STATENS GEOTEKNISKA INSTITUT

SWEDISH GEOTECHNICAL INSTITUTE

No. 55

SÄRTRYCK OCH PRELIMINÄRA RAPPORTER

REPRINTS AND PRELIMINARY REPORTS

Supplement to the "Proceedings" and "Meddelanden" of the Institute

New Lines in Quick Clay Research

Rolf Söderblom

1. A New Approach to the Classification of Quick Clays
2. Application of Remote Sensing in the Quick Clay Research
3. Aspects on Some Problems of Geotechnical Chemistry —Part III

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STOCKHOLM 1974

of the Jordbro landslide
to K. Hellman-Lutti)

PREFACE

Instable slope conditions have resulted in many severe landslides, e.g. in the Göta River Valley in the southwestern Sweden. The existence of quick clays has undoubtedly in many cases been of importance for the propagation of these slides. Quick clays and their importance in connection with slides have been treated in e.g. SGI Proceedings No.22 in 1969: "Salt in Swedish Clays and its Importance for Quick Clay Formation". Another report on quick clay to be published in the Proceedings series is under preparation and deals with the importance of organic matter to quick clay formation, with special reference to dispersing agents, also with Mr Rolf Söderblom as the Author.

In the present report, which consists of three parts, an attempt has been made to systematize the quick clay studies with respect to classification and degree of potential danger of the appearance of the quick clay and to the localization of such clays.

The first part deals with the conception quick clay and the work required to break down the structure of these soils. A proposal for the classification of quick clays is presented and the so called rapidity number is introduced. In the second part, a remote sensing method for localizing quick clays is described. The third part, which is a reprint of a paper published in 1970, is, in principle, a summary of the investigations reported in the above-mentioned SGI Proceedings No. 22 with some additional results.

The work was carried out at the Research and Consulting Department A of the Institute in co-operation with Professor A. Ölander of the Physico-Chemical Department of the University of Stockholm. It has been supported by grants from the Swedish Board of Technical Development.

The report has been edited by Mr N. Flodin and Mr O. Holmquist.

Stockholm, March 1974
SWEDISH GEOTECHNICAL INSTITUTE

A NEW APPROACH TO THE CLASSIFICATION OF QUICK CLAYS

Rolf Söderblom

Summary

Highly sensitive clays with $S_t > 50$, according to common definitions called quick clays, show very different behaviour when influenced by vibration, shocks and other external forces. In extreme cases quick clay samples are impossible to handle and are liquefied when subjected to only small deformations. In other cases a large amount of working is needed to break down the quick clay structure. This means that quick clays can be broken down more or less rapidly. The first type of clay has therefore in this report been called "rapid quick clay" and the other "slow quick clay".

In order to obtain a measure of the rapidity and prepare a rough classification of the quick clays a testing procedure, based on Casagrande´s liquid limit device, was tried and a rough classification scale formed. The scale ranges from a rapidity number of 1 for the most stable clay to a rapidity number of 10 for the most fragile.

When comparing the rapidity scale with old descriptions of quick clays, it is found that quick clay in its original sense corresponds to a rapidity number of at least 8. Tentatively, a new definition of quick clay is proposed by the Author, viz. a clay with a sensitivity of at least 50 and with a rapidity number of at least 8.

Field studies from three places in western Sweden indicate that highly sensitive clays throughout the whole scale range exist. The importance of highly rapid quick clays and the potential risks in connection with their existence in mechanically unstable slopes is touched upon.

Introduction

In a previous paper (Söderblom, 1969) it was stated that there exist at least two main types of quick clay with quite different mechanical properties, though both have all the properties necessary to be qualified as a quick clay according to the definition which is common today.

The first main type is very sensitive to mechanical disturbance and requires only a small amount of working to be transformed into a liquid. If one takes a piece of this clay in one´s hand and shakes it just a little, its surface first becomes wet due to migrated water, then it looses its form and flows out as a liquid. In extreme cases clay samples of this type, if pressed out of a sampling cylinder, are impossible to handle.

The second main type of quick clay requires a great amount of remoulding to be mechanically broken down. Samples of such clays are not so sensible to handling and can be loaded considerably without being destroyed (Crawford, 1963). They are only little deformed if dropped from a moderate height. If intensively remoulded, clays of this type become as liquefied as quick clays of the first type.

Quick clays of the first type were by the present author called "rapid quick clays" because of the rapidity with which they liquefy when mechanically deformed, and those requiring a large amount of remoulding were termed "slow quick clays".

A third type of "quick clay", not earlier discussed in literature, as known to the Author, seems, however, to exist in Sweden. This clay has a moderate sensitivity when remoulded in an inert atmosphere, e.g. nitrogen. Probably atmospheric oxidation of some organic substances during the remoulding process (cf. Jerbo, 1967) in this case form dispersing organic substances which react with the clay materials, giving a low viscosity. These "quick clays", which are non-quick in situ and probably have nothing to do with real quick clays, are not further dealt with in this report (could possibly be called "pseudo-quick clays").

It is evident that the chemical processes forming these different types of quick clay are not the same, which must be kept in mind when treating the quick clay problem. In most of the existing literature the assumption is made that all quick clays are formed by only one type of natural process.

Scope of Problems

The rapid quick clays are, from a geotechnical point of view, the most interesting ones. Their strong tendency to be liquefied by moderate mechanical treatment makes them unsafe to slope stability. If quick clay of this type exists in a slope, a local slide of small extent may spread into a large one. Pile driving and dredging etc in slopes with rapid quick clays may be the initiating factor. Vibrations from heavy traffic on roads or railways in slopes may also cause a reduction in strength and result in a slide.

To obtain a preliminary understanding of these problems the following working program was set up:

1) Development of a method of studying the different types of quick clay with respect to the amount of remoulding required to break down the soil structure.

2) Modification of the definition of quick clay with respect to the varying reaction to remoulding.

3) Searching for quick clays in situ requiring different degrees of remoulding to break down the structure.

4) Studies of possible chemical processes transforming slow quick clays (low rapid quick clays) into rapid quick clays.

Remoulding Studies and Presentation of a Rapidity Scale

Direct measurements of the working required to break down a quick clay are made in USSR according to a lecture in Stockholm by the late Professor Rehbinder (1970). No details were given, however.

To begin with, however, it is not necessary to get an absolute value of the working required to break down the structure; a relative number would be sufficient. For this purpose one can form a scale of "rapidity numbers", for instance, ranging from slow quick clays with low rapidity numbers to rapid quick clays with high numbers.

An approximate classification of the quick clays into groups of different rapidity numbers can be made very simply by means of a common Casagrande liquid limit device (ASTM, 1964); the apparatus being standard equipment in most geotechnical laboratories.

In the studies by the present author specimens of undisturbed samples, (SWEDISH COMMITTEE ON PISTON SAMPLING, 1961) 40 mm in height and 50 mm in diameter, were placed in a Casagrande liquid limit device (Fig. 1) and were allowed to drop 10 mm 250 times. Visual examinations can suitably be made during the whole process. The procedure generally gives the result that the bottom part is first affected, then the other parts of the sample.

When testing very rapid quick clays, one can see that the edges of the specimen are very soon smoothed out and rounded, the clay being transformed into a liquid mass, while clays with low rapidity are almost unaffected even after 250 percussions. From the test observations of quick clays having different rapidities, a classification scale with ten rapidity numbers was suggested (Table 1).

As can be seen in the table, quick clay with $R_n = 8$ to 10 can easily be liquefied, while a quick clay sample with $R_n = 4$ (very common for the quick clays in the Göta River Valley) is only little affected at the bottom after 250 percussions. The working produced by means of the 250 percussions in the testing device for the latter type of clay is not sufficient to break the structure down completely. By intense further stirring of this clay type, however, the gel can be broken down into a liquid mass. By studying the course of the simple percussion test it is thus possible to make a rough estimation of the energy required for breaking up the binding forces between the clay particles.

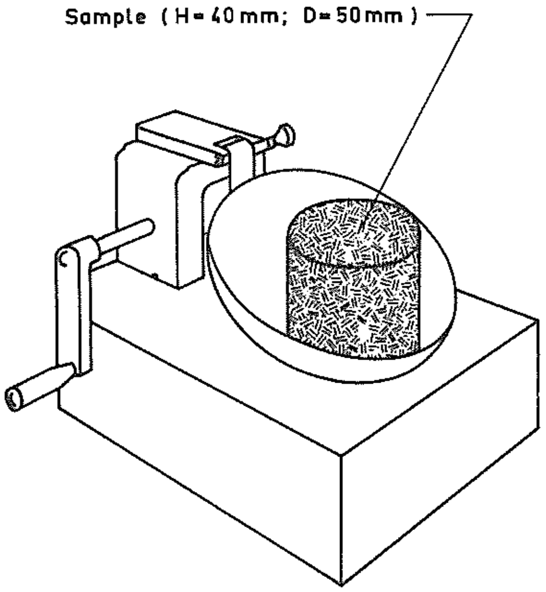

Fig. 1. Casagrande's liquid limit device used for determination of rapidity numbers

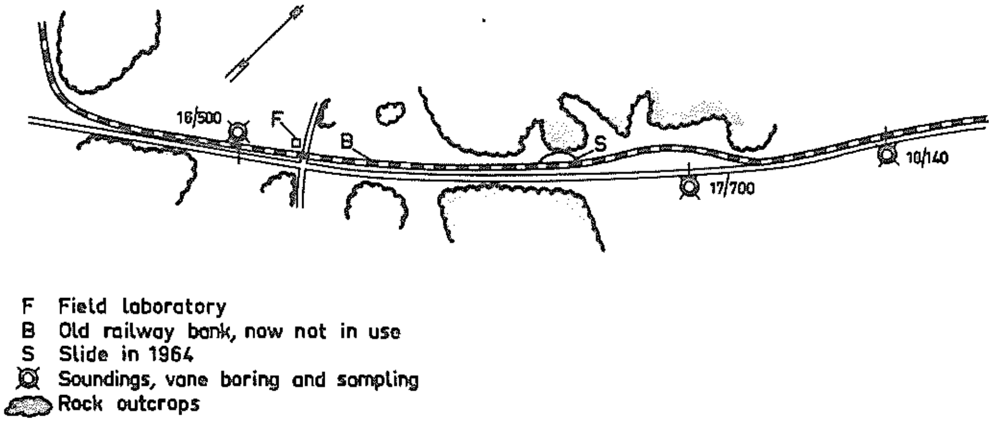

Fig. 2. Map showing the places investigated at Färgelanda along the Road 172

Table 1. Classification scale for determination of rapidity numbers

Rapidity number R_n	Degree of influence
1	Sample not visually affected
2	Hardly visually affected
3	About 1 mm of bottom part deformed to a gelatinous mass
4	About 5 mm of bottom part deformed, gelatinous mass formed. Upper part visually unchanged
5	About 5 mm of bottom part deformed, gelatinous mass and liquid mass formed. Upper part visually unchanged
6	About 10 mm of bottom part deformed, gelatinous mass and liquid formed. Upper part visually unchanged
7	Bottom part highly deformed, liquid mass formed. Upper part visually unchanged
8	Whole sample begins to deform, liquid mass formed. Sharp edges and irregularities disappear
9	Whole sample highly deformed, liquid mass forms and begins to flow out from the vessel
10	Whole sample transformed into a liquid mass

Common Definitions of Quick Clays

Norwegian quick clay was early characterized by Reusch (1901) as a "clay which has the property of being comparatively stiff when it lies in its original bed, but becomes fluid when it is set in motion. For instance, if one carefully cuts a small cube of "quick" clay and places it in the open hand and shakes it a little, the cube becomes apparently more and more damp, and looses its form." Similar characteristics of quick clay can also be found in old Swedish literature.

The quick clay described in old literature was taken from fresh slide scars. From the descriptions of old slides and from several more recent reports it may be assumed that mostly "rapid" materials were concerned.

When geotechnical methods for measuring strength properties were developed, one tried to find methods giving a basis for a classification of the quickness of the clays (cf. Holmsen, 1946). It became a practice that clays with a sensitivity (S_t) exceeding a certain value (usually 50) should be regarded as quick. A quick clay was thus defined as a clay with a H_3/H_1 ratio larger than 50. (H_3 and H_1 are so called "relative strength numbers" obtained by the fall-cone test introduced by the Swedish Geotechnical Commission 1914 - 1922, cf. Söderblom, 1969).

This simple classification of a quick clay as a clay with high sensitivity implies that also high-sensitivity materials requiring a great amount of remoulding to be broken down are classified as quick clays. As already mentioned, the slow quick clays are rather stable in the natural state for moderate shear deformation and show other properties than those attributed to quick clays in the original sense (Reusch, 1901), i.e. rapid quick clays.

The chemical processes producing the above two main types of clays must be of different kinds. Up to now this has not been taken into consideration. Papers can be found treating what in this article is called slow quick clay (cf. Crawford, 1963 and Talme et al., 1966). The chemical formation processes are treated by the authors as if there is only one type of quick clay.

Some authors have, however, considered that the sensitivity ratio was not sufficient as a definition of a quick clay. Odenstad (1951) stated that quick clay is defined "as a clay in which the H-ratio H_3/H_1 is greater than 50, while H_1 is at the same time less than 1". The definition used by the Geotechnical Department of the Swedish State Railways includes in practice an H_1-value < 0.33 besides the H-quotient > 50.

A recent (1973), not finally settled, definition of quick clay is suggested by the Laboratory Committee of the Swedish Geotechnical Society as $\tau_f/\tau_r > 30$ and $\tau_r < 0.4$ kPa ($H_1 < 2$), where τ_r is the remoulded shear strength.

In Norway the preliminary new definition of quick clay does not involve any S_t-value but calls a clay quick when it becomes liquid on remoulding and has $\tau_r < 0.05\ t/m^{2*}$ ($H_1 < 3.1$).

As can be seen there is today a great confusion with respect to the definition of a quick clay.

The definitions above take no consideration to the amount of remoulding required for breaking down the structure, and thus cover materials of different type.

None of them seem to be a suitable definition when studying the importance of the cementation and dispersing effects, respectively. When discussing the development of retrogressive landslides quick clays of the slow type are apparently of less importance.

Suggested New Definition of a Quick Clay

When comparing Reusch's description of a quick clay as given above with the rapidity scale in Table 1, it is obvious that his type of clay may correspond to a clay with a rapidity number of about 9, i.e. to a clay being greatly affected by a moderate amount of working. According to the present author the name quick clay ought to be reserved for clays of this high rapid type, forming a characteristic group from a mechanical and probably also from a chemical point of view.

The following definition is suggested: A quick clay is a clay with a sensitivity of at least 50 and a rapidity number of at least 8 as given in the scale in Table 1.

If, by tradition, "quick clay" should be kept as a general term, the two types should at least be distinguished and called rapid quick clay and slow quick clay (cf. Söderblom, 1969).

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[*] ≈ 0.5 kPa

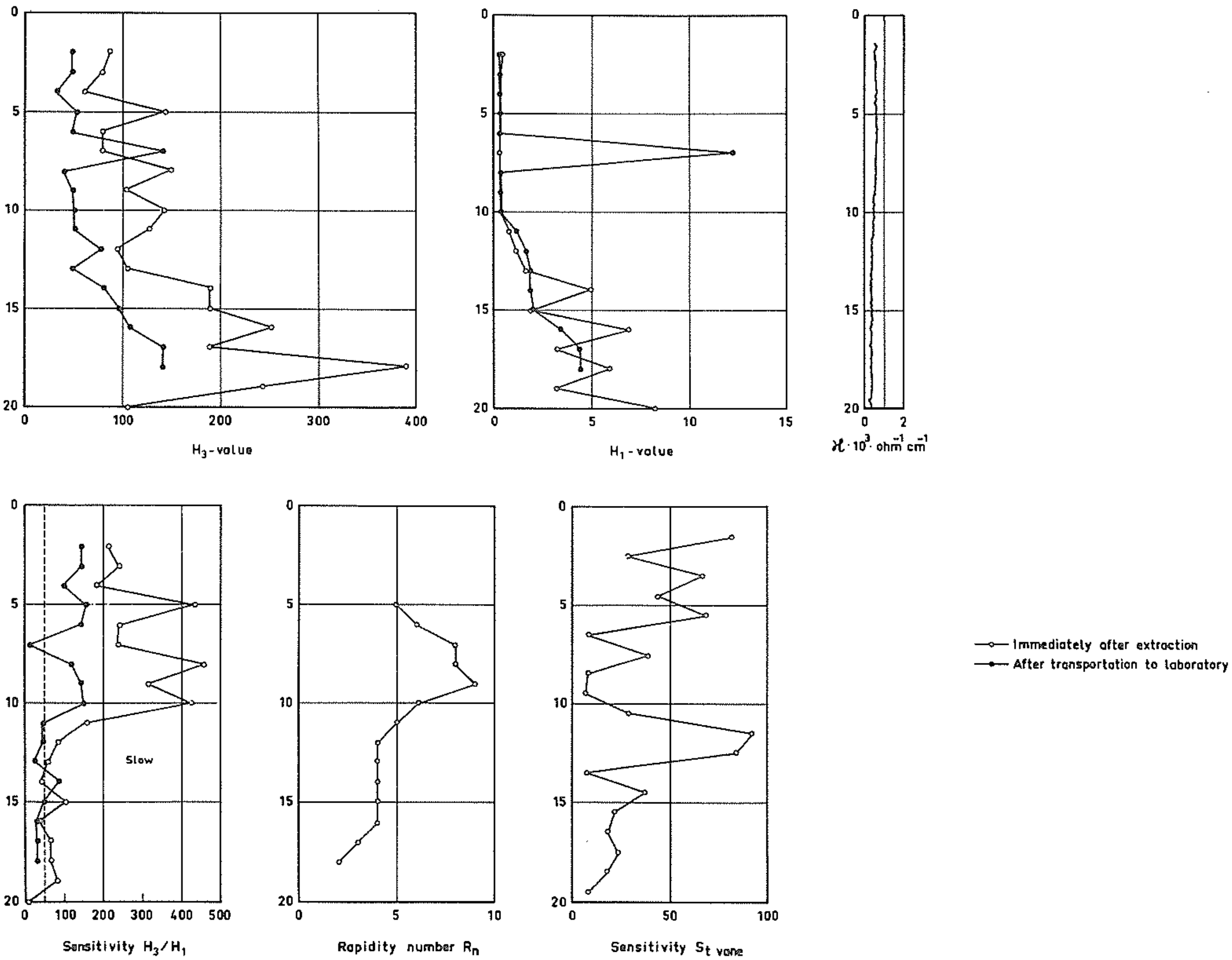

Fig. 3. Relative strength values, conductivity and rapidity number from a clay profile from Färgelanda (Point 16/500)

Rapidity Studies in Field and Laboratory

Studies of the distribution of quick clays in situ with different rapidity numbers have been initiated by the present author. It was especially desired to find places with highly rapid quick clays. At the beginning of the study no method was, however, available of obtaining an indication of where and how to search for such clays. Some sites were found in the archive of the Swedish Geotechnical Institute, with results from quick clay samples which had been severely damaged during the sampling process or/and during transport.

A promising site was situated in the parish of Färgelanda, province of Dalsland in western Sweden. Investigations were carried out here along the County Road 172. Three points were studied, viz. 16/500, 17/700 and 18/140. A plan of the test site is shown in Fig. 2.

