into very sensitive clays (quick-clays) by leaching processes. Some minor land slides occurred here due to allied bombing during the last war.

The Ullensaker area, and its slide sites.

Further to the north-east the excursion continues towards the Ullensaker area. The quick-clay slide at Ullensaker is the characteristic representative of the quick-clay slides of Norway. Fig. 7. This slide occurred on December 23rd, 1953, and totally destroyed a small farm with the surrounding fields. This area around Ullensaker, Romerike, is one of the most slide-damaged territories in south-eastern Norway. Minor slides occur every year, and most of them are of the same type as site to be demonstrated on the excursion. Most of them are on a small scale, and in uninhabited places. The slide to be demonstrated took place on a terrain which falls with a very gentle slope down to a small brook. The average inclination of the slope is only about 4 %, and most geologists

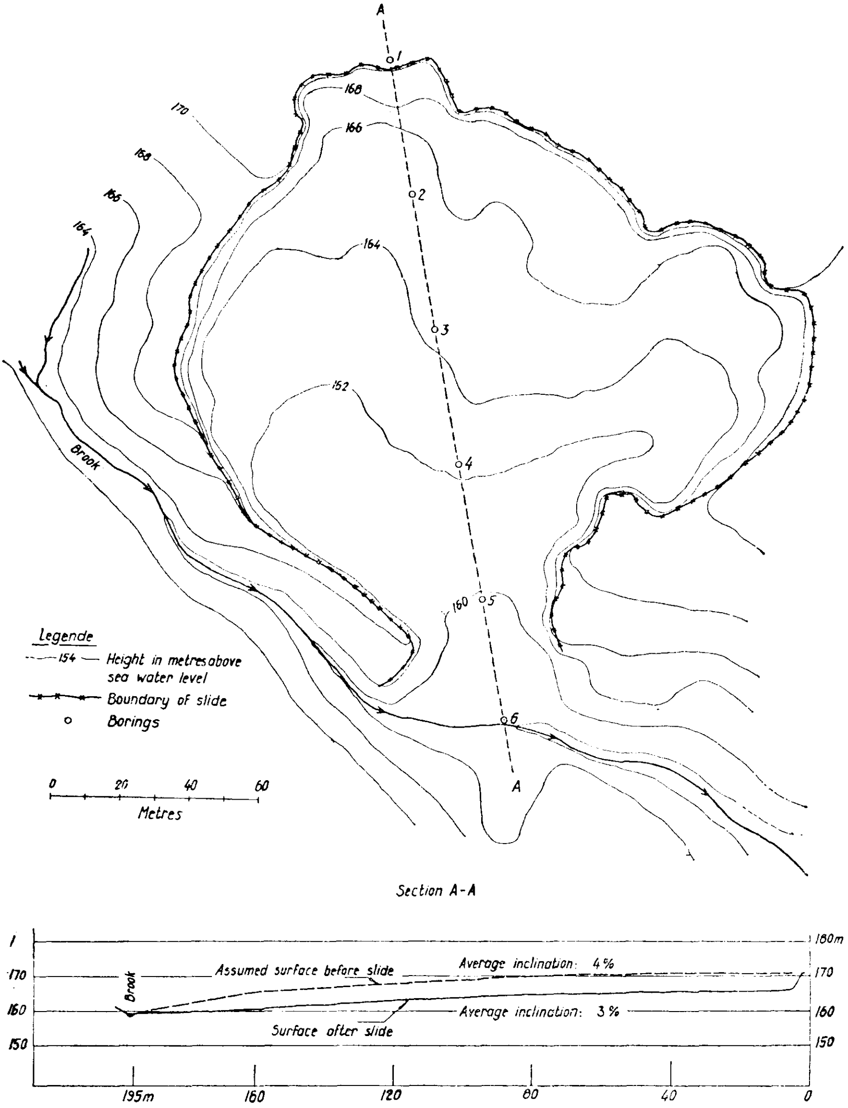


Fig. 7. The quick-clay slides at Borgen, Ullensaker, Dec. 1953.

