A FIELD STUDY OF FACTORS RESPONSIBLE FOR QUICK CLAY SLIDES.
ETUDE SUR PLACE DES FACTEURS RESPONSABLES DES GLISSEMENTS EN ARGILES TRES SENSITIVES

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SYNOPSIS The paper describes the result of a field study of a 45 km^2 large marine clay area 40 km north-east of Oslo. The scope of the study was to isolate, describe, and evaluate the relative importance of the various factors and processes responsible for the occurrence of quick clay slides. The most important finding of the study is probably the establishment of a zone of aggression within which the risk of quick clay slides is greatest. It is concluded that the possibility of preventing quick clay slides may exist by the construction of thresholds in the streams to reduce further erosion.

INTRODUCTION

Within Norway's 40000 km^2 of marine clay area, quick clay slides present a serious problem, each century leading to loss of lives and property. In the study of this problem the Norwegian Geotechnical Institute has hitherto concentrated its activity on detailed investigations of individual slides. The real solution to the slide problem is not, however, to explain a slide which has already occurred, but to find some means of predicting and preventing potential slides. To do this, it is necessary to relate our understanding of the mechanics of a slide to the forces at work in nature which are the causes of instability. As the first phase of such a study, the Institute in 1967 initiated a regional mapping study of a 45 km^2 area in the Romerike district (Fig. 2) situated about 40 km NE of Oslo.

This area was selected due to the fact that (I) it has been the scene of numerous disastrous quick clay slides of which the Ullensaker slide in 1953 has been studied in great detail, (II) the quaternary geology is well known and the originally sea bottom plain is still intact adjacent to the northern and western boundaries of the area, and (III) the lower stream in the southern part of the area has reached a grade of equilibrium, whereas those in the northern part showed active erosion.

In the study of the selected area all scientific disciplines relevant to the quick clay slide problem were used, namely geology, geomorphology, and hydrology which included erosion studies. The techniques of air and terrestrial photogrammetry were applied. Seismic and geoelectrical methods were employed as well as conventional geochemical and geotechnical methods and procedures.

The study is certainly not complete. This brief review of the results to date is presented, however, in the belief that they will demonstrate some of the methods by which such problems must be attacked.

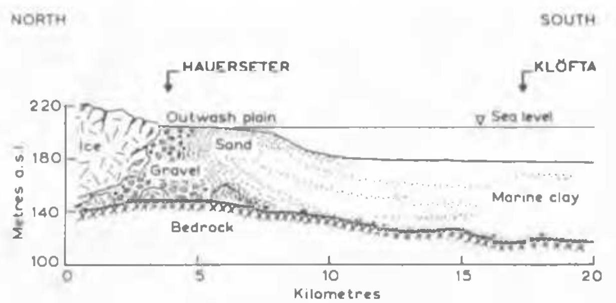

Fig. 1 Geological cross section illustrating deposition of the marine clay 9800 years ago.

QUARTERNARY GEOLOGY

In common with the rest of Norway the area of Romerike was heavily eroded by the ice during the glaciated periods. The bedrock is a granitic gneiss of Pre-Cambrian age with a tectonic structure in the NE to SW direction which has been accentuated by ice erosion. This has resulted in the formation of valleys and oblong knolls in the bedrock, and these can be seen clearly in the outcropping rock formations.

After the final glaciation the marine clays at Romerike were deposited in the sea in front of the retreating ice masses during deglaciation about 9800 years ago. The ice front stopped temporarily or even advanced slightly at Hauerseter just north of the research area, building up an outwash plain of sand and gravel (illustrated in Fig. 1). The finer particles were carried further south and sedimented as marine clays interspersed by a few nearly horizontal silt strata, which probably resulted from shorter periods of greater discharge of melting water. The marine limit in the area has been established at 205 m above present sea level by Holtedahl (1924). Due to the isostatic land