Point 16/500. Quick clays of the rapid type occurred at Point 16/500 from about 2 m to about 10 m depth. Below this level the clay was of the slow quick type. The results obtained from the archive and from the present borings showed that the rapid quick clay deposit was very local, about 50-100 metres horisontally along the road, and seemed to occur as a "lens" surrounded by clays of the slow quick type similar to that described from Vaerdalen (Reusch, 1901).

The curves of the relative strength values from Point 16/500 are indicated in Fig. 3. It can be seen, with respect to the sensitivity H_3/H_1, that the samples from the part with rapid quick clays and tested both in the field and the laboratory show considerably lower values of the laboratory results due to marked effects of ageing and transport. This figure also shows a supplementary sensitivity curve obtained by the field vane borer type Nilcon. The difference between the sensitivity obtained by the vane borer and fall-cone test is an interesting task for further research.

The rapidity curve, from the laboratory tests on transported material, is also shown in Fig. 3. The rapidity number increased towards 9 m depth where it showed a maximum $R_n = 9$. Below this level it decreased. According to the new definition suggested in this paper, only the clay at 6, 7 and 8 m was quick. From field inspection (shake test) on fresh samples, however, all samples from 3 - 11 m seemed originally to have had a high rapidity number. The rapidity number may thus have changed during transport to the laboratory.

A continuous core was also extracted with the Swedish Foil Sampler at this point (16/500). The core showed that the clay is varved to a depth of 3.8 m and thus sedimented in rather a fresh water. Below this level it is non-varved and thus probably sedimented in salt water. The varved part of this core is shown in a photo (Fig. 4). Quick clays were found both in the varved and in the non-varved part indicating that the sedimentation environment has very little to do with the creation of high sensitivity. No transition zone between quick clays of high rapidity and quick clays of low rapidity could be seen in the core. The core showed plant remains in the part consisting of rapid quick clay. It was observed that the quick clay was attacked by these remains, giving free water in the contact surface between plant and clay. This may possibly be an indication of the formation of dispersing substances from the remains.

Point 17/700 showed rather a curious profile (Fig. 5). The sensitivity has a value of about 150 at 3 m depth but decreases distinctly to a value of about 4 (!) down to about 4 m depth. This layer of very hard clay and of very low sensitivity was about 1.5 m thick, as confirmed by core sampling. At greater depth clays with high sensitivity occur again, but the sensitivity shows irregularities. Great damage and ageing effects occurred in the sample due to transportation to the laboratory and storage as can be seen in Fig. 4. The rapidity number was at most levels lower than at Point 16/500.

A continuous core was also extracted at this point, but unfortunately only to 8 m depth, because the clay below that level became disturbed during the sampling process and probably liquefied close to the foils. The same tendency was observed with the intermittent piston sampling and at some levels the samples were lost. The sampling operation therefore had to be made several times.

No varved clay was found at Point 17/700. The varved sediment was thus rather local. From 2 m depth to the total sampling depth (8 m) the core

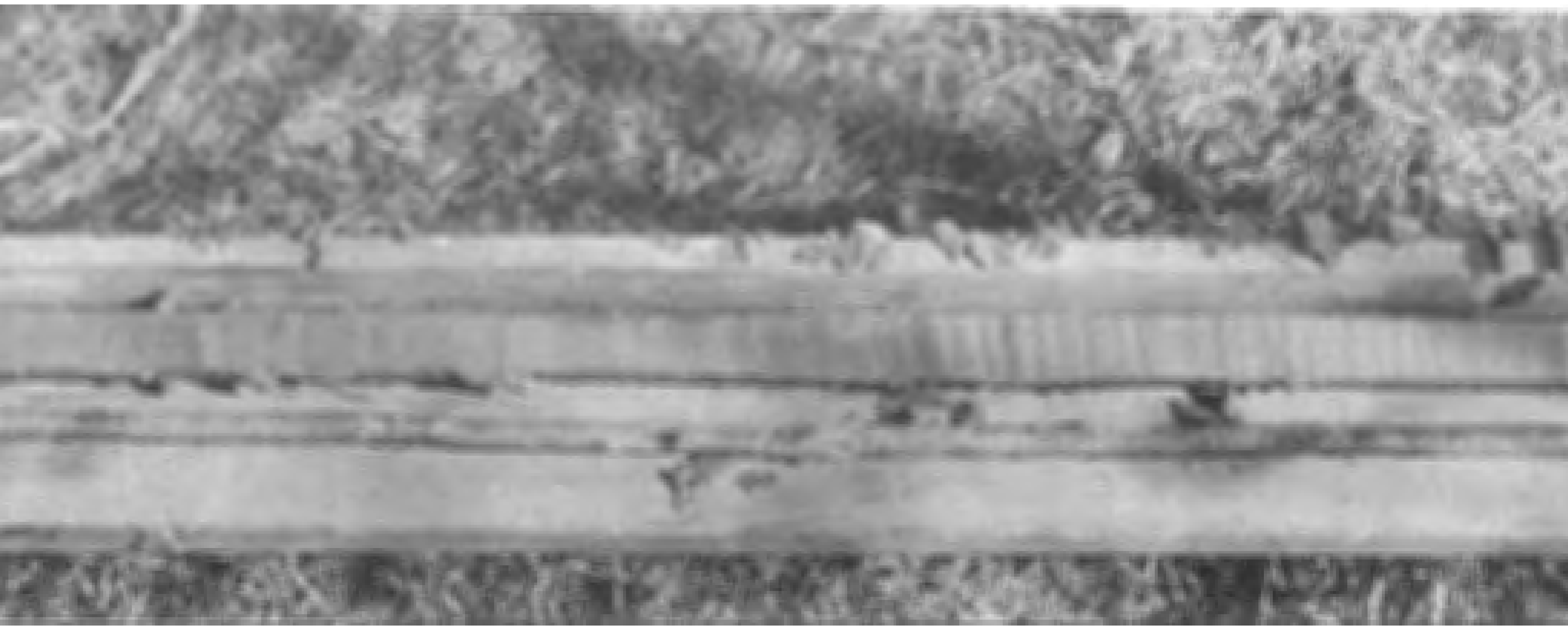

Fig. 4. Photo of a clay core from Färgelanda (Point 16/500) showing a varved quick clay

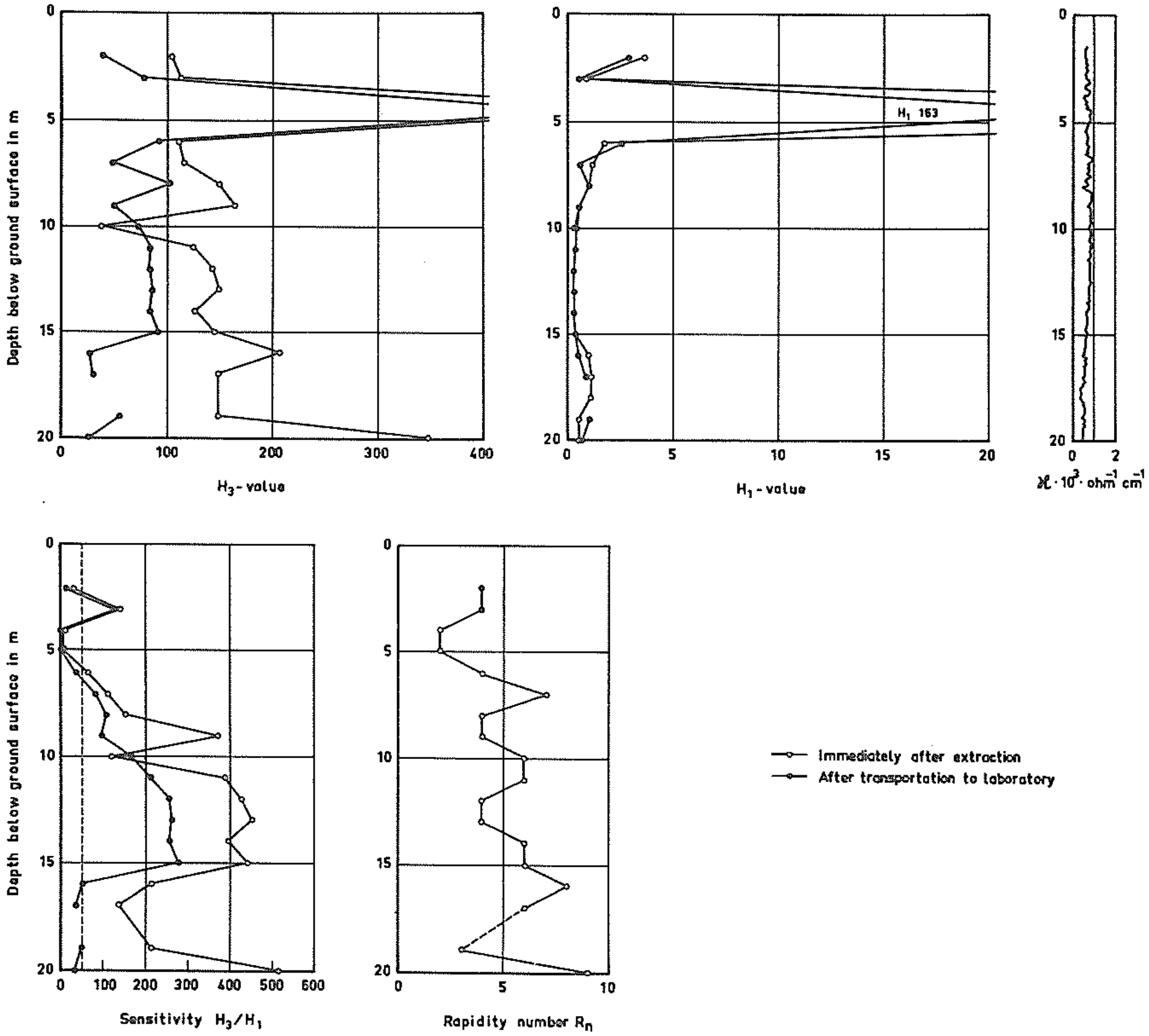

Fig. 5. Relative strength values, conductivity and rapidity number from a clay profile from Färgelanda (Point 17/700)

showed plant remains as was the case in Point 16/500. The top and the bottom of the transition between the high sensitive clay and the extreme low sensitive clay (about 4 - 5 m depth) was also studied (Fig. 4). The transition was about 20 cm in which hard and soft clays occurred alternatingly in 1 - 2 cm thick layers.

The core showed throughout its length a clay without visible silt or sand layers or signs of any so called "double dry crust".

It should be observed that this transition between high sensitive and extremely low sensitive clay has no corresponding discontinuity in the salt sounding curve (Fig. 5). The very sudden variations of the sensitivity and of the hard clay layer remain unexplained.

Point 18/140. The sensitivity curve from Point 18/140 (Fig. 6) shows that clays with varying sensitivities occur irregularly. No corresponding transitions were to be seen in the salt sounding curve. The rapidity curve shows that the clays in this profile are of the very slow type at some levels. At 9 m depth, however, the clay had locally a rapidity number of 8. The sensitivity at this level was, however, relatively low in comparison with other levels.

At 19 m depth a maximum of the sensitivity ($H_3/H_1 \approx 650$) was obtained. The rapidity number of that clay was, however, so low ($R_n = 2$) that it could not possibly be called a quick clay, in spite of having all the properties of a quick clay according to the common definition ($H_3/H_1 > 50$, $H_1 < 1$).

Discussion and Conclusion

It is possible to group the Swedish so-called quick clays into classes according to amount of remoulding required to break down the clay structure.

A comparison between rapidity curves and sensitivity curves shows that the rapidity has no direct relation to the sensitivity; a clay with a high rapidity number can have a low sensitivity and vice versa. Slow quick clays ($R_n = 3 - 4$) exist with a sensitivity (H-quotient) as high as 650, or, at other sites, even higher and a remoulded strength value (H_1-value) less than 0.33 (the lowest

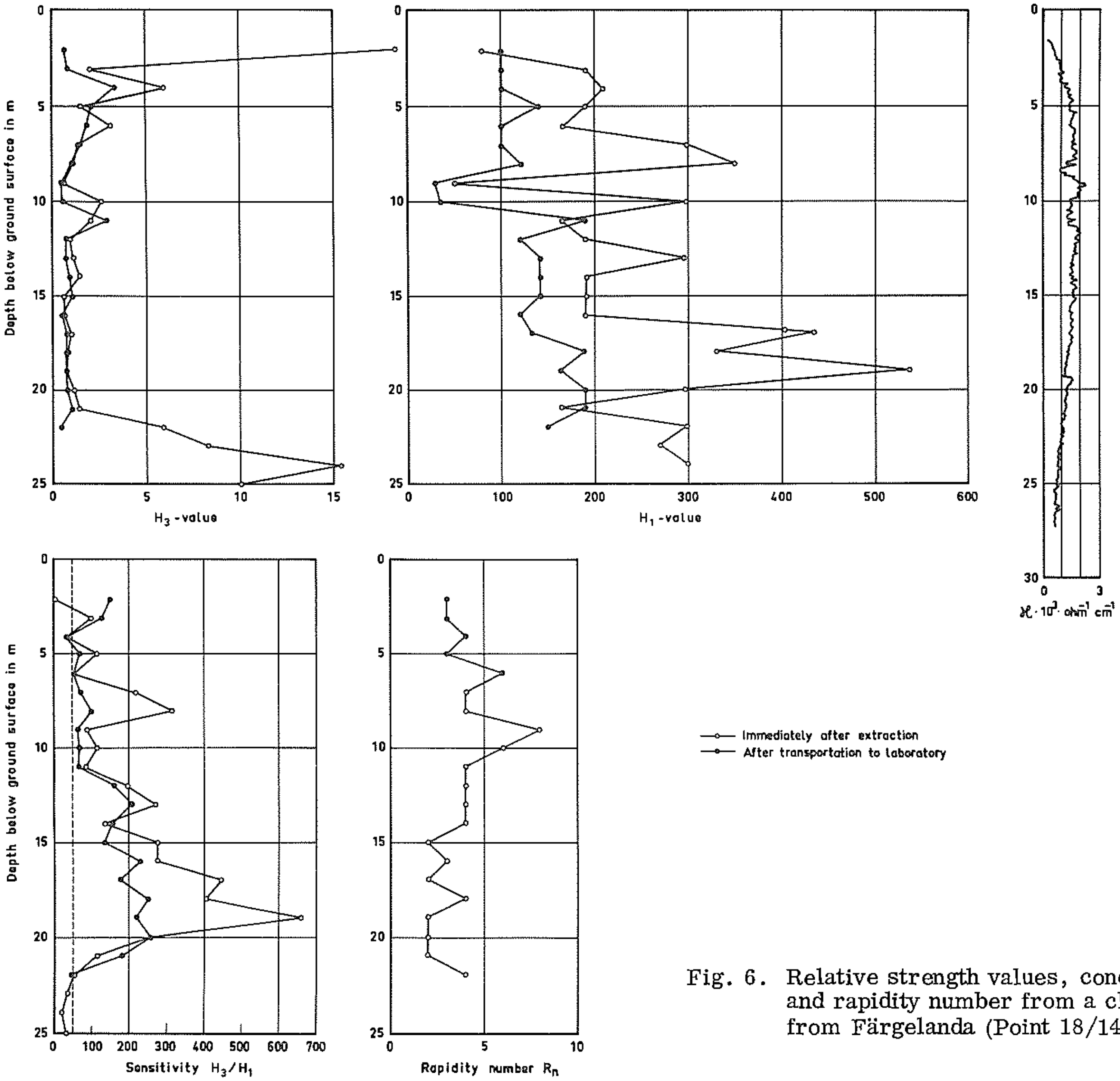

Fig. 6. Relative strength values, conductivity and rapidity number from a clay profile from Färgelanda (Point 18/140)

value in the scale used, cf. Söderblom 1969). Quick clays with high unremoulded strength value (H_3-value), high sensitivity and high rapidity, on the other hand, also exist. Quick clays with a high rapidity number seem to occur very locally and are surrounded by quick clay with low rapidity number. Some important questions in this connection are treated in a later publication (Söderblom, 1974).

Further, the chemistry of the formation of the different quick clay types is supposed to be very different as indicated by Söderblom (1974), giving very complex colloid chemical characters. Slow quick clays can in the laboratory be transformed into rapid quick clays and vice versa.

The quick clays with low rapidity number must have other binding forces between the particles than the rapid quick clays. Also the ground water conditions seem to play an important role.

The occurrence of high rapid quick clays in the vicinity of water arteries makes it necessary to work out methods of localizing such arteries and investigating them in detail with respect to the influence upon the surrounding clay before any systematic studies can be made to gain a better knowledge of the formation of high sensitive clays of different kinds. A localizing method for this purpose is described in the following paper in this publication.

As mentioned earlier, quick clays according to all definitions are not chemically stable (Söderblom, 1969) and quick clay samples are gradually transformed into materials with low sensitivity due to ageing processes. It is apparent that chemical or microbiological reactions are going on in the vicinity of local water arteries preventing short-term ageing processes in situ.

The concept of "rapidity" gives new aspects to the problem of so-called quick clays. This new concept can be of importance for a better understanding of the extension and propagation of land slides. It is evident that a clay with a very high rapidity number is more dangerous in this respect than a quick clay with a low rapidity number. This problem is further treated in the next paper in this publication.

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APPLICATION OF REMOTE SENSING IN THE QUICK CLAY RESEARCH

Rolf Söderblom

Summary

A remote sensing method has been worked out by which it is possible to trace areas with abnormally high dielectric properties, differing from the surrounding terrain. The method utilizes electro-magnetic waves with a frequency of about 100 MHz.

In most cases the dielectric anomalies are due to superficial water arteries. With the remote sensing results as an exploratory basis, the studies are supplemented with different types of geotechnical investigations including salt soundings. It was found that quick clays with a high rapidity number sometimes occur in areas with the above mentioned ground water conditions. These areas usually have an infiltration zone allowing surface water to spread into lower lying sediments in the formation. The deposits seem to have a connection with infiltration of waste water containing e.g. phosphates. No deposits of so called high rapid quick clays of natural origin have been found.

Sewage systems passing through such infiltration zones are rather common in Sweden. It is stated in the report that there is a potential danger if the systems leak, especially when the water infiltrates unstable slopes. A recent slide connected with a failure of a sewer pressure-tube is described.

Further, the investigation has shown that in an apparently homogeneous marine sediment with a high salt content, streaks can exist with almost salt-free clay deposits sometimes containing quick clay. The possibility of chemical stabilisation of certain types of sediments is also discussed.

Introduction

In the previous paper in this publication, the conception rapidity was introduced as a measure of the work required to break down the structure of a quick clay. It was also stated that areas with quick clays of a high rapidity number must be more dangerous when existing in mechanically unstable slopes than those with a low rapidity number. In order to proceed in the systematic research in this case, it seemed desirable to find some simple method of localizing areas in which the existence of quick clay of different types appears and which could be regarded as potential slide areas.

The rapid quick clays occur very locally and have hitherto only been found in areas rich in soft ground water in the form of arteries. This water originates in part from water in ditches influencing lower lying sediments. As a rule, one can observe water in such ditches even in dry summers. The formations of high rapid quick clays hitherto found seem to occur in connection with a special type of assorted sediments rich in ground water, called "lee formations", Swedish "läbildningar".