and soil mechanic engineers would without doubt consider the area to be safe from any danger of slides. On the night before Christmas Eve of 1953 the farmer of a small farm observed some fissures in the frozen ground on the lower part of the slope towards the brook. Because this area is particularly cursed by land slides, the farmer removed his family to a neighbouring farm, to stay there during the night. At midnight the slide occurred, that totally destroyed the farm. As far as the event can be reconstructed, the slide started with a 20 m wide initial slide in the lowest part of the slope towards the brook. From this initial slip the slide developed backwards simultaneously widening in all directions. The most characteristic feature of this and similar slides is a change of consistency of the clay in the process of the sliding. As the clay became involved in the slide, and therefore remoulded, it changed to a viscous liquid with a consistency like heavy oil. Through the opening formed by the initial slide the clay slurry moved from the cavity and descended with considerable velocity along the brook valley. Flakes of the stiff upper dryingcrust were taken by the slurry and carried downwards. In all, about 200,000 cu.m of clay flowed away from the cavity of the slide. At a distance of 1.5 km from the slide the brook runs under a road embankment. At this place the clay slurry was dammed up, resulting in i big clay lake. Next morning the farmer found the demolished remains of his houses, and a cow and a horse were extricated while still alive.

Thorough investigations of the slide have been carried out by the Norwegian Geotechnical Institute. The results of a survey are shown on a plan, giving the contour of the slide and the position of the borings. Below the plan is shown a cross-section through the slide with the terrain surface before and after the slide (Fig. 7).

The results of the borings are shown on Fig. 8, which gives a graphical plot of the results of a series of vane tests made on an axis through the centre of the cavity formed by the slide.

In broad outline the borings have shown that below an upper crust of stiff fissured clay a silty, soft marine clay is encountered to a depth of about 20 m. The clay is decidedly quick in the lower part of the slope which was involved in the slide, whereas the sensivity is lower in the clay outside the slide. It is thus believed that the slide has removed all the quick clay above a certain level, but that it came to a standstill when it reached the less sensitive clay in the higher part of the slope.

As will be seen from Fig 2, the Atterberg limits of the quick clays are very low. This is the result of a reduced content of the salt in the