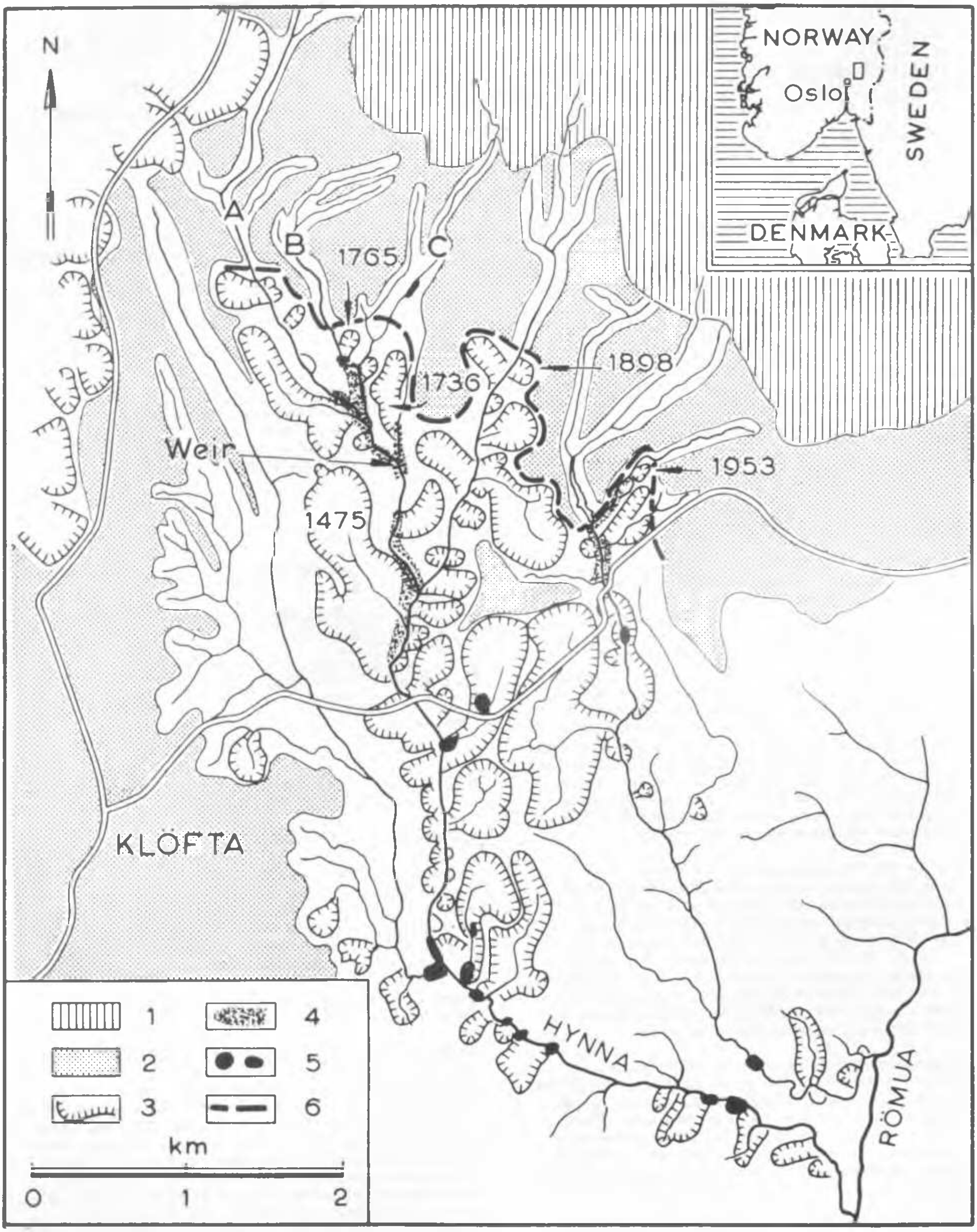

Fig. 2 Map showing the research area.
1. Bedrock area, 2. Old sea bottom plain, 3. Quick clay slide scars, 4. Redeposited quick clay slide masses, 5. Outcropping bedrock, 6. "Front of aggression".

Fig. 3 Example on stream erosion in old sea bottom plain from an area next to the 1967 quick clay slide in Trögstad.

uplift following the withdrawal of the glaciers (Kenney, 1964) the marine clay deposits which now have a surface elevation of 170-185 metres above sea level came above the water level about 9500 years ago.

At the present time the clay deposits have consolidated under their own weight, and, in addition, the upper layers have been changed to a more or less stiff crust by drying and weathering. If a boring is made in the old sea bottom plain, first a 5-7 m thick crust of stiff fissured clay is encountered. Below this clay layer the normally consolidated soft marine clay is found, extending to depths which can exceed 70 m. The clays which were laid down in marine water with a salt content of 35 g/l are mainly composed of hydrous mica, chlorite, quartz and feldspar. A description of their geotechnical properties has been given by Bjerrum (1954a). At some locations where leaching has occurred and the salt concentration in the pore water has been reduced, the clays have been transformed into quick clays, which are characterised by the peculiar property that, when remoulded, their consistency changes to that of a liquid.

Since the marine clay area rose above sea water level about 9500 years ago, at which time it appeared as a wide, nearly horizontal, plain, it has been subjected to a dramatic period of denudation leading to the highly dissected landscape found today, as illustrated in Fig. 3. In the development of this landscape the following processes have been of governing importance: consolidation, weathering, seepage and leaching, frost action, erosion, slope failures and slides, redeposition of slide masses, vegetation, human activity. The occurrence of disastrous quick clay slides, the scars of which can be seen in great number within the area, depended entirely on the relative rate at which some or all of these processes were working. An engineering-geological evaluation of the problem of quick clay slides presumes therefore a thorough understanding of these processes and the factors governing their rate.

QUICK CLAY SLIDES

Detailed descriptions in English of typical quick clay slides have been published by G. Holmsen (1929), G. Holmsen (1946), P. Holmsen (1953), Bjerrum (1955b), Kenney (1967b) and Drury (1968). The slide always starts with a relatively shallow initial slide in the slope towards the stream valley, frequently caused by brook erosion, and occurring in clay which is generally weathered and not quick. From this initial slip the slide develops backwards into the quick clay, towards the rear slope, simultaneously widening in all directions, see Fig. 4. The most characteristic feature of the slide is the change of consistency of the clay in the process of sliding. As the clay becomes involved in the slide movements, and therefore remoulded, it changes to a viscous liquid. Through the opening formed by the initial slide the clay slurry moves from the cavity and descends down the valley carrying with it flakes of the upper dry crust. The speed with which these slides occur can be illustrated by the Ullensaker slide of 1953, during which about 200000 m^3 of liquid clay flowed away from the slide within a few minutes. The number and magnitude of the quick clay slides occurring in the marine areas can be illustrated by the fact that an estimated 50 mill. cu. metres of quick clay have been removed by the slides which have occurred within 25 km^2 of the research area.