It is known that soils in areas with ground water arteries have electrical properties (conductivity and dielectric constants) differing from ground with normal conditions. Theoretically, it is possible to localize areas of this type by means of systematic salt soundings, but this method is in most cases time-consuming and expensive. The same is valid for the so called four-probe method which has been described for the use of in subsurface water exploration by e.g. Liesch (1969).

It is, however, possible to approach the problem by means of remote sensing. It has for many years been known that subsurface water can be localized by means of electromagnetic waves in the VHF-range (cf. Heiland, 1940). During the last few years a rapid development of such methods has taken place. A special technique has been developed by which it is possible to estimate different conditions in soil as well as pollution in sea water, atmosphere, etc. Radar beams are used for detecting, e.g. oil on water, impurities in the air. In searching for ore bodies waves in the "long wave band" have been found useful.

In searching for areas rich in ground water arteries, waves with a frequency from 30-200 MHz, i.e. the VHF-band, are suitable. Measurements have shown that the propagation of the ground wave is affected by the change of the electric ground constants. In most cases this influence is dependent on water streaming in the upper layers of the soil.

Remote sensing measurements are made from aircraft and satellites or from the ground. At the preliminary stage of the present studies it was, however, economically necessary to use a simple method. Therefore a hand-carried field strength meter was used as a prototype.

Scope of Test

The following program was then carried out:

1) To modify this type of remote sensing equipment to make it suitable for geotechnical purposes.

2) To investigate chemical and geotechnical conditions in connection with "lee formations".

3) Application of the method for preliminary slide studies.

4) Application of the method for a study of the chemical stabilization problem.

Theory of Remote Sensing in the VHF Band

The most reliable deduction of the theory of electro-magnetic wave propagation over ground with varying electrical properties was originally given by Norton (1937). His relatively complicated mathematical expressions will not be repeated here, but after several simplifications one obtains the expression

$$\varepsilon_k = \varepsilon - jx = \varepsilon - j\,60\,\lambda\sigma$$

where ε_k = complex dielectric constant of the ground
ε = dielectric constant of ground relative to vacuum
σ = ground conductivity ($S/m = 10\ ohm^{-1}cm^{-1}$)
S = unit for conductance
λ = wave length (m)
j = the imaginary unit (in most mathematical textbooks called i)

The influence of the ground constants on the electrical field vector is determined by ε_k. In the long wave band, the ground behaves as being conductive, and the imaginary part is the most dominating. (Waves of this frequency are suitable for localizing large ore bodies deep in the ground.) But at frequencies on the VHF band the expression of ε_k is practically real, i.e. the ground behaves as a pure dielectric. This is the case in frequencies above 30 MHz when using the values of the constants ε and σ, which generally occur in Swedish soils. By measuring the tilt of the field vector it is possible to calculate a mean value of ε in the neighbourhood of the receiver antenna.

The penetration depth of the waves in the ground is approximately about the same as the wave length. At a wave length of e.g. three metres, the penetration is thus in most cases less than five metres, and if the wave length is several kilometres, the penetration is also found to be kilometres.

On the other hand, the horizontal magnitude of the area influencing the measurement is also about the same as the wave length. If one wants to obtain local indications of anomalies in the ground, one must use waves in the meter wave range. For exploration of large ore bodies etc, very long wave lengths are used.

Description of Equipment Used

In remote sensing measurements of the dielectric properties of the ground, one generally employs a test transmitter working with a suitable frequency. Blomqvist (1960, 1969) describes such equipment working with a transmitter and a receiver. Driscoll (1972) describes a similar apparatus to be used by the Apollo XVII Expedition to search for underground water on the moon. The transmitter sends out radio waves on six different frequencies. Transmitter and receiver can also be built together into one unit.

Kick (1973) uses such equipment which transmits a directed "radar beam" in the ground. Törnqvist (1958) uses a similar airborne unit working with very long waves to detect ore bodies. He suggests to use the method in e.g. geotechnical connections.

Generally, vertically polarized waves are utilized and the theory existing is worked out for such waves. In dealing with transmitters with a high effect and giving a good field strength in the case that the transmitter antenna is so far away that the angle of incidency of the waves can be approximated to zero, it has been shown that one can use the same mathemathical theory for horizontally polarized waves. This implies that in many cases the ordinary broadcasting network working between 90-100 MHz (about 3 m) can be used.

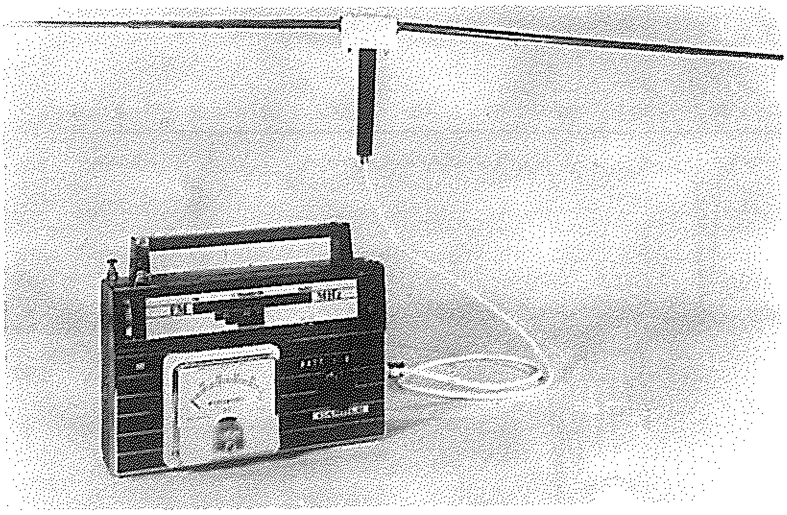


Fig. 1 Electrical field strength meter
(Photo S. Almstedt)

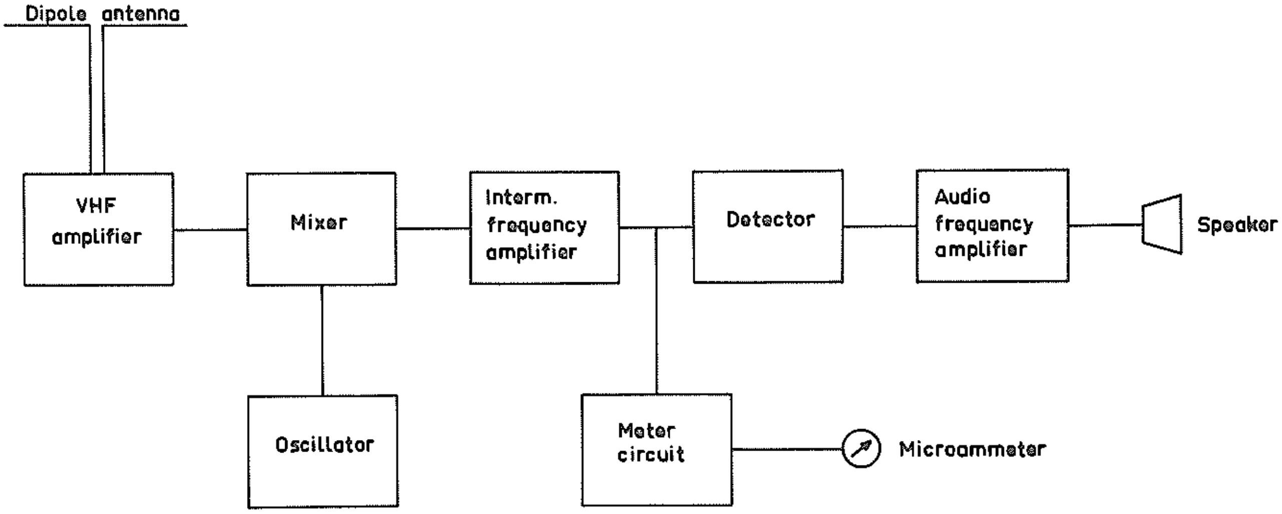
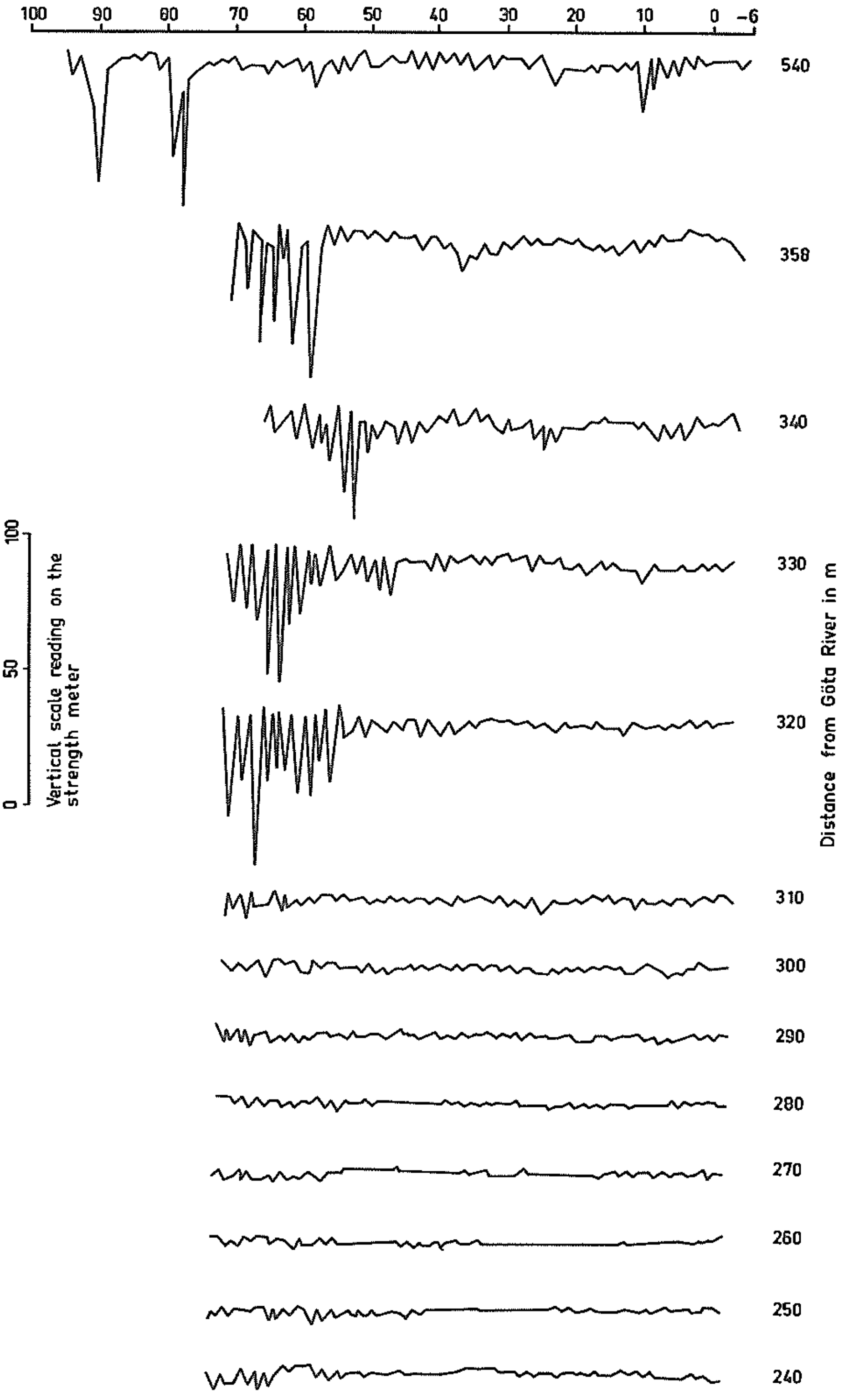


Fig. 2 Principle outline of the field strength meter



Battery voltage 5.4 volt
Transmitter Trollhättan 99.8 MHz.
Dipole antenna 1.5 m above ground suface perpendicular to the direction to the transmitter. (Maximum field strength in areas without polarization.)

Fig. 3 Electrical field strength variations at Lödöse football ground

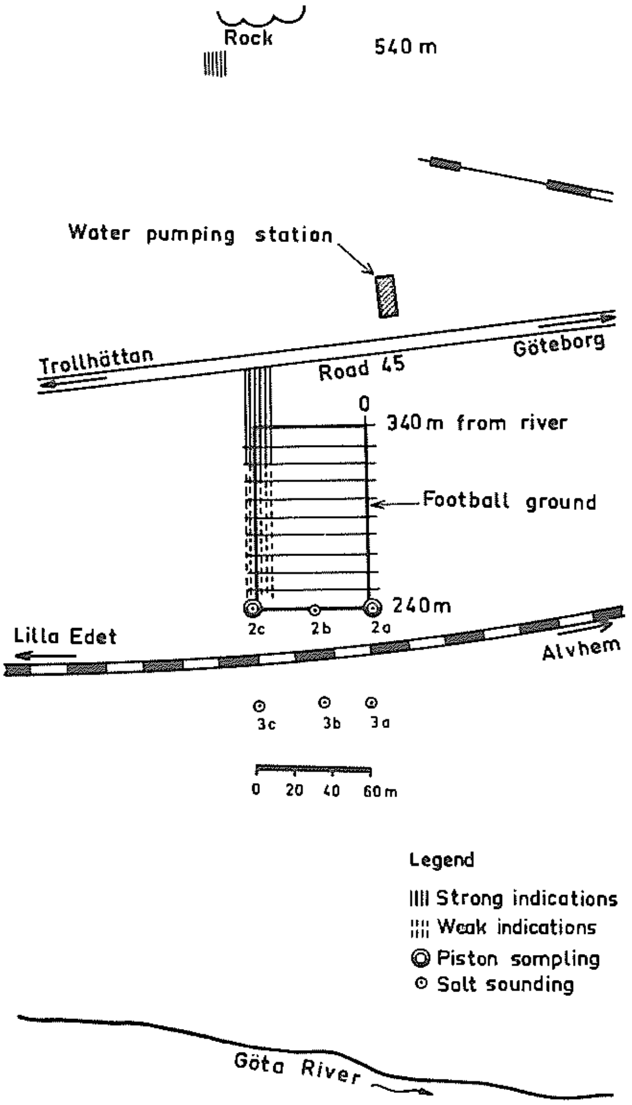


Fig. 4 Plan of site investigations at Lödöse football ground

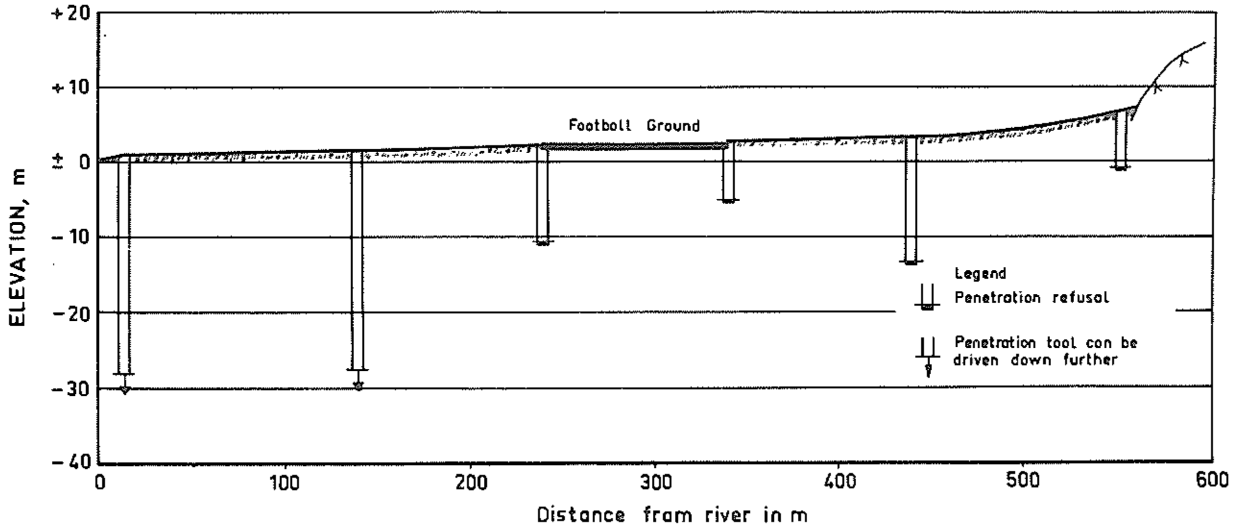


Fig. 5 Section at Lödöse football ground showing depth and slope conditions (after Tullström, 1961)

For the present experimental work a field strength meter was constructed[1] in accordance with the Author's concept and with a common transistor radio set as a basis. A photo of the meter is shown in Fig. 1 and the electric circuit in Fig. 2. The meter has a dipole antenna of half the wave length (1.5 metres). The equipment is hand-carried.

In the measurement procedure, the antenna is held 1.5 m above the ground perpendicular to the transmitter (maximum signal obtained). When passing dielectric inhomogeneities in the upper part of the soil profile, the polarization of the field vector will change and become elliptic. This meens that, in practice, the strength of the y-composant measured with the receive antenna changes which is indicated on the field strength meter. When passing areas of assorted materials rich in water arteries, great variations of the y-composant of the field strength are obtained (cf. Fig. 3).

Studies at Lödöse

An area with a local quick clay formation was earlier observed at the Lödöse football ground[2] and was suspected as being of special interest in this connection. The ground, 100 x 60 m, is shown in Fig. 4. It is situated in an area which slopes gently towards the Göta River. There are rocky hills about 200 m east of the football ground. A section showing the depth to firm bottom is given in Fig. 5. It is seen that this depth increases from the eastern side of the ground in the direction to the river.

The area is rich in subsurface water both with respect to artesian ground water and arteries. As seen in Fig. 4, a pumping station is situated east of the football ground. There was originally an artesian well here giving 600 l/h. Test pumping gave 54000 l/h during a period of one month with a considerable lowering of the ground water surface.

Measurements to investigate the occurrence of ground water arteries were made with the field strength meter along 10 sections parallel to the short

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[1] By Mr B. Thorén, Stockholm.

[2] For the localization of sites investigated, see Appendices 1 and 2.

sides of the football ground (almost parallel to the river). Readings were taken at points of a distance of 1 m in each section. Some additional measurements were also made outside the football ground, as shown in Fig. 4. The results of the field strength measurements are shown in Fig. 3. Pronounced field strength variations were obtained especially in a limited area in the northeastern part of the football ground as illustrated in Fig. 4 showing local dielectric inhomogeneities. As also seen the indications are weaker towards the western end of the football ground. From Fig. 5 it is seen that the depth of the profile increases where the indications disappear. From section 240 to 320 there is a slight indication that the artery streak continues, but at a greater depth as proved by salt soundings (see Figs. 6 and 7). According to the theory for the method (see above), this indicates that the conductivity properties in the area may also differ.

To verify this, salt soundings (cf. Söderblom, 1969) were made in Holes 2a-2c and 3a-3c (Fig. 4). Samples were taken in Holes 2a and 2c and were tested with respect to geotechnical properties, immediately in the field and after 1 à 2 weeks in the laboratory in Stockholm.

The results from the salt soundings in Holes 2a-2c are shown in Fig. 6. The resistance curve from Hole 2a shows an unleached Göta River clay (pore water salt content about 3%). It should be noted that hardly any leaching has occurred from the bottom. Usually, the Göta River clays are leached both from the top and the bottom (cf. Söderblom, 1969). The curve from Hole 2b gives a somewhat higher resistance (lower salt content) than 2a. Here some leaching has occurred at the bottom of the profile.