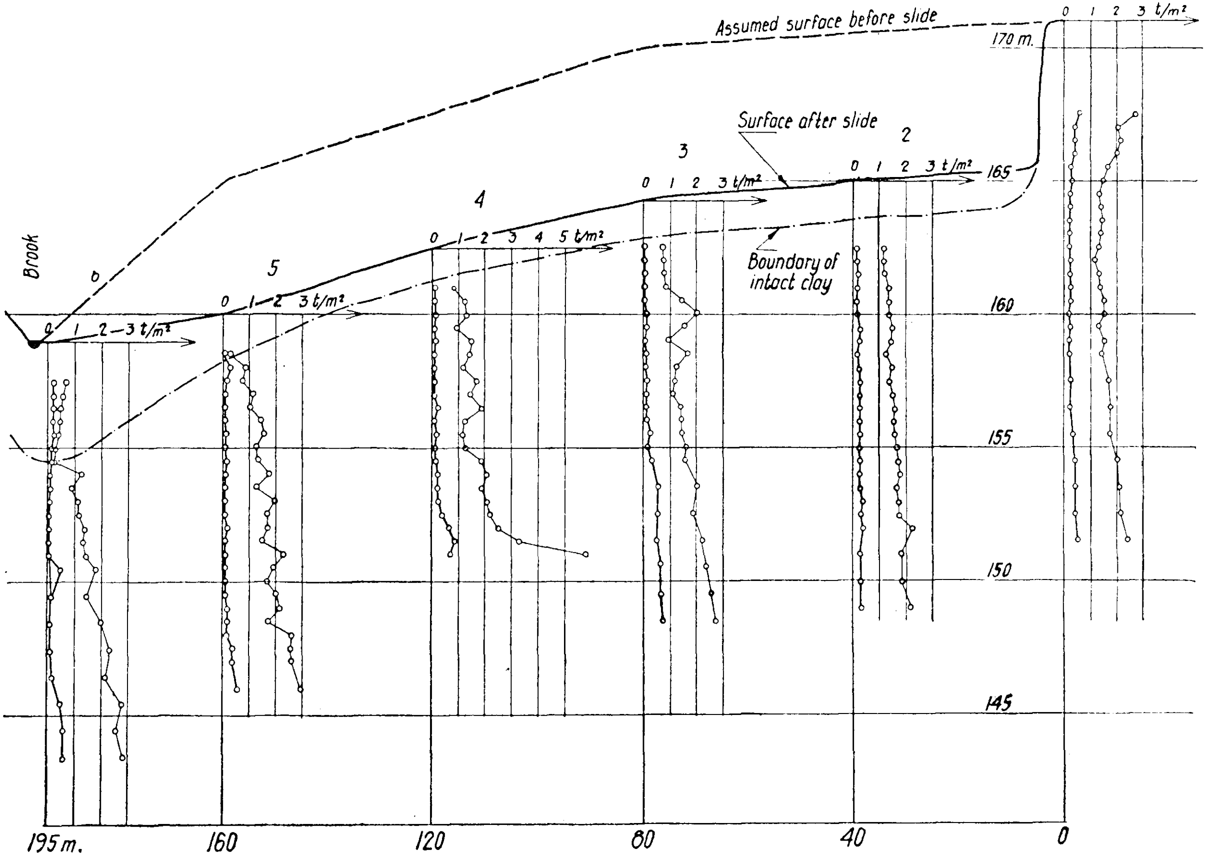


Fig. 8. *Results of vane tests. Slide at Ullensaker, Dec. 1953.*

pore-water, due to leaching-out by ground-water movements. Originally the salt concentration in the pore-water was 20 to 30 g/l; today it is from 1.2 to 2.9 g/l. If salt is added to the clay until a concentration of 35 g/l is reached, the liquid limit increases from 26 % to 34 %.

From the constant increase in shear strength with depth (Fig. 8) it is concluded that the clay is normally consolidated. The ratio of shear strength to effective overburden pressure, which is a characteristic constant for a normally consolidated clay, amounts to 0.09 to 0.13 for the borings in the sliding area and from 0.13 to 0.16 for the boring outside the slide. These values are relatively low, and they can only be explained as a result of a reduced salt content in the pore-water. Originally, the ratio of shear strength to overburden pressure is believed to have been 0.17, corresponding to the plasticity index 13 % determined at the original salt concentration.

Above the quick clay there was a crust of stiff, fissured clay. From borings outside the slide it is found that this "drying crust" showed a thickness of approximately 5 m. The shear strength of the drying crust decreases with depth. The average shear strength of the drying crust outside the slide amounts to from 3 to 5 tons/sq.m.

From the borings in the cavity of the slide it is found that the soft and sensitive clay, which took part in the slide, has disappeared almost completely during the slide. The bottom of the cavity consisted mostly of flakes of the drying crust, resting on thin layers of partly remoulded clay. Such a complete removal of the quick clay can only be explained as an effect of a squeezing of the clay under the weight of the drying crust, occurring as the material from the single slides moved out from the cavity.

The district between Ullensaker and Kongsvinger.

Eastwards from Ullensaker the fertile undulating plain of Romerike is made up of clays, silts and clay-sands. The top-soils are mostly coarser than the deeper parts, and represent flood deposits and partly finiglacial loesses. This loess was formed shortly after the retreat of the land ice. In these districts the marine deposits rose above sea level simultaneously over large areas. As the areas were not covered by any vegetation the first years, the winds were able to attack and replace the sediments.

The Kongsvinger area.

Continuing eastwards along the Glomma river valley, river sand deposits form the upper strata of the soil profiles. At the brick works of *Spedalen Verk* south west of Kongsvinger an interesting soil profile is seen. The upper layers down to 2 m consist of partly oxidised weathered dry crust containing rust nodules along roots holes from the vegetation. This soil is very much fissured, mainly along vertical fissures. The clay is a typical *varved-clay,* with silty layers at a distance of 0.2″ to 2″ apart. From 2 m down to about 3½ to 4 m below ground level the soil consists of reddish-brown varved-clay, without marked secondary weathering phenomena. Below this reddish varved-clay homogeneous highly sensitive bluish clay may be found to a thickness varying of 2 m to ½ m.

Below the blue clay a thin cover of brownish-grey or greenish, glacial clay is found. Although these clays have very different colours and mechanical properties, their mineralogy seems to be nearly the same. They are obviously all sediments from waters coming down the broad Glomma river valley.

The lowermost brownish glacial clay is supposed to be deposited close to the land ice as a proximal deposit. The homogeneous, bluish, plastic sensitive-clay represents the marine deposit. At the time when the ice had retreated south from the land, the melt water had mixed up in the fjord water, thus giving possibilities for brackish-saline deposits. This clay, which may partly be described as quick-clay, is today free from or nearly free from marine salts. The sulphate content and the bivalent-iron indicate, however, activity of sulphate reducing bacteria, *e.g.* sulphovibrio desulphuricans.

The brownish varved-clay of low sensivity and high density represent fresh water conditions, sedimented at the time when the land uplift had gone so far that the upper Romerike fjord changed into an estuarine area. Related extend over large areas into Värmland in Sweden.