To guide the study of the factors and processes responsible for the quick clay slides the following analysis of the conditions for their occurrence has been made:

1. The first requirement is obviously the existence of a body of quick clay near and active erosion feature. As the quick clays are formed by leaching with fresh water of marine clays, the occurrence of quick clay deposits is governed by the seepage conditions.

2. A second prerequisite is active erosion of valleys by streams, so that the stability of the

Fig. 4 The Ullensaker quick clay slide, 1953.

Fig. 5 Terrace of redeposited slide mass from the 1765 quick clay slide.

valley slopes is being reduced and initial slides are being precipitated. As mentioned above, it is these slides which trigger off the flow slides.

3. A third requirement, generally satisfied by the normal pattern of stream erosion, is a topography which allows the liquid clay to flow away from the slide.

4. It is a further condition that the rate at which the clay behind the valley slopes is being changed to a stiff crust by weathering should be small compared with the rate at which the valleys are cut down by erosion. Should the rate of weathering be faster than the rate of erosion, the slope failures would not cut deep enough to expose a soft unweathered clay and thus to start a quick clay slide.

The relative importance of the factors and processes governing the occurrence of the quick clay slides will clearly vary from place to place. It is the purpose of the study of the research area presented below to obtain a picture of this complicated problem.

GEOMORPHOLOGY

The area of study is mainly used for farming, the flat plateau being cultivated for crop and the slopes of the valley being used as pasture. Man-made work is very limited.

Based on a detailed field study of the research area the various features of the landscape have been classified, mapped and described. In Fig. 2 the various types of landforms are shown, and the 5 main categories of land features will be described below.

Bedrock area and rock exposures. Along the northeast boundary of the research area the landscape is characterised by the outcrop of bedrock, rising up to 80 m above the plain of the sea bottom. This area appears today as an undulating forest-covered rock area dominated by hills reaching heights of up to 265 m above sea level. Within the research area the most important bedrock outcrops occur in the southern part where the brooks have eroded their valleys to the greatest depth, see Fig. 2. In the stream beds these rock outcrops form thresholds resulting in small waterfalls. From the point of view of the development of the streams these outcrops are important as they form fixed points governing the depth of erosion in the upstream part of the valley. A few rock exposures have also been observed in the scars of some of the old quick clay slides.

Old sea bottom plain. The oldest and still easily recognized feature of the sedimentary deposits in the landscape of the research area is the remains of the wide nearly horizontal plain which represents the old fjord bottom. Bordering the bedrock area in the northern part of the research area where development of the stream valleys is still in progress, the horizontal plain dominates the landscape. The same is the case in the western part of the area where the village Klöfta is located.

In the central part of the area where the development of the stream valley system has reached a further stage of maturity and quick clay slides have intensified the denudation, the remains of the old plain are found as isolated areas in between the valleys and the slide scars. The old plain is today mainly cultivated farmland and nearly all farm buildings and houses are built on this plain.

Stream valleys. The most dominating feature in the landscape is the system of deep valleys cut down into the old sea bottom plain as a result of erosion by the streams and brooks draining the area. Within the area studied the stream valleys tend to run in the north-south direction, see Fig. 2, possibly following a system of old buried rock valleys. The young valleys in the northern part of the area show depths of 10-15 m. They have a distinct "V-shaped" form with sharp angles of intersection with the horizontal plain into which they are cut down; see for illustration Fig. 3. The slope angle varies between 20 and 25°. The more mature valleys in the central and southern part of the area may be up to 25 m deep and they have a more rounded shape, and their topography is frequently complicated by stream meandering and slide activity.

Scars of quick clay slides. One of the main results of the detailed mapping and field study of the area was the discovery of a large number of scars from hitherto unknown small and large quick clay slides. The characteristic features of these scars are the wide bowl-shaped depression and the nearly horizontal bottom having a very slight inclination towards the brook. Most of them showed the typical bottle-neck opening towards the stream valley. The remains of the oldest quick clay slides appear today as concave wide hanging valleys demonstrating that they occurred at a time where the stream valleys had not reached their present depths. Fig. 4 shows the 1953 slide. Behind this slide, between its upper left corner and the small barn, the indistinct scar of an old, still larger quick clay slide can be distinguished.

In Fig. 2 all the identified scars of quick clay slides have been plotted. Where the date of the slide is known it is shown, but most of them are undated. In the southern and central parts of the area the stream valleys are bordered by a closely spaced system of scars of quick clay slides, clearly demonstrating how the development of the stream valleys in this area is accompanied by the systematic occurrence of quick clay slides. In the northern part of the area where the brooks are still in the process of cutting their valleys into the old sea bottom plain, no quick clay slides have occurred. It has thus been possible to draw a border line which in Fig. 2 has been called the "front of aggression" and which separates the northern intact area from the southern area of quick clay slides. The name has been chosen to draw attention to the significant fact that all the youngest slides occurred just south of this front.

Terraces of redeposited slide masses. In the main stream valleys of the upper central part of the area a number of terraces are found, which have been identified and mapped on Fig. 2 as redeposited slide masses. Such a terrace deposit is shown in Fig. 5. These slide masses originated from quick clay slides which have occurred higher up in the valley.