Hole 2c is situated in the artery streak. The salt sounding curve in this hole differed markedly from those in Holes 2a and b. The clay is almost salt-free (salinity about 0.2%, below 10 m depth less than 0.05%).

The results from the salt soundings in Holes 3a-3c are shown in Fig. 7. Similar variations in salt content as in Holes 2a-2c were found, but were less pronounced.

The results obtained from the samples are shown in Figs. 8 and 9. The sensitivity ratio H_3/H_1 of samples from Hole 2a did not exceed 50 at any level.

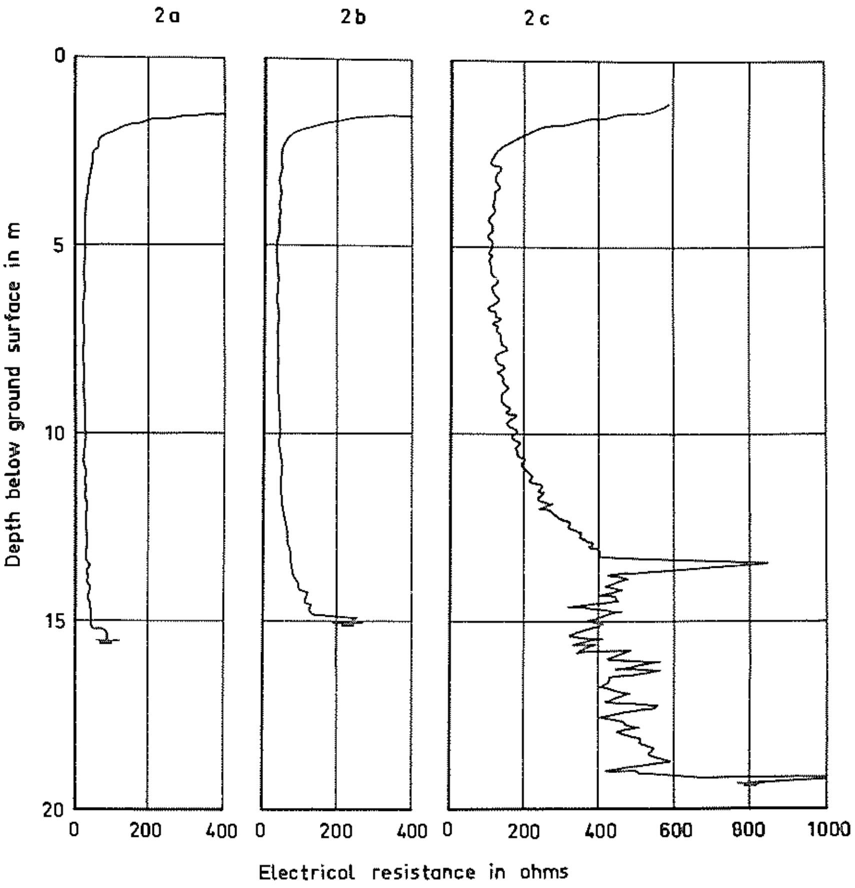


Fig. 6 Electrical resistance curves (salt sounding curves) from Lödöse football ground, Holes 2a, 2b and 2c

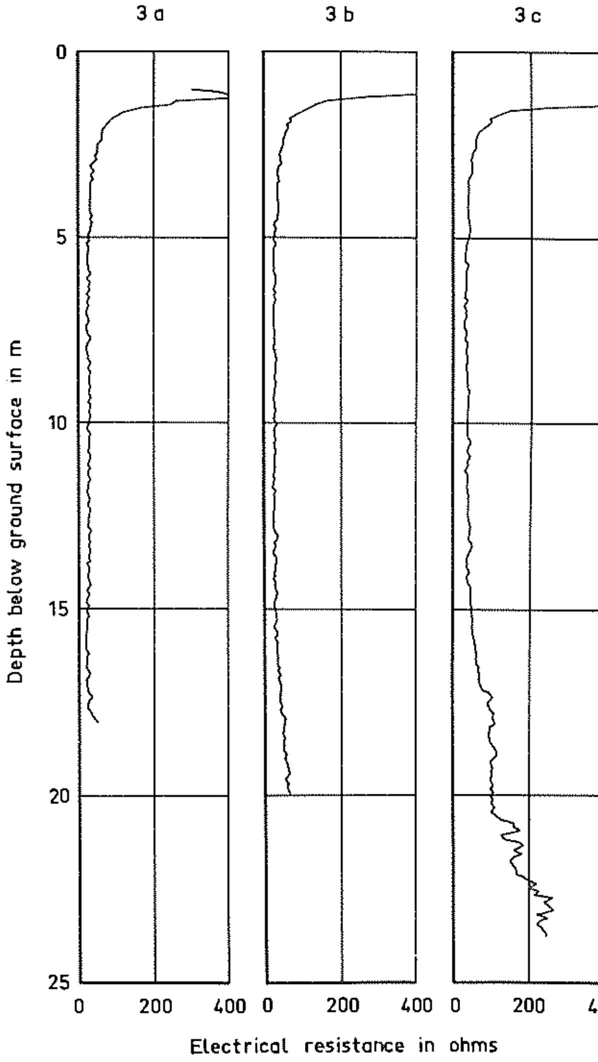
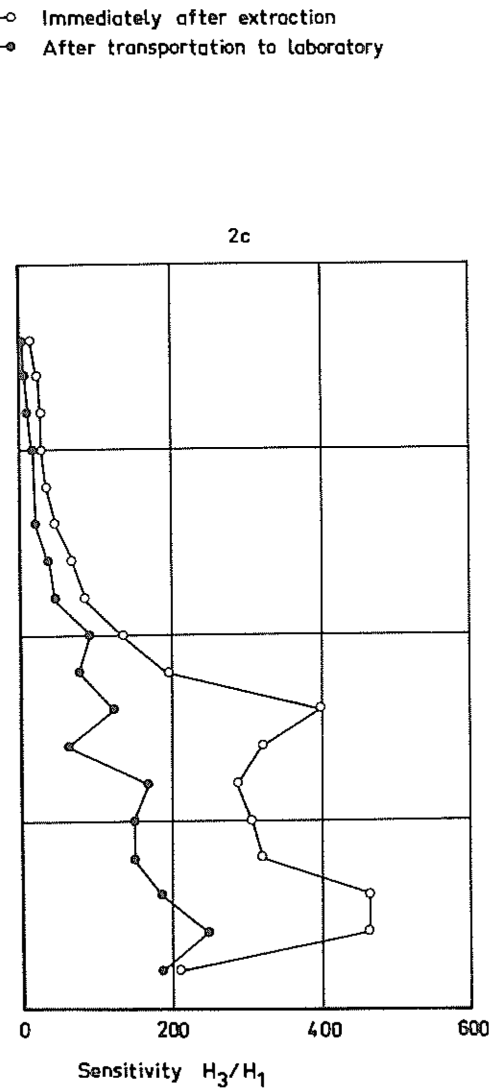


Fig. 7 Electrical resistance curves (salt sounding curves) from Lödöse football ground, Holes
3b and 3c



sitivity curves from Lödöse football
und, Holes 2a and 2c

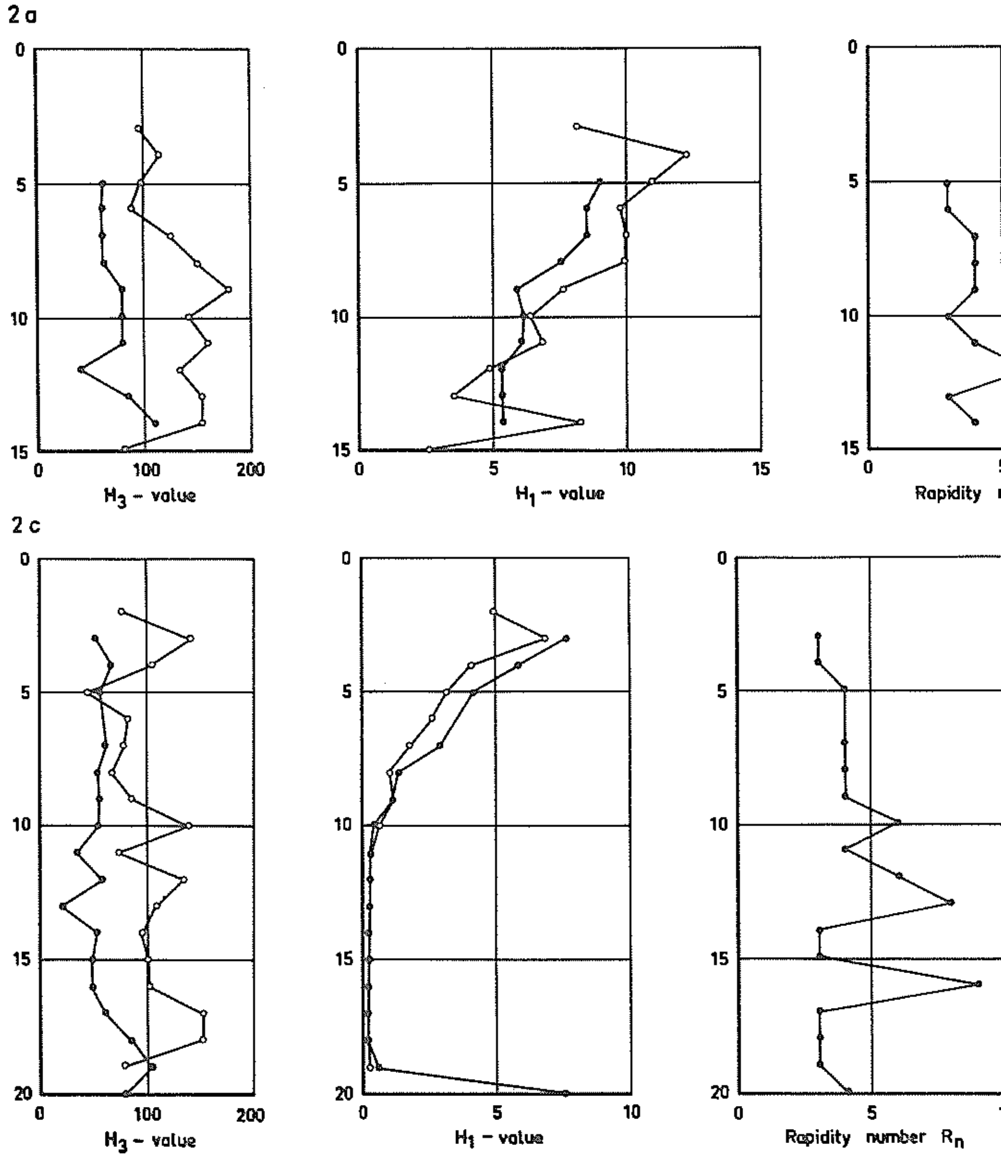


Fig. 9 Strength values from Lödöse football ground,
Holes 2a and 2c

These clays are thus non-quick even according to the common definition. In Hole 2c the ratio exceeded 50 at a depth of 6 m. At greater depths very high sensitivity values were found (H_3/H_1 about 450).

Also the undisturbed relative strength values (H_3) of the clay were different (Fig. 9). For Hole 2c they were, with a few exceptions, lower than those in Hole 2a.

The largest difference was noted for the remoulded relative strength values (H_1) of the clay. The H_1-values were high for Hole 2a. In Hole 2c, on the other hand, very low H_1-values were obtained at depths below 7 m. In both holes, changes in the geotechnical properties due to sample transportation and ageing were noted.

The rapidity numbers for Holes 2a and 2c measured 1 to 2 weeks after the samples had been extracted and transported to the laboratory are also shown in Fig. 9. The rapidity was very high at some levels in Hole 2c and a rapidity number of 9 was obtained at 16 m depth.

The results from the investigations at Lödöse thus show that a local streak of the area had a clay with geotechnical properties differing noticeably from those in the vicinity.

As will be seen below, similar streaks of salt-free clay with quite different geotechnical properties often occur in so called homogeneous marine clay. This must be taken into consideration when calculating stability conditions for a sloping area.

Investigations at Strandbacken and Fuxerna

Two sites giving pronounced indications with the remote sensing method are Strandbacken and Fuxerna in the Göta River Valley. The location of the investigations is shown on the map in Fig. 10. No large slide is known to have occurred at these places in historical time. The stability of the two areas seems, however, to be relatively poor according to an investigation made by the Swedish Geotechnical Institute (SOU, 1962).

At Strandbacken the ground water pressure is locally high. Remote sensing investigations performed by the Author indicated that the area was rich in water arteries. Quick clays with a high rapidity number could thus, from the knowledge at the time of the investigations, be suspected to exist here. The supplementary investigations, however, showed negative results. The investigations were therefore discontinued here.

The investigations at Fuxerna at the other side of the river indicated, on the contrary, very interesting conditions. Salt soundings were made in areas with pronounced remote sensing indications (Fig. 10). They showed that the clay at all levels was almost salt-free also close to the river. This indicates that ground water has removed the stabilizing salts from the soil also at greater depths. Conditions for quick-clay formning processes are therefore present here. It should be added that the ground water table has been lowered by three pumping stations (after 1973 the stations are no longer in use).

As shown earlier (Söderblom, 1969), salt clays are never quick, but leached clays can be either quick or non-quick. Therefore, at Fuxerna quick clays should be present anywhere in the area between the river and the rock about 500 m east of the river.

Salt-free clay in the river bank is not common in the Göta River Valley. According to an earlier investigation (Söderblom, 1969), the clays in the Göta River Valley usually have a rather high salt content close to the river decreasing with increasing distance from the river bank. Thus,the salt conditions at Fuxerna are rather unique.

A section in the southern part of the area was selected for further investigation. This section followed marked water arteries as obtained by the remote sensing method and was, for the same reason as at Strandbacken, supposed to contain high rapid clays. The geotechnical properties from this section are shown in Fig. 11 and App. 3. The results from the salt soundings, indicate that the clay has been leached along the whole section. The sensitivity curves compared with the salt sounding curves are given in Fig. 11 and show very interesting variations.

A schematic view of the whole investigated section at Fuxerna showing

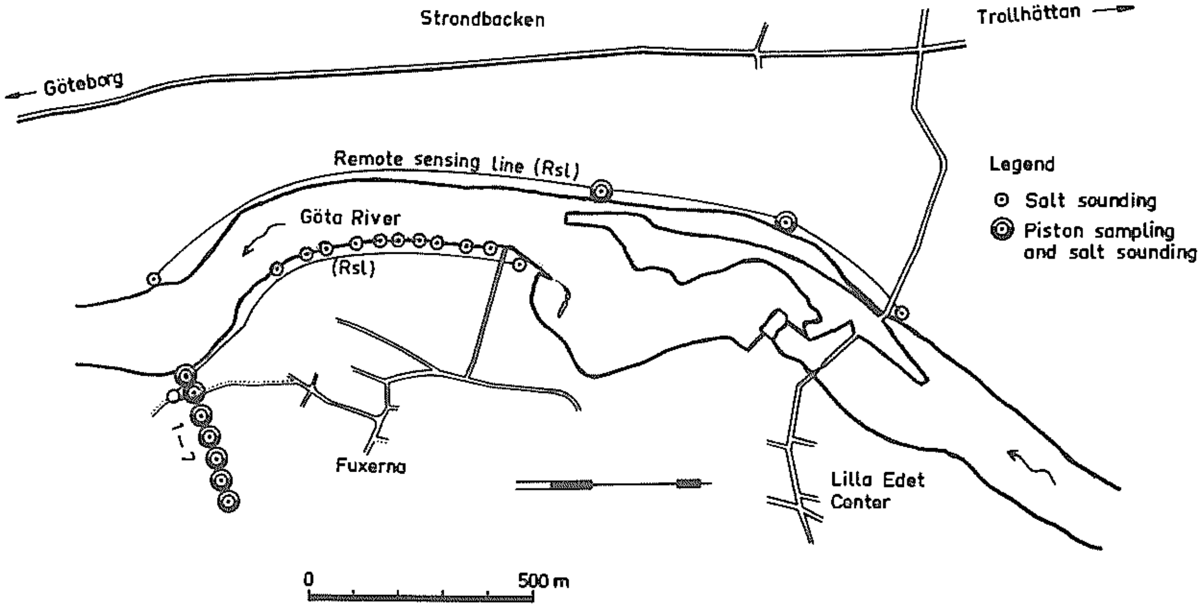


Fig. 10 Map showing the sites investigated at Strandbacken and Fuxerna

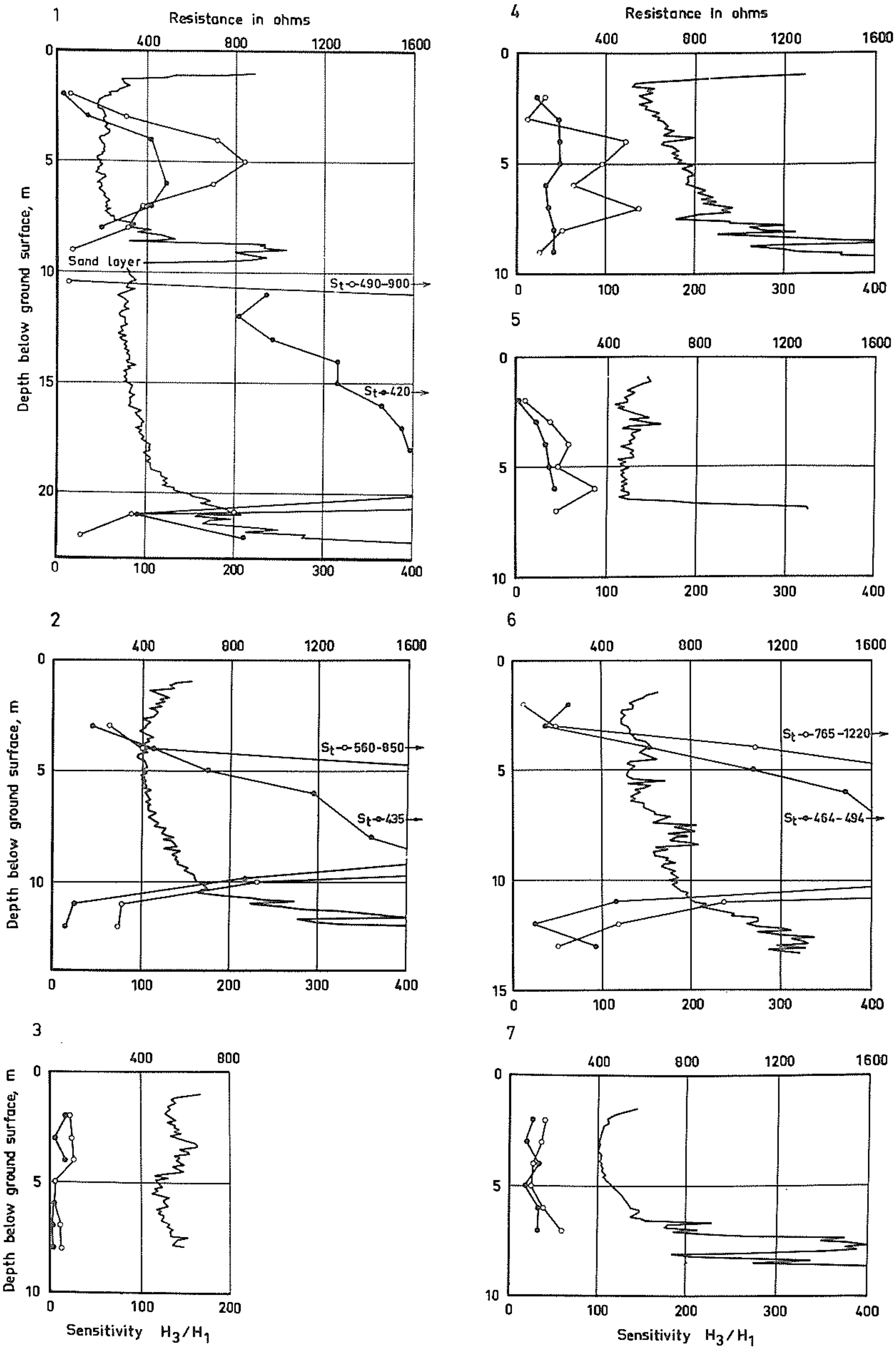


Fig. 11 Sensitivity curves from the section investigated at Fuxerna compared with salt sounding curves, Holes 1-7

lines with equal sensitivity is given in Fig. 12a. The results verify e.g. the facts stated in old literature (cf. Reusch, 1901) that quick clays occur in lenses surrounded by clay of lower sensitivity. Fig. 12b shows the same section with equal conductivity lines and Fig. 12c gives a section with equal strength lines (H_3-values).