At another site, *Kongsvinger Lervarefabrikk* (Pottery) similar deposits will be examined. In this site it is seen tat the undermost deposit consists of layered greyish silt with variable layering. On the top younger sandy river deposits are seen.

Flow slides in the Trondheim area.

Sub-aquatic flow slides in medium fine grained sands are frequent in the Trondheimsfjord area. One slide in Orkdalsfjord, about 29 km south-west of Trondheim, occurred on May 2nd 1930. From Fig 9 the position and extension of the slide are seen. The black dots indicate the points at which the depth of the water is known. The contour lines of the sea bottom were tentatively traced on the basis of the results of the soundings which were made at the points marked by the dots. The contour interval is 100 metres (330 feet). According to Bjerrum the bottom of the fjord is covered with silty sand, resting on bedrock. The lateral boundaries of the sand blanket are not known.

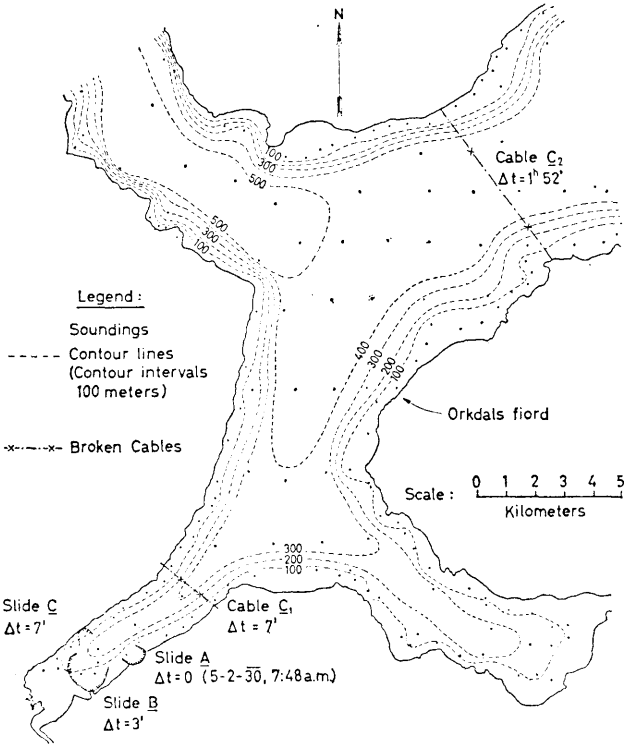


Fig. 9. The flow slides at Orkdalsfjord.

The slide started at point A (Fig. 8) close to the south-western end of the fjord. At this point a small fill (about 1500 cu metres) had recently been laid down along the shoreline. The width of the slide, measured along the shoreline, was about 500 metres and the artificial embankment, collapsed out into the sea. At the time when the slide started, the seismographic station of Bergen registered an earthquake and the level was exceptionally low. The epicenter of the earthquake was in the New Hebrides.

A few minutes after slide A went off, a slide occurred at site B close to the head of the fjord whereby some waterfront structures dropped into the sea. The upper end of the slide scar had a length of 600 to 700 metres. Finally, about 7 minutes after slide A, a third slide took place at point C on the northern shore of the fjord, facing site A.

Also seven minutes after slide A the submarine cable C_1 located at a distance of about 3 km from point A snapped, and 1 h 52' after slide A calbe C_2 at a distance of about 20 km from A went out of service. There was no visible evidence of sliding between site A and cable C_2.

The velocity at which the breakdown of the equilibrium of the sediment advanced from site A to cable C_1 was about 26 km (16 miles) per hour, and from C_1 to C_2 about 10 km (6 miles) per hour. The average gradient of the sea floor between A and C_1 is about 10 percent and between C_1 and C_2, over a distance of 17 km, it is practically zero.

K. Terzaghi dealt with this and similar slides. His theory concerning the influence of the rise in pore water pressures in metastable sand structures during structure collapse seems to give the best explanation for this and several similar slides along the Norwegian coast.

The Verdalen area, and its slide site.

On May 19th, 1893, half an hour past midnight, the largest land slide within historic time in Scandinavia took place. Altogether 292.4 hectares of ground slid out. The volume of the masses has been calculated to be 55 million m^3. 112 people and more than 600 domestic animals were killed. 22 large farms were destroyed. The clay masses from the slide covered an area of 864 hectares. The extent of the slide can be seen from the map.