Each quick clay slide was accompanied by the flow of remoulded slide masses descending like a liquid down the stream valleys until they finally met an obstruction and stopped, forming a huge lake of liquid clay. With time these redeposited slide masses consolidated to a relatively stiff clay. It is this clay which is found as terraces in the valleys below the younger quick clay slides, see Fig. 5. There were no problems involved in identifying the redeposited slide masses from the 1953 slide, see Fig. 4, and the terraces in the main stream valley could be identified as belonging to the 1765, 1736, and possibly the 1475 slides, see Fig. 7b.

In spite of their limited extent these redeposited slide masses have payed an important role in the rate of downcutting of the stream valleys. The filling up of the valley with slide masses obviously means a delay of upstream erosion until the stream has cut a new channel through the slide masses. Because the redeposited slide masses are more resistant against erosion than the virgin sediment, this delay can be considerable. It is thus a matter of fact that the main stream in the central part of the area is still flowing on redeposited slide masses originating from the slides which occurred in the eighteenth century.

LEACHING

It is well established (Rosenqvist, 1946; Bjerrum and Rosenqvist, 1957) that the Norwegian quick clays have been formed by leaching of the marine clays during the period that they have been above sea water level. The available evidence indicates that in this process the effect of the downward percolation of surface water is negligible and that the formation of quick clays in almost all cases is due to leaching caused by an upward flow of fresh groundwater. The artesian condition creating the upward flow originates in general in the cracks and fissures in the bedrock which communicate with a "free groundwater" in fissures at higher elevations. The consequence is that where the depth to rock is small the rate of flow and the chances of encountering quick clay will be greatest.

During the leaching of a marine clay the reduction in salt concentration in the pore water from the original 35 g/l to about 5-10 g/l will have little effect on the sensitivity, which is of course a measure of the degree of instability of the clay structure. It is only when the concentration drops below 5-10 g/l that the increase in sensitivity occurs. In the extremely quick clays the salt concentration is generally lower than 1 g/l. This non-linearity in the leaching process explains why quick clays in general are found as isolated lenses or layers surrounded by marine clay with a normal low sensitivity; in spite of a reduced salt concentration, the marine clay still contains more than the critical 5-10 g/l.

Evidence of this process within the research area is given by the correlation which can be established between the occurrence of quick clay slides and the depth to rock. As seen from Fig. 1, most of the quick clay slides are concentrated within a zone running North-South, through the central part of the area. Available borings, rock outcrops and seismic profiling indicate that within the zone of closely spaced quick clay slides the depths to bedrock below the original horizontal plain were 15-35 m, compared with depths of more than 70 m in the area immediately west of this zone where few scars of quick clay slides have been found.

The results of a detailed study of the 1953 slide in Ullensaker (Bjerrum, 1954b; Kenney, 1967a) also confirm the postulated correlation between depth to rock and occurrence of quick clays. In the cross section in Fig. 6 are plotted the results of 20 borings which demonstrate clearly that the zone of quick clay, and the slide, occurred exactly where the depths to rock were smallest. At both sides of the buried "rock hill" the clay still has a low sensitivity, proving that the leaching has not proceeded as far as above the hill top where the gradient is highest.

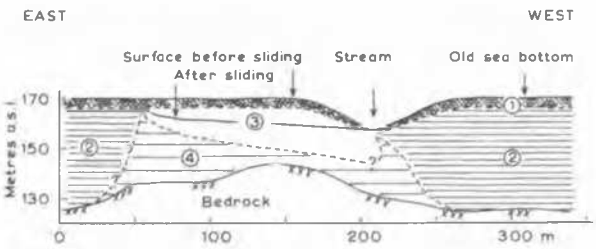

Fig. 6 Schematic cross section through the Ullensaker quick clay slide, 1953.
1. Weathered crust
2. Marine clay
3. Marine clay, leached until quick
4. Marine clay, leached until quick, then weathered.

WEATHERING

As mentioned above, where exposed, the upper 4-6 m of the marine blue soft clay have by drying, freezing, leaching and oxidation been changed to a crust of brownish fissured stiff clay. The geotechnical properties of this crust have been discussed by Bjerrum (1954b), Moum and Rosenqvist (1957) and DiBiagio and Bjerrum (1957).

As a result of surface water penetrating through the system of fissures the upper crust has been leached and the salt concentration in the pore water is low. The crust is, however, not quick because the weathering processes accompanying the leaching with oxigen-rich water lead to an increase in strength and plasticity of the clay which more than offset the simultaneously occurring effect of the salt leaching. By weathering is here understood a disintegration of the clay minerals occurring as a result of the low pH and the high oxidation capacity of the surface water which has replaced the pore water. This disintegration of the clay particles leads to a release of cations which partly are removed by leaching, but which partly also are absorbed at the surface of the clay particles, thereby increasing the plasticity of the clay, or precipitate as nearly in soluble compounds acting as cementing agents (Rosenqvist, 1955; Löken, 1967; Moum et al, 1968). Recent research indicates that iron and aluminium ions dominate in this process (Moum, 1968)

The rate at which the weathering process proceeds at depths depends on the rate at which oxigen-rich surface water will penetrate and this again depends on such factors as depth of fissures and roots of vegetation. As far as these factors can be evaluated it is believed that the rate of weathering is very high immediately after the exposure of a clay surface - as can be observed on the valley slopes - but is extremely small when the thickness of the crust has reached the depth at which chemical influence is negligible.