In contrast to that which applies in the case of the sensitivity (Fig. 12a), the electrical resistivity curve (Fig. 12b) shows no tendency to form lenses. The whole profile has a high resistivity indicating a low salt content. This profile is thus in part a typical example of a case when the salt leaching theory cannot be applied.

The boundary line between clay and sand/gravel (till ?) is mainly obtained from the salt sounding penetration, i.e. the maximum depth obtained with this method. In Hole 7, however, a penetration test was made further into the sand/gravel with an ordinary penetration rod and a depth of 14 m was obtained. At this depth the rod was broken. The depth to rock is therefore unknown.

Regarding the individual holes, it is seen in Fig. 11 that in Hole 1, close to the river bank, clays with a very high sensitivity ($S_t > 400$) but with a low rapidity number (cf. App. 3) exist. The sensitivity had a minimum on both sides of a sand layer at a depth of 10 m. A chromatogram of the salts in the water in the sand layer, Fig. 13, indicates that this layer carries water with Ca^{2+} and Mg^{2+} as dominating cations (hard water). According to the Donnan theory, a leaching by hard water will cause an accumulation of divalent ions in the surrounding clay, giving a low sensitivity (cf. Söderblom, 1969). The relatively low Ca^{+2} and Mg^{+2} ion content relative to Na^{+} in the pore water of the quick clays at other levels in the hole must depend on other processes than the leaching with hard water.

High sensitive clays with low rapidity numbers were also found in Hole 2, (Fig. 11) located 50 m up the gentle slope.

The clay in Hole 3, 100 m from the bank, had, unexpectedly, a very low sensitivity and high strength values (H_3 and H_1, see App. 3). No quick clay was found. A local lense of quick clay appeared in Hole 4 located another 50 m away from the river. The sensitivity had two maxima at 4 m and 6 m depth. In Hole 5,

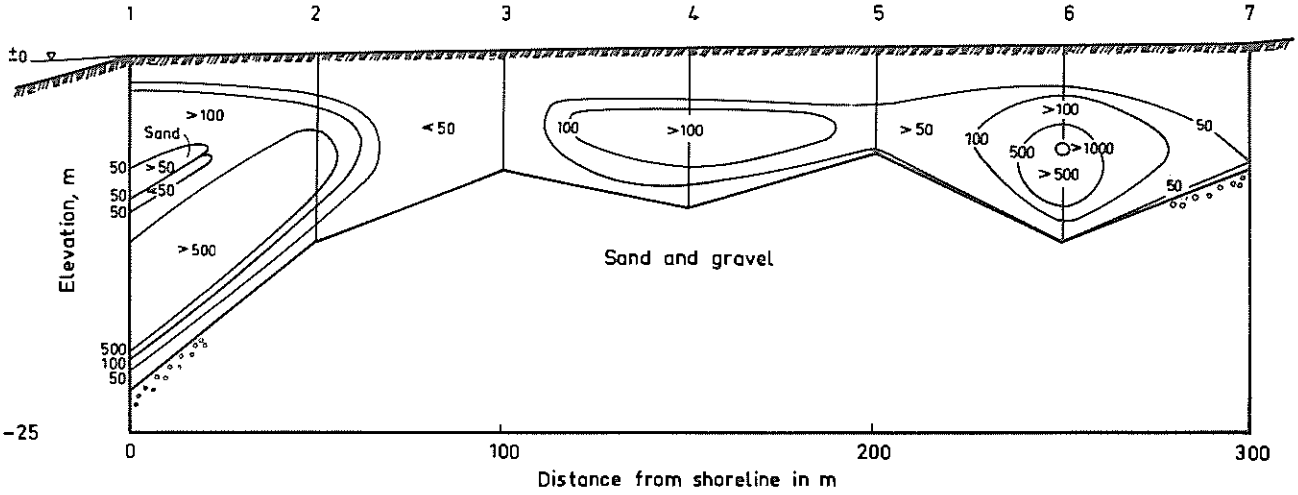


Fig. 12a Schematic section from Fuxerna with lines of equal sensitivity

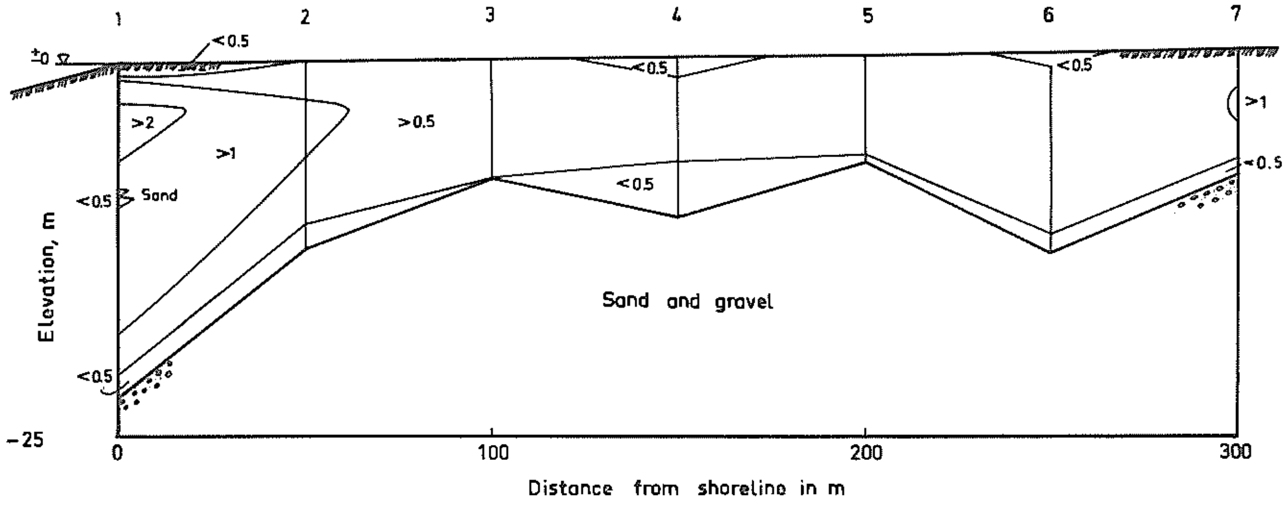


Fig. 12b Schematic section from Fuxerna with lines of equal conductivity

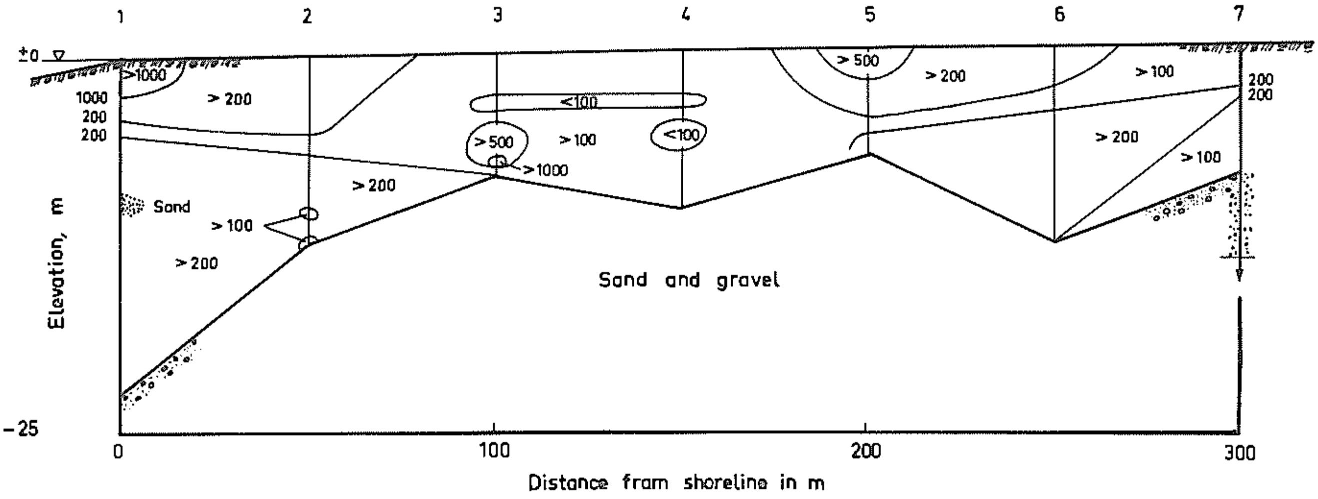


Fig. 12c Schematic section from Fuxerna showing lines of equal strength-value (H_3)

200 m from the river, a small zone with a sensitivity somewhat greater than 50 was present.

In Hole 6, 250 m from the river, glands with very high sensitivity could be found. At about 8 m depth a local lense with a sensitivity of more than 1000 was measured in the field laboratory (cf. Fig. 11). The high sensitive clay is not present in Hole 7, 300 m from the river bank.

The rapidity of the clay was generally found to be low near the river and increased up the slope (cf. App. 3).

Conclusions from the Tests at Lödöse, Strandbacken and Fuxerna

The experiments with remote sensing combined with salt soundings showed that in homogeneous marine clay sediments with salt clay, local areas with almost salt-free clay exist. This can be explained by assuming that local ground water arteries have leached these areas.

It is, however, not certain, as assumed by the Author, that the sediments with these local artery streaks have been precipitated in a marine environment and thereafter leached. The occurrence of varved clay in some of them indicates a fresh water sedimentation. Quick clays can occur in these formations, but not necessarily (Söderblom, 1969). Already the present few investigations indicated that the remote sensing method was a valuable supplement to the salt sounding technique and it seemed worth-while to study the technique further.

Investigations at Vassända Naglum

Vassända Naglum is situated between Trollhättan and Vänersborg, some 10 km west of the Göta River Valley. It is one of the few places in Sweden where quick clays of high rapidity have been found by the Author.

Here the quick clay of high rapidity occurs locally as shown in the plan, Fig. 14. As seen, 8 piston sampling holes and two salt soundings were made in the area. All test results are collected in App. 4. A representative hole in this respect is Hole 1, the results of which will be discussed below (Fig. 15).

The curve of the undisturbed strength values (H_3) show sharp local variations in the profile. E.g. at 3, 5, 9 and 14 m depths, minima with very low undisturbed strength values were found. The strength values obtained after extracting and transportation of the samples to the laboratory in Stockholm were also here generally lower than those obtained immediately in the field. As seen, some exceptions can be noted, but the general tendency was that the sharp minima and maxima in H_3-curve were not found when investigating the samples in the laboratory. Similar tendencies can be noticed for the other bore holes in the area, but the results are somewhat irregular (cf. App. 4). The remarkably large difference between test results in the field laboratory and in the laboratory in Stockholm must be due to ageing effects and transport damage of the high-rapid quick clay samples.

The remoulded strength values (H_1) were low in both laboratories. Also the sensitivity curve shows very different values in the two laboratory tests. The same tendency is present in the whole area.

The rapidity curve, Fig. 15, shows very high values down to 8 m depth. At 6 m depth values of 10 (the highest in the scale) were observed. At greater depths the rapidity values are lower and vary, but at 20 and 25 m depth the highest value 10 was again measured. Similar rapidity curves were found in the other bore holes in the area (App. 4).

The conductivity curve (Fig. 15) has another course than a "normal" curve. Clays with different conductivity occur with sharp gradients indicating that convection processes may go on in the profile disturbing the natural diffusion. Similar curves as in Fig. 15 were also obtained from other holes investigated in the area but are not accounted here. The place thus seems to differ from natural conditions with regard to the salt sounding results, indicating that some disturbances are present.

A place with clays of such a high rapidity number as in Vassända Naglum, and

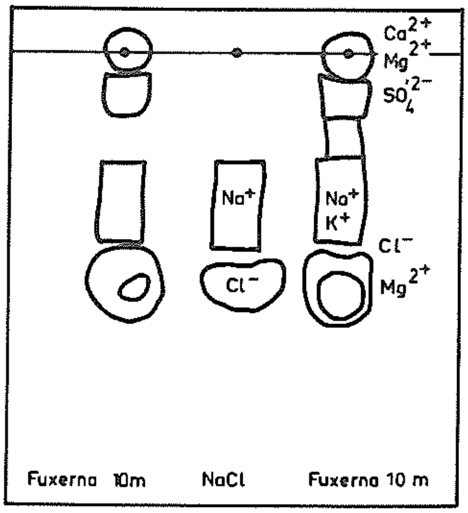


Fig. 13 Chromatogram of the ionic composition of salts in the pore water of a clay from Fuxerna, 10 m depth

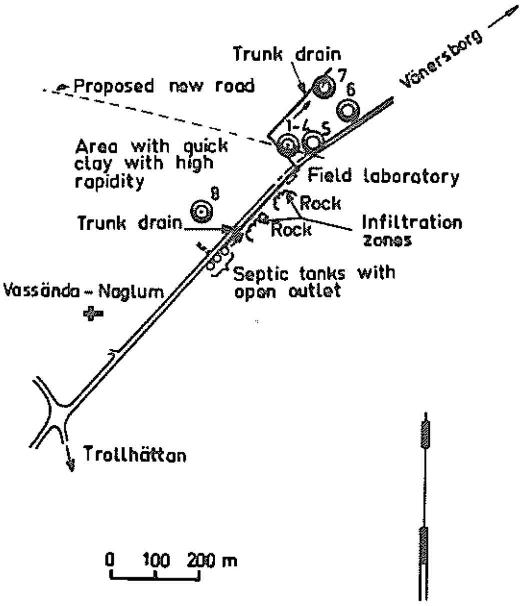


Fig. 14 Plan of site investigations at Vassända Naglum (legend, see Fig. 10)

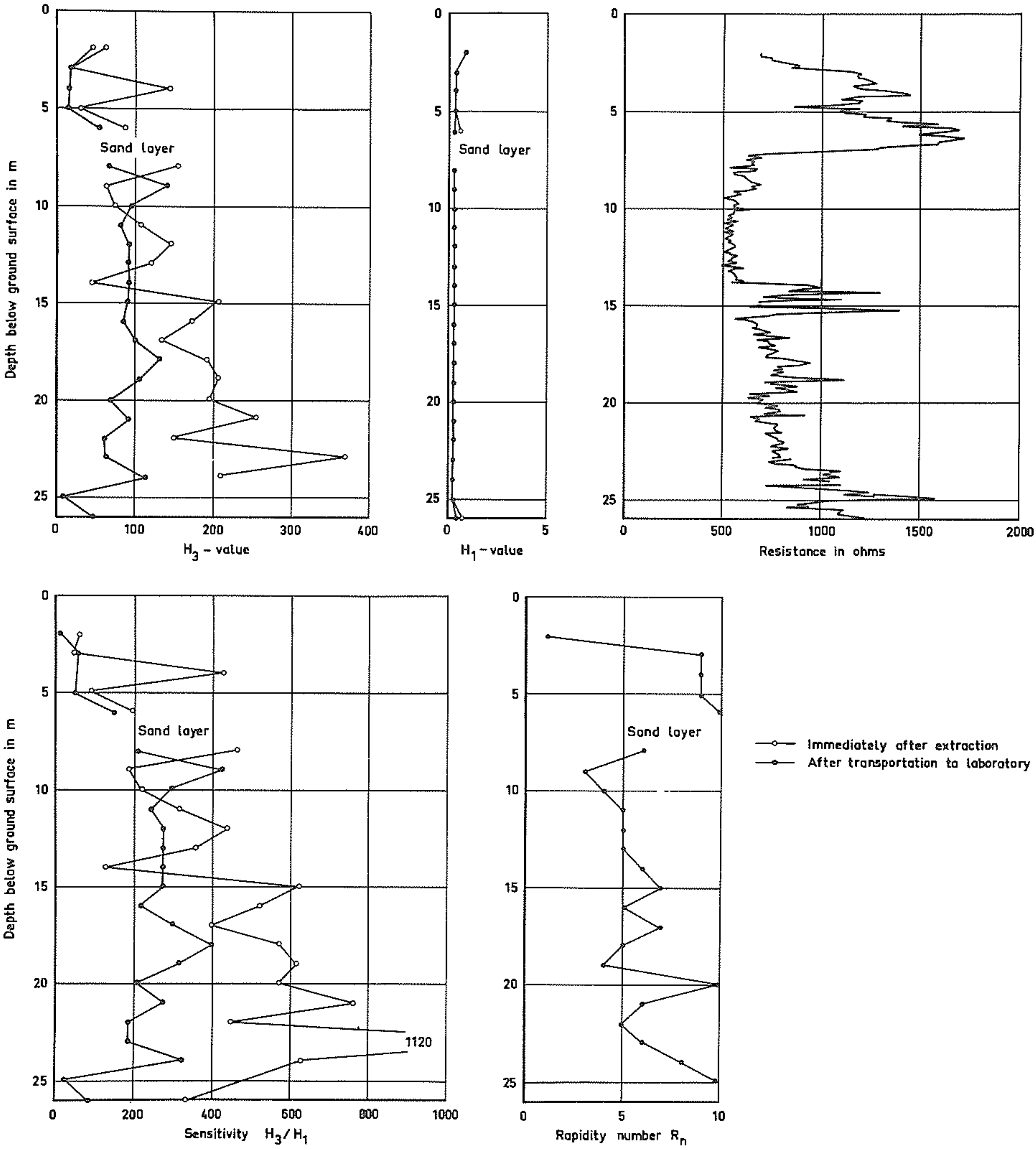


Fig. 15 Strength values from Hole 1 at Vassända Naglum

in Färgelanda (see preceding report and App. 5), should under unfavourable stability conditions be dangerous as regards slides.

Lee Formations and Other Formations Rich in Ground Water

Lee formations occur locally in sediments in connection with rock hills in most parts in Sweden. The sediments are rich in local sand and silt layers and lenses favouring the collection of ground water. Lee formations in moraine are treated by, e.g., Björsjö (1949) and Möller (1960). See also De Geer, 1970.

To disentangle the geology of lee formations and other formations rich in ground water is a task for the quarternary geologists.