The slide took place in three successive steps. It started in Krogsdalen. Fig. 10. Part of the fields on Haga farm slid out, and was transformed into a liquid mush. This semi-liquid streamed up and down the river valley, and drowned several people. This part of the slide sequence was the smallest, and seems to have been relatively noiseless.

The second part was much more violent, and several farms were destroyed.

The third step followed about a quarter of an hour later, and was actually made up of several successive slides by retrogressive slide machanism. The slide widened, while chunk after chunk of the clay fell down and became remoulded, so that the liquid clay was streaming out from the opening of the slide and covered areas which were not already destroyed by the slides. The clay masses had dammed the river, and a large lake was formed. By the 21st of May the water broke through the clay dam and followed an entirely different course than it had before. This change of the river course involved some damage, but no human life was lost.

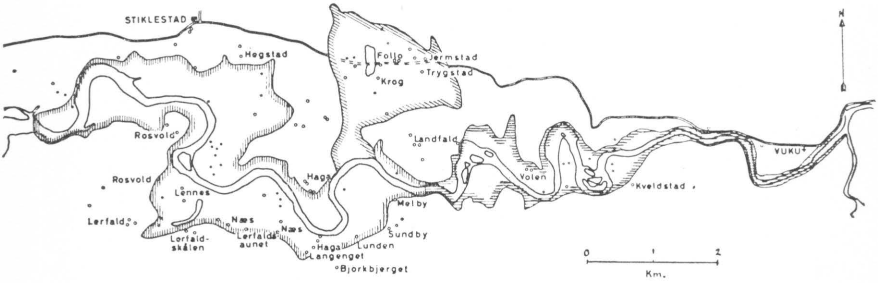


Fig. 10. The Verdalen slide area. Horizontal hatching: area submerged by water. Vertical hatching: area submerged by slurry. Oblique hatching: boundary of slides.

Subsequent to the big slide several smaller slides took place. In all some 40 hectares were involved in these secondary slides.

Today the valley of Verdalen still shows traces of this catastrophy. However, new farms have been built, and the ground is reclaimed.

This slide involved several investigations in the mechanism of clay slides and the properties of clays. Fig. 11. Until then it seems as if the quick-clay properties had been unknown by geologists. Investigations carried out subsequent to the slide proved that the soil had the now well-known sensitivity and not as earlier believed, viz. that under the dry crust large basins of liquid clay slurrey existed. Until then such and similar slides had been explained on the basis of hypothetic liquid bowls which for some reason or other had broken through the stiff cover. Today the slide site provides an opportunity to investigate the properties of remoulded and consolidated clays, and compare them with the properties of the virgin quick-clays. The most striking feature is

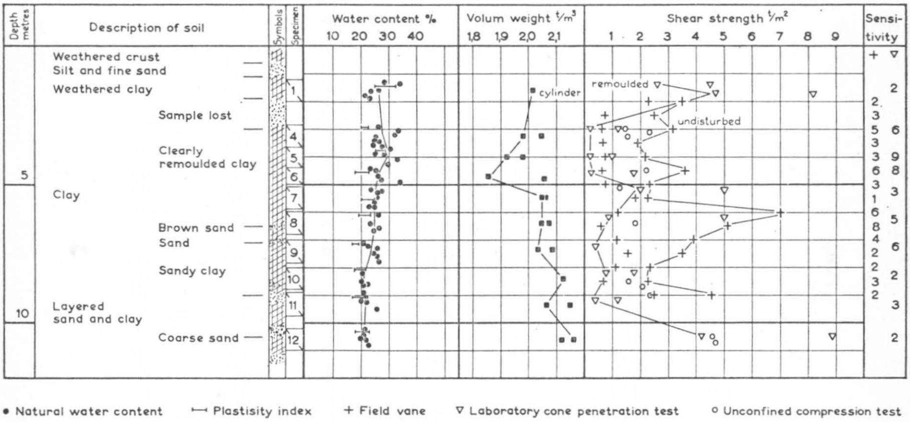


Fig. 11. Profile through the reconsolidated clay of Næss, Verdalen. (Redrawn from E. Tesaker, University Thesis, 1959.)

that the increase in shear strength with depth in the remoulded quick clay, which again consolidated under its own weight, is much higher than in any other clay sediment of corresponding mineralogical composition. C/p values found by boring through the reconsolidated quick clay in Verdalen may give values as high as 0.7, though the plastic index of the sediment is mostly low to moderate (plastisity index average 17, liquid limit average 24).

The land slides in Namdalen.