Whereas the weathering proceeding from the surface is a well studied phenomenon, it has only recently been appreciated that a similar chemical phenomenon takes place from the bottom of the sediments accompanying the upward leaching and this causes a reduction in sensitivity. For instance, under the quick clay formation in which the 1953 slide at Ullensaker took place, there was found a clay of low sensitivity which showed a low concentration of salt in the pore water. A detailed chemical analysis of this clay is not available, but it is believed that its low sensitivity can be explained by the chemical analysis of a similar clay from Drammen. In Drammen the chemical analysis showed a change in composition of the pore water. The concentration of Magnesium ions was as high as 150 mg/l compared with 20 mg/l in the corresponding quick clay. This increase, which probably results from a disintegration of the chlorite minerals, is accompanied by an increase in liquid limit and a decrease in sensitivity. This improvement in properties of the clay thus results from the exchange of absorbed cations rather than the cementing effect dominating in the surface weathering process.

STREAM EROSION

The only agents of erosion of real concern are the streams draining the research area. It should immediately be mentioned that these streams are small. The average discharge of the stream where a measuring weir was established, see Fig. 2, is about 180 litres per second and in the fall of 1968 a peak of about 1500 litres per second was observed, and in most of the dry period the discharge was less than 5 litres per second. That this is, however, a significant discharge is indicated by the amount of material transported out of the area per year, which has been estimated on the basis of observation of sediment concentration at the measuring weir. The loss of material from the 6 km^2 catchment area is estimated to be 500-1000 m^3 per year and by far the greatest transport occurs during the peak discharge. This material consists not only of soil removed by the active erosion of the stream beds, but also soil carried down to the streams by sheet wash, frost action, etc.

In order to describe the erosion occurring it is useful to follow the stream Hynna from the outlet in the main river, Rømua, to the watershed at the northern part of the area. In this description it is possible to distinguish between three significantly different reaches:

(1) The first 6 km, the zero point being the outlet in the River Rømua, is the lower reach, see Fig. 7 a. This stretch of the stream years ago reached a stable elevation governed by numerous rock outcrops. In between the rock outcrops the stream flows in virgin marine clay with very small gradients, 1 : 300 to 1 : 500. Of the total head loss of 27 m, 15 m are lost by water falling over rock outcrops. Whereas the further downcutting of the valley has stopped, at sharp bends in the stream there is undercutting and minor slope failures. The slope in this reach have, however, in general come into equilibrium and this reach is considered to have reached maturity, so that the danger of quick clay slides is small.

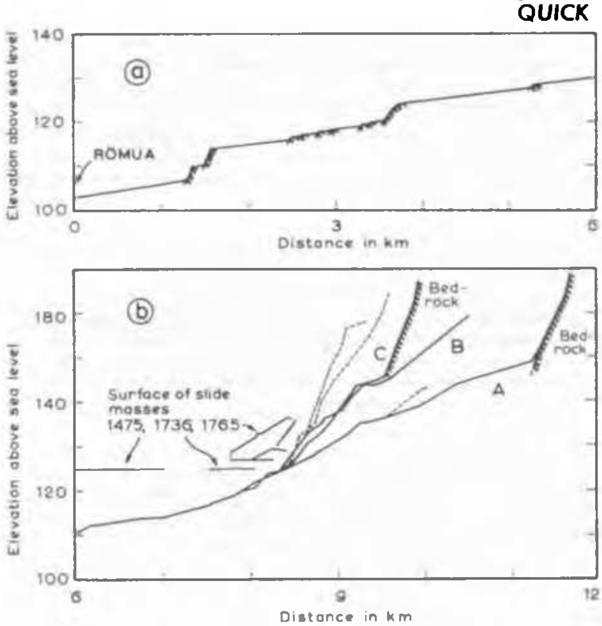

Fig. 7 Longitudinal profiles of the main stream Hynna, (a) "lower reach", (b) "intermediate reach" and "upper reach".

(2) The intermediate reach starts approximately at km 6.0. The longitudinal section through the streams and their tributaries north of this point is shown in Fig. 7b. At km 7.7 the tributary stream B leaves the main stream A. The intermediate reach continues in stream A up to km 9.3 and in stream B to km 8.6.

The intermediate reach of the stream is defined as the portion where streams are flowing almost entirely on redeposited slide material. At an earlier stage the stream beds were lower than they are today, and generally speaking the streams are in the process of working themselves back to their old levels.

The thickness of the redeposited slide masses upon which the streams are flowing varies over the length of the reach depending on where the slide masses from the various quick clay slides came to rest. At locations where the slide masses were redeposited the new conditions led to a reduction in the erosion when the stream passed over the slide masses and an increase in erosion where the stream cut through the downstream part of the slide masses and continued in the old stream bed.

For instance in Fig. 7b at km 6.0 there is a sharp drop in the stream bed. At this location the stream flows over the downstream end of redeposited slide masses originating from a slide which occurred about 20 years ago. Upstream of this drop, where it flows through 2 km of redeposited clay, the gradient of the stream has been reduced from the original 1 : 200 to 1 : 400.