A schematic picture of such a formation based on several borings is shown in Fig. 16. The coarse layers reach the ground surface at the intersection between rock and sediments, usually called the infiltration zone. Chemicals, oils, etc in such a zone can easily spread very deeply in a clay profile and cause changes in the geotechnical properties. Examples are the football ground at Lödöse and the section at Fuxerna, described above. Sometimes, e.g. at Fuxerna, layers of still coarser materials, which also are rich in ground water, occur. The large slide areas in Sweden studied by the Author are located at such formations, rich in remote sensing indications.

Probable Explanation of the Formation of Rapid Quick Clays

The quick clay deposits at Färgelanda and Vassända Naglum are both situated in areas rich in ground water arteries and having ditches where water runs even in dry summers and passing through infiltration zones. It was anticipated that dissolved substances in the water were infiltrated into the ground.

Investigations of water from the ditches at these two places were therefore made. The conductivity was high (Table 1) indicating that the water was strongly polluted. Paper chromatograms were made on evaporation residues from both places. An example from Vassända Naglum is shown in Fig. 17. All water is rich in sodium and phosphate ions. The pore water of the high-rapid

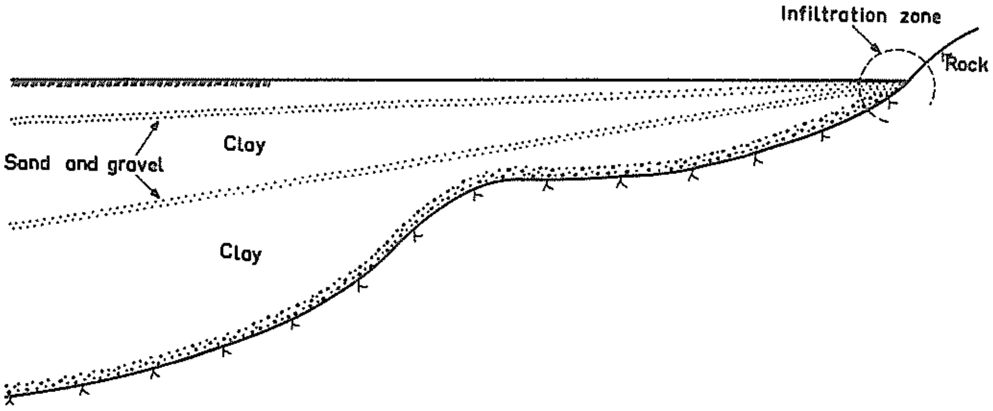


Fig. 16 Schematic view of a section disposed to ground water flow

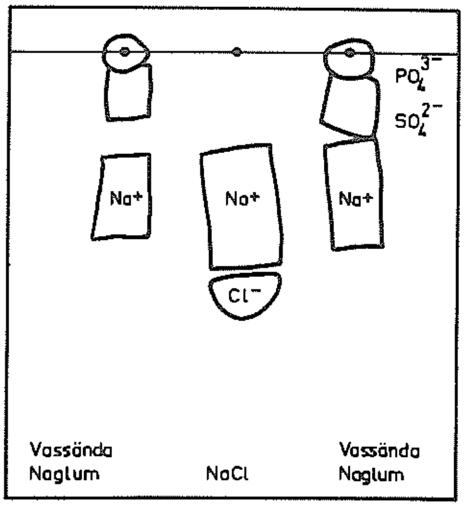


Fig. 17 Chromatogram of the ionic composition of salts in infiltration water from Vassända Naglum

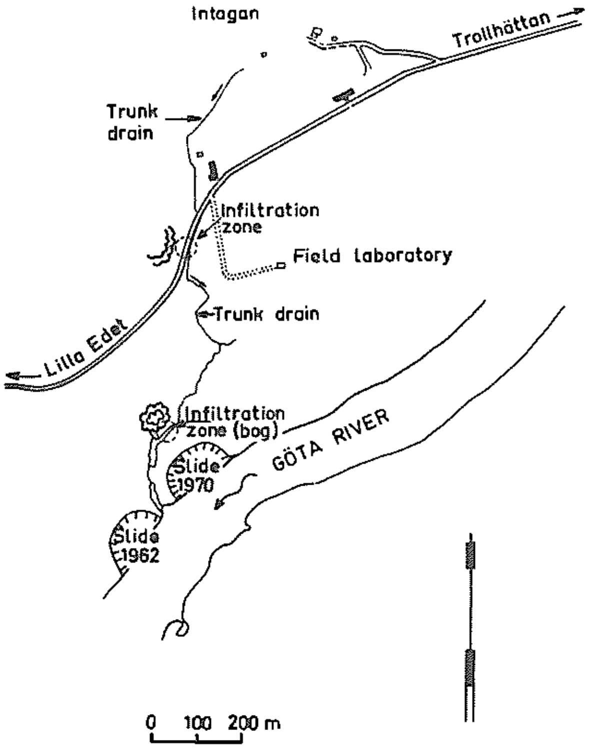


Fig. 18 Plan of site conditions at Intagan, 1970

Table 1. Conductivity in septic tanks and trunk drain at Vassända Naglum

Place	R ohm	$\varkappa \cdot 10^3$ ohm^{-1} cm^{-1}
Septic tank 1	840	0.48
Septic tank 2	800	0.50
Septic tank 3	770	0.53
60 m from tanks	710	0.56
120 m from tanks	620	0.65
180 m from tanks	675	0.59
240 m from tanks	1150	0.35

quick clays also contained phosphate ions in an amount abnormal for Swedish conditions (unaffected Swedish clays usually contain no phosphates). The high phosphate content present at Färgelanda and Vassända Naglum must depend on local, special conditions.

When clay material from Vassända Naglum was boiled with 5% NaOH for 4 hours, a dark-brown solution was obtained. The solution was dialysed to $\varkappa \approx 1$ ohm^{-1}cm^{-1} and the dialysate thereafter evaporated. A strong high molecular, clay-dispersing agent containing phosphates was obtained.

The ditch water, influencing the stability conditions at Vassända Naglum and containing phosphates,originates from three septic tanks indicated in Fig. 14. About 200 m from these tanks, deposits of quick clay with high rapidity occur. All signs indicate that the formation of the rapid quick clay is due to the dispersing agents from septic tanks (cf. White & Kyriazis, 1968).

As a conclusion for the formation of high rapid quick clays, certain conditions must be fulfilled. The main factor is the existence of subsurface water arteries. The water must not be of the hard type (Ca^{2+} and Mg^{2+} are dominating cations) because the process then results in the formation of either non-quick or, as was found in Fuxerna, low rapid quick clays. (The full explanation in this respect requires further comprehensive studies.) The typical high-rapid quick clays hitherto found by the Author cannot reasonably be natural in origin but dependent on the infiltration of waste water in water arteries.

Infiltration of Waste Water and Landslides

The presence of excessive ground water is generally accepted as a potential cause of landslides (Legget, 1962). It is still worse if this water is polluted with dispersing agents. Thus, systems carrying waste water over infiltration zones above clayey slopes can, under unfavourable conditions, be dangerous from a stability point of view, increasing the slide risk. In Sweden, especially in smaller communities, waste water from several houses is often collected and led to a secluded place where the water is let out into an open ditch. In many cases such ditches pass, as mentioned above, over infiltration zones and the dispersing agents in this water can be spread in a large area causing a clay of high rapidity. In slopes this can lead to "natural" catastrophes. Still more important is the proper placement of the sewage constructions. Waste water from densely populated areas is collected and led into pumping stations and pumped by high pressure through plastic pipes. Pipes of this kind often pass through infiltration zones situated above clayey slopes. A pipe break in such a zone can be still more dangerous than the above mentioned ditches (cf. Chapter about the Jordbro slide, p. 27). This problem is, of course, also pertinent in ordinary water supply (cf. Legget, 1973).

A typical example of a slide (from 1970) in connection with waste water infiltration is shown in Fig. 18. The site is situated at Intagan about 500 m south of a place where a large landslide occurred in 1648. Waste water from the village is led into an open ditch (trunk drain), as shown in the figure. This trunk drain passes through infiltration zones at two points and water is infiltrated into the ground. In the marked area, situated at the southern infiltration zone, there is a bog contaminated with waste water. Penetration tests have shown, that sand and silt layers are in direct contact with the polluted water. A slide occurred in the adjacent river bank (Göta River) in the winter 1970.

Bodies of water(wells)appear in the scar of this slide (as in most slide scars in Sweden). Chromatographic investigations have been made of water both in the bog and from several surface water bodies in the slide scar. Phosphates were found in all this water. Details of this investigation will be reported later.

The conditions are similar in the slide at Norsälven near Trossnäs in Värmland which occurred on April 12, 1969. Chromatographic analyses show that both within and around this slide area, the ground water contains phosphate. Also this slide occurred in a formation with an abnormal high dielectricity constant according to remote sensing investigations which indicate ground water arteries. When the slide at Trossnäs was fresh, one could sense the characteristic smell of sewage in the scar. Infiltration of waste water may have contributed to the slide.

It was proved that industrial waste water had infiltrated into the ground at the slide area at Göta (1957) and from interviews it has been found that domestic waste water was led in open ditches at the slide area at Surte. No analyses based on this have been made and it was not taken into consideration in the main investigation in the slide year 1950 (Jakobson, 1952, and Caldenius & Lundström, 1956).Thus the conclusion is that infiltration of waste water is connected with recent large landslides, a fact which is easy to check with simple analyses.

Infiltration and Long-Termed Changes of Quick Clay Slopes

During the last decades the rainfall in, e.g., south-western Sweden has become more acid due to sulphuric emission from industries, especially from oil-fired power plants. Therefore, the ground becomes successively more acid. According to the conditions of infiltration given in Fig. 16, this acidification spreads into the ground and can penetrate in deep layers. An acidification of the soil counteracts the formation of the alkaline quick clays. Recent investigations by the Author in several scars in the Göta River Valley from so called bottle-neck slides (flow slides in quick clay) indicate that the clay there now is non-quick or quick with low rapidity. It is possible that the long-term changes of clay soil properties are partly due to changes in the environment.

Studies of Old Slide Scars with the Remote Sensing Method

Studies have been made by the present Author utilizing the field strength meter in sections within and around the slide scars at Surte, Göta, Intagan (slide scar of 1648), Vesten (all in the Göta River Valley), Trossnäs, Guntorp, Svärta and Kyrkviken. For the location of these places, see App. 1 and 2.

As a rule, the upper part of the slide is situated close to rock (cf. Alkhoia & Scott, 1970). Remote sensing curves with pronounced indications were obtained at all slide scars investigated (similar to those obtained in Fig. 20 from the Jordbro slide described below). This must indicate that landslides occur in a special type of local clay sediments having an abnormally high dielectricity constant (i.e., areas rich in ground water arteries and differing from more homogeneous clay deposits in the vicinity).
Due to the above facts, there seems to be no doubt that there is an obvious connection between remote sensing indications and slides. For further speculations of using remote sensing methods in slide studies, see Chang (1971).

Studies of a Recent Slide at Jordbro

A large landslide occurred at Jordbro, about 30 km south of Stockholm, on October 17, 1972. At the time of the slide, one-family houses were being constructed. The slide took place at night. No house in the vicinity of the slide was yet inhabited. Fortunately, no people were killed, but the damage was relatively great. In the upper part of the site earth fill had been placed. A sewage pumping station is situated close to the upper part of the slide area. The soil consists mainly of alternating silt, sand and layers of soft clay. Preliminary penetration tests in 1969 showed the occurrence of layers of soft material also at great depth. Artesian pressure was noticed. Here and there rock outcrops were present.

An air photo of the slide area is shown in Fig. 19 and a plan in Fig. 20. The length of the slide was about 500 m and the width varied from about 60 to 200 m. The narrowest part is the middle of the slide where rock figuration have influenced the shape. In the upper part of the terrain the inclination was 1 to 4 à 1 to 6, the lower part was practically horizontal. The average gradient was

Fig. 19 Air photo of the slide at Jordbro in 1972

Aerial photography carried out by the Geographical Survey Office of Sweden in 1972. The photo is approved of printing by the Office 1973-01-22.

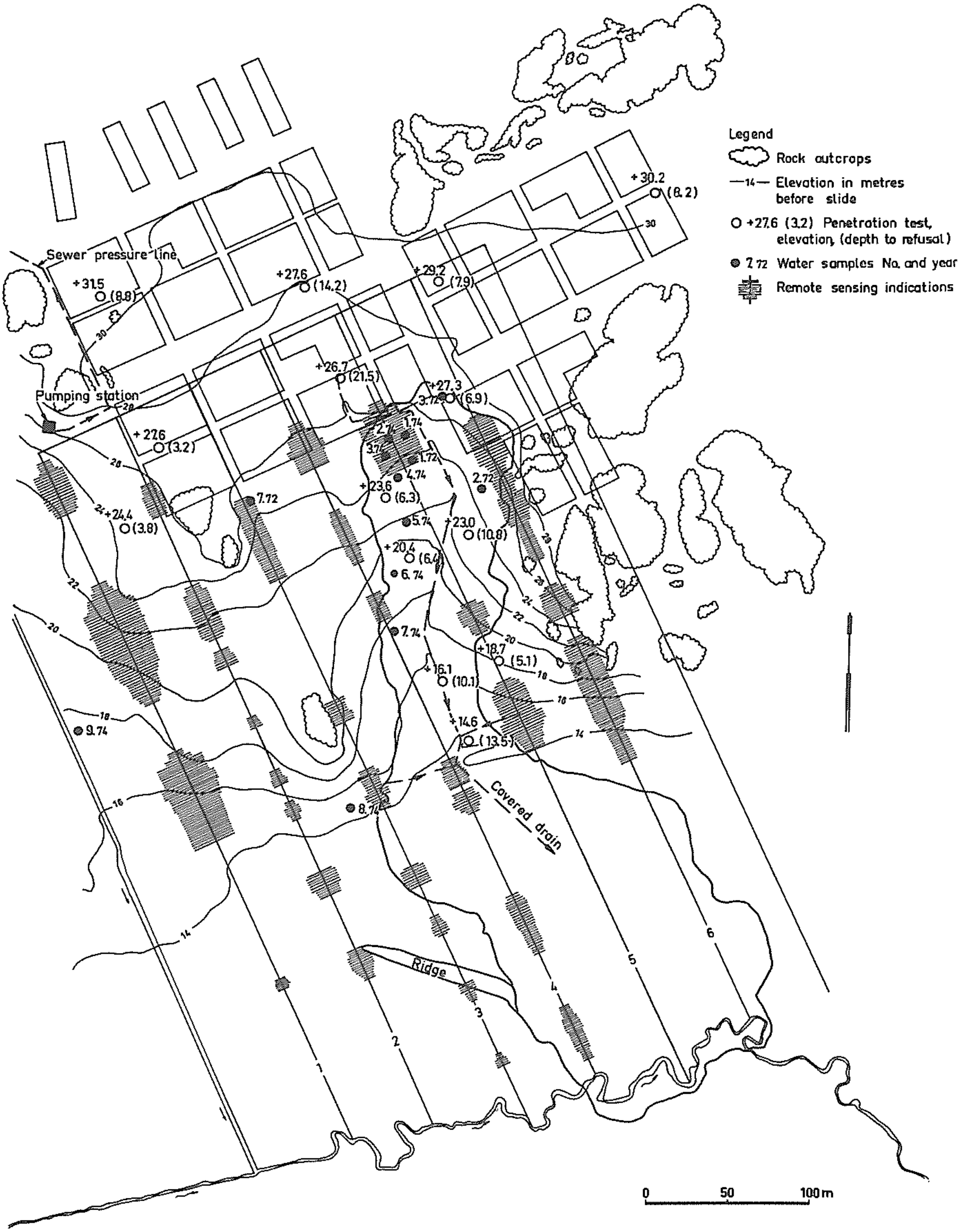


Fig. 20 Plan of site conditions and remote sensing indications in 1973 at the slide area in Jordbro

1 to 17 and the stability conditions were assumed to be satisfactory. The course and the extent of the slide indicate that the soil material present was disposed to flowing. The mass did, however, not flow away very far and spread over a large area as in the so called "bottle neck slides". As in the case of most slides of this type, relatively undisturbed flakes of the stiff upper dry crust flowed downwards and many characteristic portions from the upper part of the slide can be recognized in the lower part. In some areas the dry crust is folded. Remarkable is a very local long, narrow ridge, about 2 m in height, in the southwestern part of the slide (see Fig. 20).

On the experience related earlier in this report the first questions from the Author's point of view were:

1) Did the slide occur in an area rich in remote sensing indications (water arteries)?
2) Is it feasable to refer the slide to some type of waste water infiltration?

An inspection of the site 2 days after the slide showed the characteristic picture of water bodies (wells) in the slide scar with impure water as described in connection with the other slides in this report, investigated with respect to infiltration. Especially in the western side of the upper part, water smelling like waste water was seeping out from the wall into the scar. A peat bog is situated in the same part. Also the water, in the drainage system, which passed through the area and had been destroyed by the slide, had the characteristic smell of waste water.

Preliminary remote sensing investigations were made indicating an area rich in VHF field strength variations thus hinting at a subsurface water seepage. Attempts were then made to trace the source of infiltration of impure water. The map in Fig. 20 shows the position of the pressure pumping station (from 1970) for waste water catering for three thousand people. It is situated about 200 m W of the upper slide edge at a transition zone of rock and sediment in a typical infiltration zone as is shown principally in Fig. 16. The pressure pipe, originally of PVC, is about 1700 m in length, and the water is pumped up 17 m in height. About 100 m of the pressure pipe passes through the above mentioned infiltration zone. During its existence, several pipe breaks have occurred, the most serious in the summer 1972, when all the waste water was pumped directly into the ground during a period of unknown length (probably some months).

About 100 m of PVC pressure pipe in the infiltration zone was replaced by a pipe of tough iron in August 1972.

Water samples were taken within and outside the slide scar. The samples were analysed with paper chromatography with regard to the presence of phosphates. Five samples were sent to a special water laboratory, "Kemibyrån", for a complete analysis of waste water. The test record for this analysis is shown in App. 6 . Supplementary samples were analysed by "Kemibyrån" in November-December 1973. From the results from the bacteriological investigations, given in App. 6 (including also the investigations in 1973),it is seen that in some points practically fresh waste water was present. Also the supplement indicated fresh waste water showing that the sewage system was still defect and sewage spread in the ground.

In order to find the slip surface, determinations were initiated with the salt sounding tool (Söderblom, 1969) but are yet not completed. So far, no definite conclusion can be drawn concerning the depth of the slide. It can be stated that the slide is not of the classical type with respect to a distinct slip surface as was the case at, e.g. Göta (Söderblom, 1969).

The detailed investigation of the slide has been started by making systematic remote sensing measurements in the slide area and its vicinity, Figs. 20 and 21. Six sections, 50 m distance between each, in NNW-SSE direction were investigated (cf. Fig. 20). Areas with indications alternating with areas without indications were found. This fact is in agreement with statements made by Takeuchi (1972) in Japan that water in slide areas follows "vein streams". The investigation is planned to be followed up by salt soundings and sampling, as reported from Lödöse.

Some experiments were made to isolate dispersing agents from clay and silt samples taken in the slide area. The samples were boiled with 5% N_aOH, the solution being dialysed and evaporated. It was possible to isolate strong dispersing agents containing phosphate. When adding lime the flow tendency characteristic of the materials from the area was inhibited, indicating that both clay and silt material contain colloidal material to a sufficient amount to make it coagulate by electrolytes. (Unfortunately, no grain size determinations have hitherto been made.)