In 1959 two major slides occurred at Furre and Vipestad in the Namdalen Valley, Trøndelag. This valley district is situated to the north of the Trondheim area. The bedrock in the western part consists mainly of granite and gneisses. The gneisses are partly biotitic and partly amphibolitic. In the upper part of the valley, metamorphic Cambro-Silurian schists together with intrusives and other igneous rocks are found. The main feature of the morphology of the rock complex is supposed to be due to the tertiary uplift of the land. Thus the palaeic plain was tilted towards the east. Later erosion by rivers and glaciers eroded the valley towards the west. When the last land-ice retreated, approximately 10,000 years ago, the sea extended up through the present valley, and formed a 90 km long narrow fjord. The highest marine coast line is situated at about 180 m above the present sea level at Grong, and somewhat lower at the present coast line at Namsos, (150 m above sea level). In this fjord are found deposits of gravel, sand, silt and clays which were sedimented in glacial and postglacial time.

In the upper part of the valley, glaci-fluvial deposits are frequent. The glaci-fluvial material consists solely of coarse material, whereas the moraines consists solely of coarse material, whereas the moraines are rich in fine fractions. Thus a separation in glacial period of the fine material from the coarse is obvious. This fine material must have been important in forming the marine deposits in the fjord.

In this particular valley the drainage conditions in the upper part of the valley system have changed in an interesting manner since the ice age. In the latter part of the glacial period, rest of ice from the glaciers was situated to the east of the water divide. In this way extensing lake systems were dammed between the rest of the land ice to the east and the water-divide to the west. The whole complex of the present lakes and the glacial lakes drained westwards through the Namdalen valley. Thus greater part of the water, which normally would drain to the Baltic, came through the Namdalen valley. Later on (about 8000 years ago) when the ice had melted further down, the two great lakes of Limingen and Tunsjøen drained towards the east. This means that during this time the amount of water coming down the Namdalen river must have been considerably lower than today, when due to the oblique uplift of the land Tunsjøen drains towards the west. Most probably this drainage of Tunsjøen towards the west began some 2000 years ago. Thus in a period from 8000 years to 2000 years ago, when the larger part of the marine sediments were formed, we were dealing with a shallow fjord and moderately amounts of water in the river draining into this fjord.

The majority of the marine deposits in the Namdalen valley consist of sand and silt. However, narrow clay seams in the frictional materials are important in this valley. 54 older slides have been registered from the topography and documents. The two slides in 1959 at Vipestad and Furre have been extensively dealt with by the Norwegian Geotechnical Institute. In Furre the slide took place along a slightly inclined thin layer of quick clay which possessed the following properties:

	Properties	*Limits*	*Average*	*Unity*
	Volume weight saturated	1.75–1.85	1.80	t/m^2
	Sp.gravity	2.82–2.88	2.85	–
With natural salt contents	Water contents	37–48	43	%
	Liquid limit	22–39	32	%
	Plastic limit	17–24	21	%
	Plasticity index	5–15	11	%
	Liquidity index	–	2.00	–
	Activity	–	0.27	–
With salt added to contents 35 g/l	Liquid limit	36–46	42	%
	Plastic limit	18–25	23	%
	Plasticity index	18–21	19	%
	Liquidity index	–	1.05	–
	Activity	–	0.46	–
	% particles 2 μ	35–54	41	%
	Natural salt contents	0.45–1.38	0.67	g/l

The slide at Furre took place in April 1959. Before the slide, the area was fairly regular, consisting of a nearly horizontal upper terrace of sand about 20 m above the river. This was a terrace of accumulation formed at the time when the sea level was situated above this attitude. Its inclination towards the river was 0.5 %. Along the river another terrace varying between 6 and 7 m above the river, with an average width of 15 m, was found. This terrace was mainly an erosion-terrace partly covered by younger sands. The terrace had an inclination of about 1 % inwards from the river. Before the slide, severe erosion had been recorded since 1877. The width of the lower terrace had thus been reduced from about 40 m to the present width. In 1957 an increased erosion started, mainly because of ice accumulation influenced by the hydro-electric power plant regulations in the upper parts of the river. This erosion unloaded the river banks on the southern side, and thus decreased the overall factor of safety. The rise in ground water level in the spring of 1959 led to a further decrease, and the slide took place most probably in two steps, with an initial slide at the river bank in the lower terrace decreasing the factor of safety in the rest of the area to such an extent that the main slide was possible. It is obvious that the initial slide must be regarded as a drained case, whereas the main slide must be dealt with as an undrained slide, as it took place immediately after the initial slide, so that no adjustment of the pore water pressure could be effected. Based upon the shear strength parameters measured after the slide, the following variations in the factors of safety have been calculated:

Factors of safety from 1877 to 1959.