Upstream of km 7.5 the stream has almost eroded its bed through the slide masses originating from the slide of 1736, the terraces of which are clearly observed at both sides of the brook at elevation 145. The rate at which the stream cut itself through these masses is of the order of 4 m per century. Further upstream, stream A and stream B both flow through slide masses which originated from the 1765 slide. As long as the streams are eroding in slide masses, the slope failures which occur are limited to slips in redeposited clays, and the danger of quick clay slides is eliminated. From the standpoint of potential quick clay slides, these areas can be thought of as temporarily neutralized. This applies to almost the whole of the intermediate reach, the only exception being at a few locations where the stream has cut almost through the edge of the slide masses and active erosion may occur in the virgin clay. At a later date, when the stream has cut through the slide masses, it is not unlikely that active erosion may be resumed in the upstream end of the reach, whereas it is most likely that equilibrium had already been reached in the downstream end prior to the deposition of the slide masses.

(3) The upper reach of the streams includes the reaches upstream of km 9.3 for stream A and 8.6 for stream B. This reach is characterised by the fact that the stream beds are in virgin clay and active erosion is occurring.

The active erosion is partly a vertical downcutting of the stream bed, but in addition "horizontal erosion" is occurring at numerous locations, for instance at bends, or where the stream is obstructed by tree roots, etc. In addition to the stream erosion there is a considerable amount of clay brought down to the stream by such agents as frost, sheet wash, slope failure, cattle, and human activity. The contributing processes are very much more important in the upper than in the lower reaches.

The "front of aggression" was defined above as the upstream boundary of the occurrence of quick clay slides. The redeposited material resulting from such slides will, by definition, introduce the stream regime referred to as the intermediate reach. Hence, the front of aggression coincides very nearly with the boundary between the intermediate and upper reaches.

At, or just above the front of aggression, at the lower end of the upper reach, the stream will have cut most deeply into the virgin clay, and hence the probability of the slopes coming into close proximity to a zone of quick clay is highest. It is, therefore, logical to expect quick clay slides to be concentrated at these points in the tributary streams.

The front of aggression will not advance at a uniform rate up the stream. After each slide, the redeposited slide masses from a step in the profile, and the rate of erosion in the upper reach will be reduced. However, when the slide masses have been cut through, there will begin a rather rapid and intense period of erosion on the virgin clay of the upper reach, concentrated initially at the front of aggression. This rapid erosion will probably occur at a much faster rate than the counter process of weathering, thus intensifying the possibility of quick clay slides. This non-uniform rate of active erosion of the virgin clay means that the occurrence of slides is inclined to be periodic.

In the above description no distinction has been made between streams A, B and C. In the upper reach there is, however, a distinct difference between the streams. Whereas streams A and B are fed mainly by surface run-off and normal drainage of the slopes, stream C has cut its bed so close to the bedrock that an artesian set of ground water conditions prevails. Occasionally the stream flows through mud volcanos, and the softening effect of the upward artesian flow has also greatly influenced the stability of the valley slopes.

To obtain a complete picture of the stream erosion in the various reaches it is necessary to appreciate that the discharge of the stream increases considerably from the upper to the lower reaches. The ability of a stream to cause erosion depends not only on its gradient, but also on its discharge which again depends on its catchment area. In order to obtain an impression of the relative importance of these two factors, data was obtained for a number of lengths of stream, and in Fig. 8 they are plotted in a diagram showing gradient as a function of catchment area. Each length of stream was designated as either aggressive, at grade or slack, depending on whether erosion is occurring, whether the stream bed is just equilibrium, or whether the stream has reached ultimate maturity.

Based on this classification a curve can be drawn through the points in Fig. 8, separating the lengths with active erosion from those which are in equilibrium or slack.

The relation between the equilibrium grade and catchment area shown in Fig. 8 can be used to predict how far erosion of a stream will proceed before equilibrium conditions are reached. As an example are shown in Fig. 9 longitudinal sections of streams A and B covering the intermediate grades using the northern-most rock outcrop at km 5.3 in Fig. 7a as a basic fix point. From this figure it can be learned that in the upper reach of stream B a further vertical erosion of the order of 5 m can be expected and that very aggressive erosion is occurring in a zone at km 8.6. In brook A aggressive erosion is at present occurring at km 8.0 in the slide masses of the 1765 slide and at km 9.2 in the remains of an undated quick clay slide. Just upstream of the boundary between the intermediate and the upper reach of stream A a further downcutting of the order of 3 km can be expected when the front of aggressive erosion eventually reaches this point. Further erosion on stream A is, however, limited to the distance from km 9.2 to 10.0. North of km 10.0 the stream is already at equlibrium grade.

The above description of the various reaches concerns the main system of streams. These streams have, however, a number of small tributaries and for each of these tributaries a similar set of conditions will exist, as described for the main streams. The tributaries have each an upper reach where erosion is occurring, but as the catchment area of most of them is small, the rate of erosion is low. Ultimately, the tributaries will reach equilibrium with gradients corresponding to the catchment area, see Fig. 8. That the tributaries may cause erosion