Many problems remain to be solved regarding the Jordbro slide and it is hoped that it will be possible to complete the studies.

Chemical Stabilization of Quick Clays

The diffusion coefficient of salts in a quick clay seems generally to be too low to permit practical chemical stabilization of the soil based on pure diffusion. This has been confirmed by experiments in Sweden (Söderblom, 1969, 1970), in USA (Gast & East, 1964) and in Russia (Rehbinder, 1970).

Results have, however, been published both from Sweden (Sandegren, 1968; Talme, 1968; Jerbo, 1969) and from Norway (Moum et al. 1968) which report that stabilization of quick clay with calcium chloride and potassium chloride is obtained, at least temporarily. The present Author studied by remote sensing some of the places in Sweden, mentioned in the above reports, where a good spreading of introduced chemicals have been found (Kyrkviken, Rossötjärn, Läggesta and Jönåker).[1] As found by remote sensing all these sites were rich in ground water arteries with anomalies in the dielectric properties. Chemicals can thus easily spread with the ground water. This type of stabilizing experiment cannot be taken as a basis for any calculation of diffusion of salts in clay, especially not by means of Fick's diffusion laws of the distribution of the salts (Fick, 1855).

Experiments by the Swedish Geotechnical Institute (to be published) on chemical stabilization of homogeneous clays based on pure diffusion have given the same magnitude of diffusion constants as reported by Söderblom (1969) from studies of the equilization with time of the sharp conductivity gradient in slip zones.

Discussion and Conclusion

The application of the remote sensing method developed at the Swedish Geotechnical Institute and described in this paper has provided new aspects on the quick clay problem, including the formation of slide-disposed soils and factors

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1) Site localization, see App. 1.

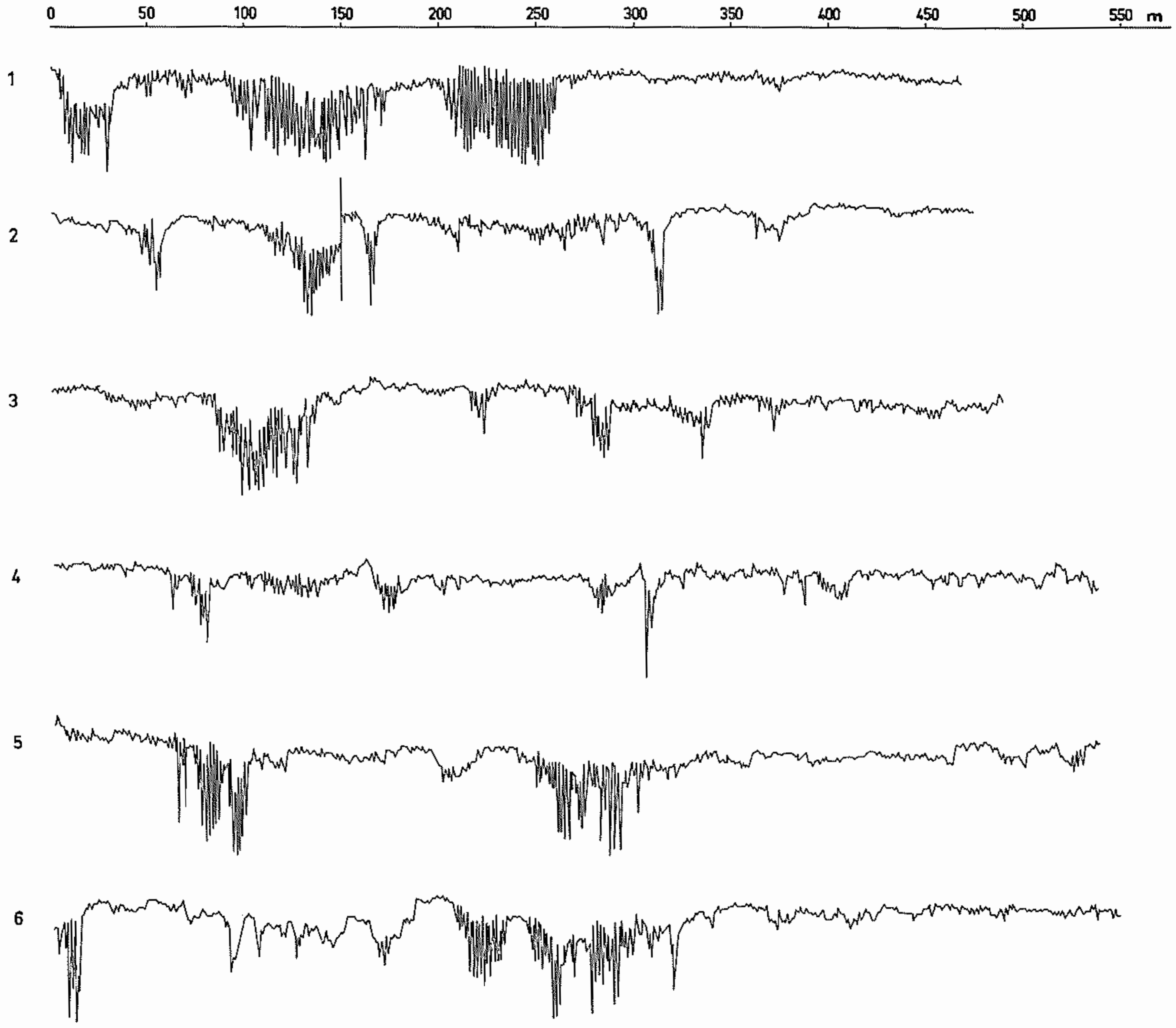

Fig. 21 Remote sensing indications at Jordbro in 1973

involved in the processes changing the geotechnical properties in the ground. So far, the remote sensing method has by the Author only been used to localize places with a dielectricity constant varying from the surroundings.

No natural factors have been found which can explain the formation of high rapid quick clays. On the contrary, it has been possible to find a relationship between the occurrence of quick clays of high rapidity and infiltration of waste water in ground water artery streaks. The basic chemical processes in this connection are being studied in many countries (cf. McGauhey & Krone, 1967) and are found to be very complex.

It has been possible to extract organic high molecular dispersing agents containing phosphates from all high rapid quick clays found. Some further results from these investigations as well as the effects of humus precipitation of the structure of clays will be treated in another report (Söderblom, 1974).

The knowledge of local ground water flows is at present too limited to allow a fruitful discussion of the relationship between such flows and quick clay formation. The investigations made by the present Author confirm, in accordance with the results obtained by Takeuchi (1972), that the water around and in a slide area flows in underground vein streams. Takeuchi also discusses in his paper the importance of underground streams to the developing and propagation of landslides. It should be mentioned that Knutsson (1971), by means of radioactive tracers, obtained an artery streaming picture of the ground water in Emmaboda, Småland, Sweden. Further experiments on the flow of ground water are planned. These experiments will probably also be combined with a detailed study of the chemical stabilization process and drainage.

If an area such as that at Lödöse, which contains local water artery streaks and having geotechnical properties differing from those in its vicinity, is investigated by too few bore holes and, further, chosen without any preceding physical study of the homogeneity of the clay sediments and its hydrological conditions, a false picture of the general stability precautions may be obtained. It would be recommendable to perform remote sensing studies also as a routine method on many sites where stability conditions are estimated to be bad and to make supplementary investigations when alarming results are found.

It seems very difficult to work out chemical stabilization methods which can be used in general for practical purposes in clay soils. This is especially difficult for homogeneous fine-grained clays, because the diffusion coefficient is too low to obtain an acceptable rapid spreading of the chemicals. Stabilization methods can, however, be applied to some extent in special types of clay and silt sediments (fissured and layered) in which ground water arteries contribute to the spreading of the chemicals. As mentioned earlier in this paper, landslides are frequently located in seepage areas and therefore stabilization methods limited to such areas can be of great value (Jones, 1973). However, the practical results of chemical stabilization work (Jerbo, 1972) obtained so far are too few, and often contradictory, to recommend a commercial application of the method. It would be desirable to continue the research in this very important field both with respect to stabilizing and to dispersing chemicals.

The study of clays with high rapidity loosing part of their strength due to a small shear action has given hints of some speculations about the reliable shear strength determinations and the development of retrogressive landslides. According to Bjerrum & Kjaernsli (1957) the use of undrained strength values to estimate the long-term stability of natural clay slopes can give unreliable results. The use of undrained strengths determined by standard procedures yields estimated values of the safety factor $F \gg 1$ for failure conditions.

According to Kenney & Drury (1973) a large sensitivity of a clay should be considered as the strain softening factor necessary for the development of a retrogressive slide. The present Author is of the opinion that soils with a high rapidity number independent of high sensitivity are dangerous in this respect.
It therefore seems to be of great importance to study the processes giving the clays high rapidity further and to refine the method for the determination of this parameter.

Involved in the chemical change processes is obviously the infiltration of waste water. The trend at present is that domestic waste water is concentrated to certain areas where it is chemically cleaned in purification plants. The conduits are in many cases not watertight,a fact which can lead to infiltration into the soil. This in its turn can result in serious consequences in instable areas.
For exploration purposes the remote sensing methods seem to be useful. The method can, of course, be still more developed to better suit geotechnical exploration.

The problem of waste water and its influence on the geotechnical properties is thus to be regarded as a very important question and must be taken up for general consideration as soon as possible. Papers from, e.g., USA indicate that the problem has already been observed there (White & Kyriazis, 1968).

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Rolf Söderblom

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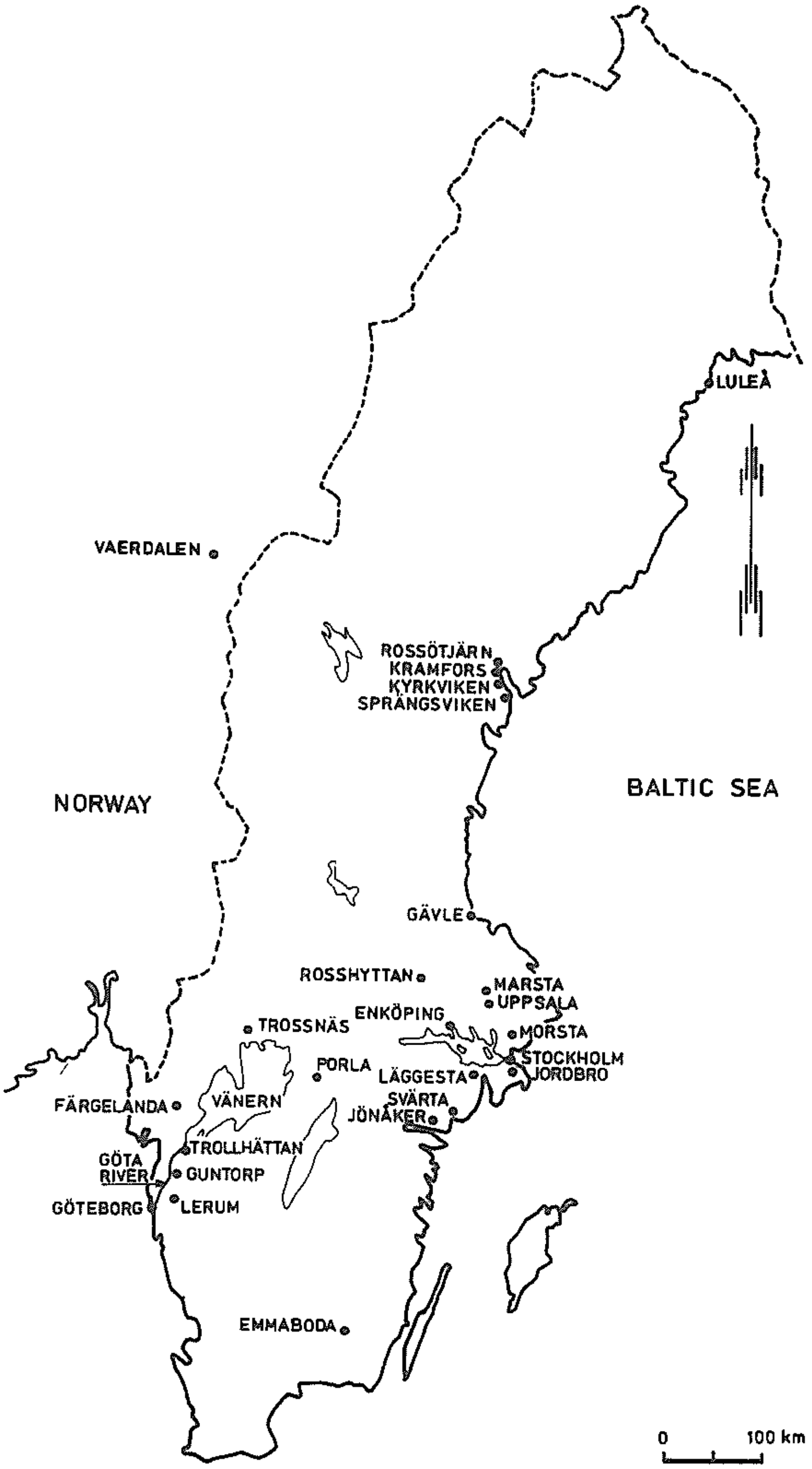
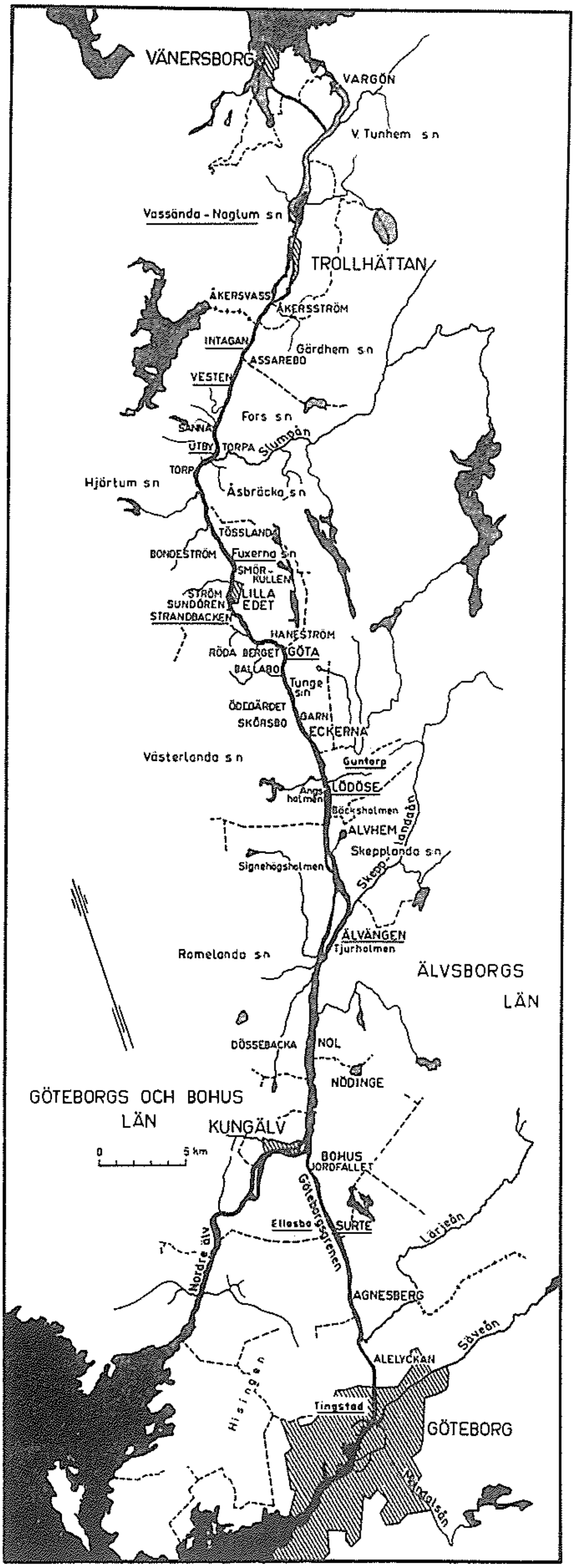
APPENDICES 1 - 6



Appendix 1. Map of Sweden showing places investigated



Appendix 2. Map showing places investigated in the Göta River Valley

3. Geotechnical data from test site at Fuxerna

atural ater ontent	Shear strength (cone test)		Sensitivity (cone test)	Strength values			Liquid limit	$\varkappa \cdot 10^3$
w%	Unremoulded t/m^2	Remoulded t/m^2	S_t	H_3	H_1	H_3/H_1 (S_t)	w_L%	$ohm^{-1}\ cm^{-1}$
53	6.14	0.89	6.9	435	57.9	7.5	-	-
62	3.14	0.085	37	163	4.93	33	-	-
79	2.31	0.0188	123	110	1.05	105	-	-
85	2.49	0.0188	132	120	1.05	114	-	-
80	3.00	0.0222	135	153	1.26	121	-	-
80	3.14	0.0265	118	163	1.51	108	-	-
69	2.79	0.0475	58.7	141	2.92	48	-	-
43	-	-	-	-	-	-	-	-
31	-	-	-	-	-	-	-	-
66	2.79	0.0102	274	141	0.602	234	-	-
72	2.37	0.0095	250	113	0.562	201	-	-
71	2.93	0.0102	287	149	0.602	248	-	-
69	3.14	0.0087	361	163	0.522	313	-	-
71	3.14	0.0087	361	163	0.522	313	-	-
69	3.14	0.0074	424	163	0.445	366	-	-
69	2.93	0.0066	444	149	0.384	388	-	-
72	2.79	0.0064	436	141	0.354	398	-	-
70	2.79	< 0.0062	> 450	141	< 0.330	> 427	-	-
71	2.79	< 0.0062	> 450	141	< 0.330	> 427	-	-
48	2.93	0.110	26.6	149	1.66	90	-	-
85	2.79	0.065	43	141	0.642	220	-	-

(Continued)

Natural water content w%	Shear strength (cone test) Unremoulded t/m^2	Remoulded t/m^2	Sensitivity (cone test) S_t	Strength values H_3	H_1	H_3/H_1 (S_t)	Liquid limit $w_L\%$	$\varkappa \cdot 10^3$ $ohm^{-1}\ cm^{-1}$
69	3.38	0.070	48.3	178	4.09	44	-	-
73	3.30	0.0265	125	173	1.51	115	-	-
79	2.79	0.0143	195	141	0.81	174	-	-
53	2.79	0.0080	349	141	0.482	293	-	-
81	2.25	$<$ 0.0062	363	107	$<$ 0.33	$>$ 324	-	-
77	2.49	$<$ 0.0062	401	120	$<$ 0.33	$>$ 364	-	-
69	2.86	$<$ 0.0062	461	145	$<$ 0.33	$>$ 440	-	-
49	2.93	0.0120	24.4	149	0.688	217	-	-
65	2.31	0.0775	29.8	110	4.48	25	-	-
24	3.55	0.182	19.5	189	10.6	18	-	-
64	1.43	0.0650	22.0	64.5	3.82	17	-	-
57	4.78	1.52	3.14	296	69.8	4.2	-	-
86	1.71	0.0780	21.9	61.5	4.4	14	-	-
-	-	-	-	-	-	-	-	-
48	6.14	2.19	2.8	435	104	4.2	-	-
50	6.36	2.49	2.6	463	120	3.9	-	-
46	6.36	2.49	2.6	463	120	3.9	-	-
114	1.37	0.0450	30.4	61.5	2.7	23	-	-
79	2.19	0.0400	54.7	104	2.3	45	-	-
81	2.19	0.0385	57.0	104	2.2	47	-	-
91	1.31	0.0222	59.0	58.5	1.26	46	-	-
94	0.77	0.0188	40.9	34.2	1.05	33	-	-
66	1.46	0.0265	55.0	52.2	1.51	35	-	-
60	2.61	0.050	52.2	128	3.1	41	-	-
45	2.49	0.050	49.8	120	3.1	40	-	-