Time	Main slide		Initial slide	
	F.	Diff.	F.	Diff.
1877	1,35	0,22	1,75	0,500
1957	1,13	0,06	1,25	0,125
1959 (before rise in ground water)	1,07	0,04	1,125	0,125
1959 (after rise in ground water)	1,03	0,03	1,000	
1959 (after initial slide)	1,00		–	

In this case extensive determinations of parameters have been carried out, both in the field and in the laboratory. The drained shear strength has been determined by large-scale field equipment, using shear boxes of 50 × 50 cm with loads up to 14—15 tons per m^2. All deformations were measured with an accuracy with 1/100 of a mm. The shearing force was supplied in 10 steps, and a curve showing the deformation in horisontal and vertical directions was taken up. The following angles of true friction were found: 8.8°, 10.5°, 12.0°, 11.4°. These values are much lower than any other values of true friction earlier measured in silty illitic material. By triaxial tests an angle of true friction amounting to 20.9° was found, and the lowest values of true friction measured until then were about 18°. The field results are in fairly good agreement with the angles of true friction recalculated from the stability analysis (7°).

The investigations prove that the main slide took place in the following way: A monolitic sand and silt body of about 100.000 m^2 and a thickness of about 15 m moved as a single unit towards the river upon a thin layer of quick-clay. In this case it seems as if it had been practically impossible to predict the low stability before the slide, as extensive boring would have been necessary to locate the continuous quick-clay seam, and determinations of the angles of friction in the laboratory would have given too high values. The investigation of this slide and the research carried out in this connection have shown that we have to revise earlier methods for investigations and evaluations of the stability of slopes in sand with quick-clay layers.

In order to ascertain the position of the sliding plain, determinations of the electric conductivity of the ground were taken into account. In all 32 borings continuous determination of the ground conductivity has been carried out. These, combined with determinations of the ground water pressure after the slide, have provided a fairly accurate underground map of the slide.

The other slide in Vipestad occurred in more silty clay with less regular topography. This slide has not been investigated to the same extent, and no values can be given. It is, however, interesting in this case to note that this slide occurred in a place where a prehistoric slide must have taken place. Chunks of reconsolidated remoulded silty clays are found in the ground together with timber logs. Age determination by means of C 14 analysis proves that this prehistoric slide took place about 1950 years ago. This earlier slide obviously dammed the valley, and the flood breaking through this clay-dam deposited a gravel layer which may be followed for 10 km. From pollen analysis and C 14 determinations the land uplift in the last 2000 years has been calculated to be about 3.2 mm per year at Vipestad about 20 km from the present shore, and 2.6—2.8 mm per year at Furre, 10 km from the shore. This is in fairly good agreement with the total oblique uplift of the land since the ice age.

LITERATURE

Bjerrum, L.: Geotechnical Properties of Norwegian Marine Clays. Norges Geotekniske Institutt, publikasjon nr. 4, Oslo 1954. (Norwegian Geotecnical Institute publication.)

– Besondere erdbaumechanische Probleme Norwegens. Norges Geotekniske Institutt, publikasjon nr. 14, Oslo 1956.

Eide, O. and L. Bjerrum: The slide at Bekkelaget. Norges Geotekniske Institutt, publikasjon nr. 10, Oslo 1955.

Holmsen, Per: Landslips in Norwegian quick-clays. Geotechnique, Volume III, 1953, p. 187–194.

Moum, J. and I. Th. Rosenqvist: Chemical weathering of minerals illustrated by some clay profiles. Norges Geotekniske Institutt, publikasjon nr. 8, Oslo 1955.

Norwegian contributions to the Fourth International Conference on Soil Mechanichs and Foundation Engineering in London. Norges Geotekniske Institutt, publikasjon nr. 26, Oslo 1957.