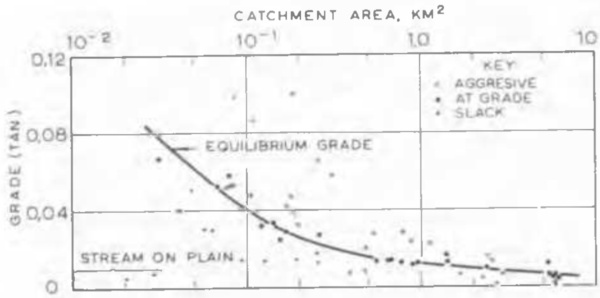

Fig. 8 Correlation between catchment area, stream gradient and erosion

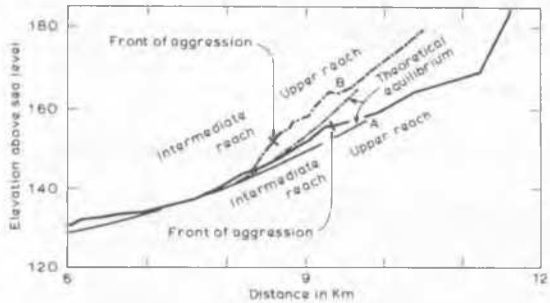

Fig. 9 Longitudinal profiles of streams A and B with theoretical equilibrium grades.

which can trigger off quick clay slides is illustrated by the 1953 slide.

SLOPE STABILITY

The field studies included a survey of the valley slopes in the intermediate and upper reaches of the streams (see below). All slides and failures and representative stable slopes, were mapped, described, and classified. A study of a number of stable slopes in virgin marine clay in the upper reach of stream A, showed that the slope came into equilibrium with a regular plane surface. Most of the stable slopes in this area appear to stand at an angle of 20-21°, independent of height. However, drainage conditions and difference in properties of the soil may cause deviation from this general set of conditions. The equilibrium shape and inclination of the slope indicate that the stability is governed by the properties of the upper weathered crust more than by those of the lower soft clay. The upper crust possesses, as mentioned, a system of fissures promoting seepage parallel to the surface, which is the only set of pore-pressure conditions which is consistent with inclinations as steep as 20°. The fissures also explain why the stiff clay in spite of a high strength behaves like a cohesionless material. To surface parallel seepage and an inclination of the slopes of 20° there corresponds an angle of shearing resistance of about 38°.

The following types of slope instability were regonized.

(1) Deep rotational shear failures

These are failures extending up into the valley slopes. They occur only where there is active stream erosion. The stream channel is deep and undercutting of the toe is proceeding. This type of failure dominates in the intermediate reach where the streams are eroding redeposited slide masses. However, a number of these slides were caused by excavations in connection with construction of the local roads.

The largest deep rotational slide which was found occurred in the upper reach of stream C in connection with an artesian ground-water condition. At this location the bottom of the valley was flat and soft, and the artesian condition manifested itself by springs where soft mud was brought to the surface.

(2) Small bank or slope failures

By far the greatest number of failures were rather small bank failures caused by meandering or downcutting of the stream. The depths of these failures are about 1-2 m only. In the same category belong the shallow flake-type surface failures which are usually caused by frost action, but may also be a result of surface seepage.

(3) Surface erosion

In addition to the above described slope failures a very considerable contribution to the denudation is the gradual downhill transport of soil by surface erosion. Among the various types of surface erosion the sheet wash by precipitation accounts for the greatest transport, most of all in cultivated areas. The erosion by sheet wash is very much accelerated by cattle breaking up the grass cover and remoulding the upper clay.

Of less imnortance is the downhill creep caused by frost action. An interesting type of surface erosion by sheet flow is occurring in the valley slopes of the upper reach where new tributaries are in development. Where this occurs, a depression is observed in the upper part of the slope and a bulge near the toe, the minimum width being in the lower half.

CONCLUSIONS

The investigations of the past 15 years into the properties of marine clays and the detailed studies of a number of quick clay slides have provided a basic knowledge of the various factors governing the occurence of quick clay slides. This knowledge has now been utilised in a regional engineering geological study of a marine clay area. The initial purpose of this study has been to describe, classify, and map all factors and processes of importance for the occurence of quick clay slides.

The conclusions of greatest interest are obviously those which have a bearing on the possible prevention of the disastrous quick clay slides endangering life and property in the 40000 km^2 marine clay area in Norway. It is still too early to present final results of the present study. However, a few important findings may be mentioned.

The study has provided a picture of how a marine clay area gradually is eroded down by streams, slope failures, quick clay slides, etc. This picture seems to be consistent, both with regard to what has happened and what is at present happening in the research area, and it can also be of help in the prediction of what is likely to happen in future.

The most significant result of this study is the interaction between the rate of erosion and the occurrence of quick clay slides. Each time a quick clay slide occurs the liquid slide masses flowing out of the slide scar will be redeposited further down the valley. These redeposited slide masses will form a threshold in the stream which will delay temporarily erosion upstream of the slide masses. The consequence of this interaction is that the quick clay slides are occurring along a front of aggression advancing stepwise in an upstream direction.

The danger of quick clay slides is thus dependent on the rate of erosion occurring in the virgin clay next to the front of aggression. The danger will, however, depend on whether the rate of downcutting of the stream exceeds the rate at which the soft marine clay in the valley slopes is transferred to a stiff clay by weathering. If the rate of weathering exceeds the rate of erosion, the slides accompnaying the erosion will be small and shallow and the risk of the slides exposing soft sensitive clay is therefore small.

Another result of the study is the determination of the equilibrium gradients for the streams from which it is possible to predict future erosion. Applied on one of the main drainage streams it is predicted that the in the upper reach north of the "front of aggression" the stream will in future cut itself a further 5 m into the clay. It is obvious that an erosion of this order of magnitude will cause numerous slope failures of which one or several may release quick clay slides. There is thus every reason to believe that the number of quick clay slides which will occur north of the line of aggression in the centuries to come will be as large as those which have already occurred south of the line.