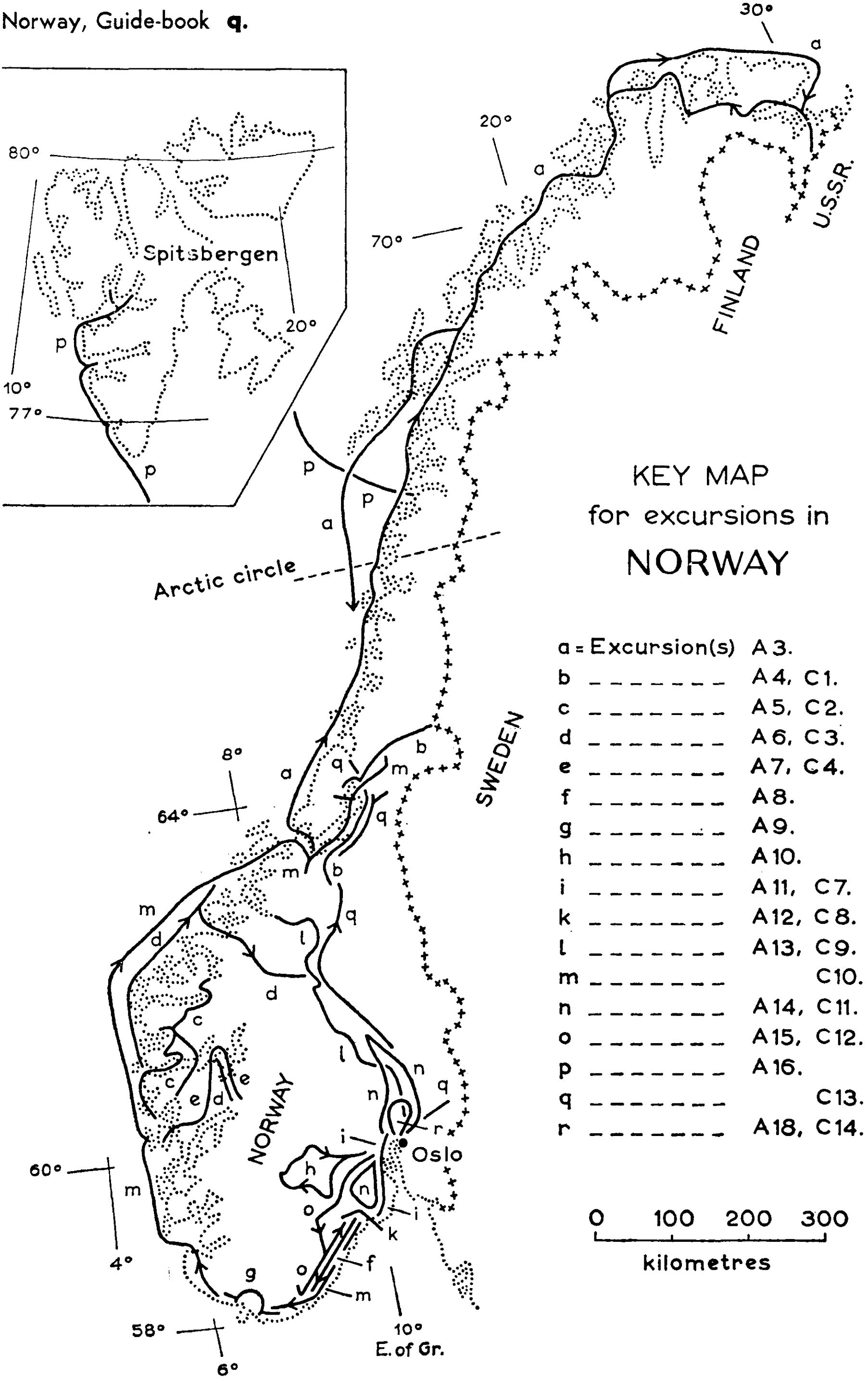
Reusch, H.: Nogle optegnelser fra Verdalen. Norges Geologiske Undersøkelse nr. 32, 1901.

Rosenqvist, I. Th.: A. Om leirers kvikkaktighet. B. Om leirers plastisitet. Meddelelser fra Vegdirektøren 1946, p. 29–36 and 36–41.

– Considerations on the sensitivity of Norwegian quick clays. Geotechnique Volum III, 1953, p. 195–200.

Notes.

Norway, Guide-book **q.**



KEY MAP
for excursions in
NORWAY

a = Excursion(s) A 3.
b ———————— A 4, C 1.
c ———————— A 5, C 2.
d ———————— A 6, C 3.
e ———————— A 7, C 4.
f ———————— A 8.
g ———————— A 9.
h ———————— A 10.
i ———————— A 11, C 7.
k ———————— A 12, C 8.
l ———————— A 13, C 9.
m ———————— C 10.
n ———————— A 14, C 11.
o ———————— A 15, C 12.
p ———————— A 16.
q ———————— C 13.
r ———————— A 18, C 14.

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