The study has also shown that it is not unlikely that the danger of future quick clay slides triggered off by further erosion can be reduced at reasonable cost. The discharge of the streams causing the erosion is small. The possibilities of constructing small artificial thresholds in the streams, such as low cost weirs, to prevent further erosion look, therefore, rather promising. A study of how this can be done and the full-scale testing of such structures in the research area will be the next stage in this study.

Finally, the geotechnical studies carried out have demonstrated that the leaching causing the clays to be quick ultimately will cause a weathering of the quick clays, proceeding upwards from the bedrock. This weathering will gradually reduce the sensitivity and increase the shear strength of the clay. Therefore, if it should prove possible to prevent future erosion and thus to "freeze" the topography, it is believed that with time the stability of the slopes will increase and thus the danger of future quick clay slides will be practically eliminated.

LIST OF REFERENCES

Bjerrum, L. (1954) a.
Geotechnical properties of Norwegian marine clays.
Géotechnique, Vol. 4, No. 2, p. 49-69.
Also published as Norwegian Geotechnical Institute. Publ., 4.

Bjerrum, L. (1954) b.
Stability of natural slopes in quick clay.
European Conference on Stability of Earth Slopes. Stockholm 1954. Proceedings, Vol. 2, p. 16-40.
Also published in Géotechnique, Vol. 5, No. 1, 1955, p. 101-119, and in Norwegian Geotechnical Institute. Publ., 10.

Bjerrum, L. and I. Th. Rosenqvist (1957)
Norske leirskred og deres geoteknikk.
Naturen, Vol. 81, No. 2, p. 108-121.
Also published in Norwegian Geotechnical Institute. Publ., 15.

DiBiagio, E. and L. Bjerrum (1957)
Earth pressure measurements in a trench excavated in stiff marine clay.
International Conference on Soil Mechanics and Foundation Engineering, 4. London 1957. Proceedings, Vol. 2, p. 190-202.
Also published in Norwegian Geotechnical Institute. Publ., 26.

Drury, P. (1968)
The Hekseberg landslide, March 1967; an illustration of the Romerike clay landslide problem.
Norwegian Geotechnical Institute. Publ., 75, p. 27-31.

Holmsen, G. (1929)
Lerfaldene ved Kokstad, Gretnes og Braa.
Oslo. 45 p.
Norges geologiske undersøkelse, No. 132.

Holmsen, G. (1946).
Leirfalltyper.
Statens vegvesen. Veglaboratoriet. Meddelelse, 4, p. 1-3.

Holmsen, P. (1953)
Landslips in Norwegian quick-clays.
Géotechnique, Vol. 3, No. 5, p. 187-194.
Also published in Norwegian Geotechnical Institute. Publ., 2.

Holtedahl, O. (1924)
Studier over isrand-terrassene syd for de store østlandske sjøer.
Kristiania, (Dybwad). 110 p.
Norske vitenskapsakademi i Oslo. Skrifter. Mat.-naturvitenskapelig klasse, 1924, No. 14.

Kenney, T.C. (1964)
Sea-level movements and the geologic histories of the post-glacial marine soils at Boston, Nicolet, Ottawa and Oslo.
Géotechnique, Vol. 14, No. 3, p. 203-230.

Kenney, T.C. (1967) a.
Shearing resistance of natural quick clays. Ph.D. Thesis submitted to University of London.
Oslo, Norwegian Geotechnical Institute. 138 p.

Kenney, T.C. (1967) b.
Slide behaviour and shear resistance of a quick clay determined from a study of the landslide at Selnes, Norway.
Geotechnical Conference Oslo 1967 on Shear Strength Properties of Natural Soils and Rocks. Proceedings, Vol. 1, p. 57-64.

Löken, T. (1967)
Recent research at Norwegian Geotechnical Institute concerning the influence of chemical additions on quick clay. Lecture presented at the Swedish Society for Clay Research. Meeting. Oslo 1967.
To be printed in Geologiska Föreningen i Stockholm. Förhandlingar.

Moum, J. and I. Th. Rosenqvist (1957)
On the weathering of young marine clay.
International Conference on Soil Mechanics and Foundation Engineering, 4. London 1957. Proceedings, Vol. 1, p. 77-79.
Also published in Norwegian Geotechnical Institute. Publ., 26.

Moum, J. (1968)
Chemical environment compared with mechanical behaviour.
Geotechnical Conference Oslo 1967 on Shear Strength Properties of Natural Soils and Rocks. Proceedings Vol. 2, p. 125-126.

Moum, J., O.I. Sopp [and] T. Löken (1968)
Stabilization of undisturbed quick clay by salt wells.
Väg- och vattenbyggaren, Vol. 14, No. 8, p. 23-29.
Also published in Norwegian Geotechnical Institute. Publ., 81.

Rosenqvist, I. Th. (1946)
Om leirers kvikkaktighet.
Statens vegvesen. Veglaboratoriet. Meddelelse, 4, p. 5-12.

Rosenqvist, I. Th. (1955)
Investigations in the clay-electrolyte-water system.
Oslo. 125 p.
Norwegian Geotechnical Institute, Publ., 9.