(Continued)

Natural water content	Shear strength (cone test)		Sensitivity (cone test)	Strength values			Liquid limit	$\varkappa \cdot 10^3$
w%	Unremoulded t/m^2	Remoulded t/m^2	S_t	H_3	H_1	H_1/H_3 (S_t)	w_L%	$ohm^{-1}cm^{-1}$
51	6.36	2.79	2.28	463	141	3	-	-
81	2.49	0.0925	26.9	120	5.3	23	-	-
84	2.49	0.060	41.5	120	3.57	34	-	-
85	2.79	0.050	55.8	141	3.1	45	-	-
71	4.78	0.129	37.0	296	7.5	39	-	-
78	2.79	0.060	46.5	141	3.57	39	-	-
59	3.38	0.452	7.5	178	26.8	66	-	-
93	1.97	0.0425	46.4	93	2.5	37	-	-
78	2.37	0.0130	18.2	113	0.74	153	-	-
71	3.14	0.0102	308	163	0.6	272	-	-
73	3.00	0.0069	435	153	0.41	373	-	-
74	2.79	0.0064	436	141	0.35	403	-	-
74	3.14	< 0.0062	506	163	< 0.33	> 494	-	-
69	3.00	< 0.0062	484	153	< 0.33	> 464	-	-
70	3.00	< 0.0062	484	153	< 0.33	> 464	-	-
59	2.67	0.0203	132	132	1.15	115	-	-
45	2.19	0.070	31.3	104	4.09	25	-	-
56	2.79	0.0265	105	141	1.5	94	-	-
97	1.87	0.0550	34.0	88.3	3.32	27	-	-
92	1.28	0.050	25.6	57.1	3.1	18	-	-
91	2.31	0.065	85.5	110	3.8	29	-	-
58	1.79	0.085	21.1	83.7	4.9	17	-	-
75	2.61	0.0550	47.5	128	3.32	39	-	-
51	1.71	0.0425	40.2	79.4	2.52	32	-	-

(Continued)

Natural vater ontent	Shear strength (cone test)		Sensitivity (cone test)	Strength values			Liquid limit	$\varkappa \cdot 10^3$
w%	Unremoulded t/m^2	Remoulded t/m^2	S_t	H_3	H_1	H_1/H_3 (S_t)	w_L%	ohm^{-1} cm^{-}
83	1.08	0.0650	16.6	49.0	3.82	13	-	-
77	1.71	0.0650	26.3	79.4	3.82	21	-	-
79	1.22	0.0600	20.3	54.6	3.57	15	-	-
86	2.19	0.0650	33.7	104	3.82	27	-	-
80	1.71	0.100	17.1	79.4	5.89	13	-	-
49	3.00	0.450	6.67	153	26.8	5.7	-	-
51	3.84	0.595	6.45	208	37	5.6	-	-
60	3.55	0.595	5.97	189	37	5.1	-	-
83	1.92	0.070	27.4	90.6	4.09	22	-	-
89	1.28	0.0425	30.1	57.1	2.52	23	-	-
43	3.38	0.890	3.8	178	57.9	3.1	-	-
35	6.36	5.70	1.12	463	389	1.2	-	-

4. Geotechnical data from test site at Vassända Naglum

atural ater ontent	Shear strength (cone test)		Sensitivity	Strength values		H_3/H_1	Liquid limit	$\varkappa \cdot 10^3$
w%	Unremoulded t/m^2	Remoulded t/m^2	S_t	H_3	H_1	(S_t)	w_L%	ohm^{-1} cm^{-1}
17	1.31	0.233	5.62	58.5	13.8	4.3	-	-
44	0.42	< 0.0062	> 68	17	< 0.33	> 52	-	-
36	0.37	< 0.0062	> 60	15	< 0.33	> 46	-	-
61	0.345	< 0.0062	> 56	14	< 0.33	> 43	-	-
23	1.16	0.0064	181	52	0.35	149	-	-
-	-	-	-	-	-	-	-	-
72	1.52	< 0.0062	> 245	69.8	< 0.33	> 211	-	-
65	2.79	< 0.0062	> 450	141	< 0.33	> 426	-	-
67	1.92	< 0.0062	> 308	90.6	< 0.33	> 275	-	-
75	1.71	< 0.0062	> 276	79.4	< 0.33	> 240	-	-
75	1.92	< 0.0062	> 310	90.6	< 0.33	> 275	-	-
60	1.92	< 0.0062	> 310	90.6	< 0.33	> 275	-	-
86	1.92	< 0.0062	> 310	90.6	< 0.33	> 275	-	-
61	1.92	< 0.0062	> 310	90.6	< 0.33	> 275	-	-
46	1.83	< 0.0062	> 295	86	< 0.33	> 261	-	-
26	2.07	< 0.0062	> 334	98	< 0.33	> 297	-	-
47	2.67	< 0.0062	> 431	132	< 0.33	> 400	-	-
59	2.19	< 0.0062	> 353	104	< 0.33	> 315	-	-
46	1.52	< 0.0062	> 245	69.8	< 0.33	> 212	-	-
45	1.92	< 0.0062	> 310	90.6	< 0.33	> 275	-	-
35	1.37	< 0.0062	> 221	61.5	< 0.33	> 186	-	-
35	1.37	< 0.0062	> 221	61.5	< 0.33	> 186	-	-
37	2.37	< 0.0062	> 382	113	< 0.33	> 342	-	-
29	0.809	< 0.0062	> 130	7.5	< 0.33	> 23	-	-
37	0.98	0.0087	113	44.1	0.52	85	-	-

(Continued)

Natural water content	Shear strength (cone test)		Sensitivity (cone test)	Strength values			Liquid limit	$\varkappa \cdot 10^3$
	Unremoulded t/m^2	Remoulded t/m^2				H_3/H_1		
w%			S_t	H_3	H_1	(S_t)	w_L%	$ohm^{-1}cm^{-1}$
26	1.40	0.397	3.5	63	22.8	2.76	-	-
88	0.435	< 0.0062	70	17.9	< 0.33	> 54	-	-
26	1.52	0.0066	230	69	0.384	180	-	-
-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-
30	1.55	< 0.0062	> 250	71	< 0.33	> 215	-	-
53	2.79	< 0.0062	> 450	141	< 0.33	> 427	-	-
65	2.07	< 0.0062	> 335	98	< 0.33	> 297	-	-
70	2.31	< 0.0062	> 373	110	< 0.33	> 333	-	-
67	2.31	< 0.0062	> 373	110	< 0.33	> 333	-	-
67	2.19	< 0.0062	> 353	104	< 0.33	> 315	-	-
46	1.71	< 0.0062	> 276	79	< 0.33	> 239	-	-
38	0.94	< 0.0062	> 152	42	< 0.33	> 127	-	-
48	3.22	< 0.0062	> 519	168	< 0.33	> 509	-	-
45	2.79	< 0.0062	> 450	141	< 0.33	> 427	-	-
35	2.43	< 0.0062	> 392	117	< 0.33	> 355	-	-
43	2.67	< 0.0062	> 431	132	< 0.33	> 400	-	-
52	2.31	< 0.0062	> 273	110	< 0.33	> 333	-	-
36	1.25	< 0.0062	> 202	55	< 0.33	> 167	-	-
37	3.00	< 0.0062	> 484	153	< 0.33	> 464	-	-
32	1.40	< 0.0062	> 226	63	< 0.33	> 191	-	-
42	2.37	< 0.0062	> 382	113	< 0.33	> 342	-	-
37	3.07	0.0066	465	158	0.38	416	-	-
43	2.55	0.0074	345	124	0.44	282	-	-

ontinued)

atural ater ntent	Shear strength (cone test)		Sensitivity (cone test)	Strength values			Liquid limit	$\varkappa \cdot 10^3$
w%	Unremoulded t/m^2	Remoulded t/m^2	S_t	H_3	H_1	H_3/H_1 (S_t)	w_L %	ohm^{-1} cm^{-1}
13	1.08	0.233	4.64	49	13.8	3.5	-	-
44	0.68	0.0066	103	30	0.38	79	-	-
60	1.59	0.0087	183	73.5	0.52	141	-	-
25	1.08	0.012	90	49	0.68	72	-	-
62	2.49	0.0143	174	120	0.81	148	-	-
22	1.92	0.0583	33	90	3.3	27	-	-
42	1.40	< 0.0062	> 226	63	< 0.33	> 191	-	-
36	1.75	< 0.0062	> 282	81	< 0.33	> 246	-	-
55	1.83	< 0.0062	> 295	86	< 0.33	> 260	-	-
69	2.19	< 0.0062	> 353	104	< 0.33	> 316	-	-
65	2.19	< 0.0062	> 353	104	< 0.33	> 315	-	-
65	1.83	0.0780	23.5	86	4.4	20	-	-
36	2.49	0.0915	27.2	120	6.4	19	-	-
26	3.30	0.397	8.3	173	22.8	7.6	-	-
44	3.00	0.0402	75	153	2.2	70	-	-
45	3.14	0.0449	70	163	2.5	65	-	-
49	2.79	0.0360	78	141	2.05	69	-	-
60	1.59	< 0.0062	> 256	73.5	< 0.33	> 223	-	-
54	2.79	0.0064	436	141	0.35	403	-	-
77	2.79	0.0066	423	141	0.38	371	-	-
46	1.92	< 0.0062	> 310	90	< 0.33	> 273	-	-
64	2.19	< 0.0062	> 353	104	< 0.33	> 315	-	-
52	2.79	0.0087	321	141	0.52	271	-	-
52	2.79	< 0.0062	> 450	141	< 0.33	> 427	-	-
50	1.92	0.0066	291	90	0.38	237	-	-
58	2.49	0.0203	123	120	1.15	104	-	-
69	2.49	0.0173	144	120	0.98	122	-	-
36	1.52	0.0360	42.2	69.8	2.05	34	-	-

ontinued)

tural ter ntent w%	Shear strength (cone test) Unremoulded t/m^2	 Remoulded t/m^2	Sensitivity (cone test) S_t	Strength values H_3	 H_1	H_3/H_1 (S_t)	Liquid limit w_L%	$\kappa \cdot 10^3$ ohm^{-1} cm^{-1}
54	2.79	0.0360	78	141	2.0	70	-	-
53	2.79	0.0360	78	141	2.0	70	-	-
63	1.92	0.0449	43	90.6	2.58	35	-	-
50	1.71	0.0449	38	79.4	2.58	31	-	-
38	1.16	0.0509	23	52.2	2.9	18	-	-
36	1.31	0.0509	26	58.5	2.9	20	-	-
23	1.52	0.0449	34	69.8	2.58	27	-	-
27	2.37	0.0369	65	113	2	57	-	-
-	-	-	-	-	-	-	-	-
51	1.46	0.0087	168	66	0.52	127	-	-
-	-	-	-	-	-	-	-	-
26	2.07	0.0120	173	98	0.68	144	-	-
-	-	-	-	-	-	-	-	-
54	2.79	0.0087	321	141	0.52	271	-	-
62	2.19	0.0069	317	104	0.41	254	-	-
62	1.52	0.0074	205	69.8	0.44	159	-	-
68	1.83	0.0074	247	86	0.44	195	-	-
40	0.940	0.203	4.6	42	1.15	37	-	-

ontinued)

tural ter ntent	Shear strength (cone test)		Sensitivity (cone test)	Strength values		H_3/H_1	Liquid limit	$\varkappa \cdot 10^3$
w%	Unremoulded t/m^2	Remoulded t/m^2	S_t	H_3	H_1	(S_t)	w_L%	$ohm^{-1}\ cm^{-1}$
40	1.31	0.0087	151	58.5	0.52	113	-	-
-	-	-	-	-	-	-	-	-
53	1.83	0.0066	277	86	11	7.8	-	-
69	1.16	0.0102	114	52	0.60	87	-	-
73	2.07	0.0120	173	98	0.68	144	-	-
48	1.08	0.0060	180	49	0.38	129	-	-

5. Geotechnical data from test site at Färgelanda

atural ater ontent	Shear strength (cone test)		Sensitivity (cone test)	Strength values			Liquid limit	$\varkappa \cdot 10^3$
w%	Unremoulded t/m^2	Remoulded t/m^2	S_t	H_3	H_1	H_3/H_1 (S_t)	w_L%	ohm^{-1}cm^{-1}
68	1.06	< 0.0062	> 171	47.9	< 0.33	> 145	43	0.308
76	1.06	< 0.0062	> 171	47.9	< 0.33	> 145	41	0.319
83	0.744	< 0.0062	> 120	33.0	< 0.33	> 100	45	0.319
66	1.16	< 0.0062	> 187	52.2	< 0.33	> 158	39	0.296
72	1.06	< 0.0062	> 171	47.9	< 0.33	> 145	39	0.286
22	3.00	0.210	15	141	12.3	11.5	21	0.286
68	0.862	< 0.0062	> 139	39.2	< 0.33	> 119	33	0.266
57	1.06	< 0.0062	> 171	47.9	< 0.33	> 145	30	0.222
56	1.10	< 0.0062	> 177	50.0	< 0.33	> 151	30	0.266
51	1.10	0.0200	55	50.0	1.13	44	32	0.210
46	1.67	0.0285	59	77.4	1.63	47.5	33	0.210
53	1.06	0.0324	33	47.9	1.84	26	30	0.210
49	1.75	0.0324	54	81.5	1.84	44	41	0.235
33	2.02	0.0360	56	95.5	2.0	48	43	0.182
47	2.25	0.0598	38	107	3.41	32	38	0.222
46	2.79	0.0780	36	141	4.4	32	38	0.235
46	2.79	0.0780	36	141	4.4	32	37	0.236

Continued)

atural ater ontent	Shear strength (cone test)		Sensitivity (cone test)	Strength values			Liquid limit	$\varkappa \cdot 10^3$
w%	Unremoulded t/m^2	Remoulded t/m^2	S_t	H_3	H_1	H_3/H_1 (S_t)	w_L%	ohm^{-1}cm^{-1}
70	0.960	0.0509	18.9	40.0	2.9	14	55	0.952
49	1.71	0.0087	197	79.4	0.52	153	33	0.334
35	8.54	5.7	1.5	89.5	389	2.3	40	0.364
34	6.8	3.14	2.2	526	163	3.2	41	0.527
41	1.92	0.0449	43	90.6	2.58	35	29	0.455
34	1.08	0.0102	106	49.0	0.60	82	23	0.400
43	2.19	0.0173	127	104.0	0.98	106	43	0.472
62	1.08	0.0087	124	49.0	0.52	94	42	0.617
63	1.59	0.0074	215	73.5	0.44	167	44	0.617
67	1.79	0.0066	271	83.7	0.38	220	44	0.635
62	1.79	< 0.0062	> 289	83.7	< 0.33	> 254	38	0.645
59	1.83	< 0.0062	> 295	86	< 0.33	> 261	33	0.690
56	1.79	< 0.0062	> 289	83.7	< 0.33	> 254	32	0.615
52	1.92	< 0.0062	> 310	90.6	< 0.33	> 275	30	0.520
48	0.60	0.0089	69	25.8	0.52	50	32	0.420
47	0.67	0.0143	47	29.4	0.816	36	34	0.405
-	-	-	-	-	-	-	-	-
49	1.22	0.0188	65	54.6	1.05	52	40	0.472
40	0.60	0.0130	46	25.8	0.746	35	25	0.286
-	-	-	-	-	-	-	-	-

(Continued)

Natural water content w%	Shear strength (cone test) Unremoulded t/m^2	Shear strength (cone test) Remoulded t/m^2	Sensitivity (cone test) S_t	Strength values H_3	H_1	H_3/H_1 (S_t)	Liquid limit w_L%	$\varkappa \cdot 10^3$ ohm^{-1}cm^{-1}
46	2.02	0.0107	189	95.5	0.634	151	35	0.308
48	2.19	0.0143	153	10.4	0.816	127	35	0.975
63	2.19	0.0583	37.6	10.4	3.32	32	50	1.212
33	2.79	0.036	77.5	141	2.05	69	35	1.025
42	2.19	0.0324	67.6	104	1.84	57	33	1.141
40	2.19	0.0265	82.6	104	1.51	69	34	1.212
50	2.49	0.0188	132	120	1.05	114	31	1.332
67	0.650	0.0074	88	28.2	0.445	63	43	1.60
42	0.783	0.0087	90	34.8	0.52	67	43	1.29
47	3.55	0.0509	70	189	2.9	65	28	1.54
63	2.49	0.0130	192	120	0.746	161	45	1.38
58	2.79	0.0120	233	141	0.688	205	43	1.212
46	2.79	0.0158	177	141	0.898	157	35	1.212
65	2.79	0.0188	148	141	1.05	134	49	1.332
60	2.61	0.0087	300	120	0.522	230	42	1.25
57	2.67	0.0130	205	132	0.746	177	42	1.25
54	3.55	0.0130	273	189	0.746	253	40	1.29
53	3.14	0.0130	242	163	0.746	218	40	1.025
55	3.55	0.0130	273	189	0.746	253	39	1.025
46	3.55	0.0188	189	189	1.05	180	38	0.690
44	2.93	0.0583	50.3	149	3.32	45	37	0.727
48	2.93	0.109	26.9	149	6.39	23	37	0.800
40	3.30	0.109	30.3	173	6.39	27	40	0.785
37	4.78	0.210	22.8	296	12.3	24	31	0.755

x 6. Results from chemical analysis of surface water at the slide at Jordbro

Bacteriological investigations		Chemical investigations					
Thermostable bacterium colis per 100 ml	Coliform per 100 ml	pH	$KMnO_4$ mg/l	Nitrate + Nitrite mg/l	Ammonium NH_4 mg/l	Phosphate mg/l	Tens mg/l
10	10	7.0	56	0.2	0.1	0.046	Detec
10	70	9.1	26	1.4	0.1	0.019	Detec
10	10	6.6	96	1.0	0.2	0.002	Detec
14 400	1 422 000	-	-	-	-	-	-
10	10	7.2	74	0.2	0.1	0.015	0
406 500	5 925 000	-	-	-	-	-	
10	400	7.1	18	0.01	0.13	0.081	Detec
100	15 000	7.9	7.9	110	0.01	0.96	Detec
20	4 300	7.9	7.9	96	0.02	0.74	Detec
10	550	7.6	7.6	21	0.11	0.10	Detec
10	3 500	7.0	170	2.9	0.05	0.60	Detec
10	3 500	7.8	130	0.01	0.01	1.1	Detec
10	60	6.6	280	0.01	8.5	0.34	-
10	200	7.8	3	0.01	0.01	0.018	Detec
100	5 000	7.4	290	0.02	0.01	1.5	0.
650 000	3 000 000	7.4	9600	0.02	1.2	0.015	0.
3 500*)	33 000*)	5.7	-	11**)	7.4**)	7.4**)	0
10	10	7.0	56	0.2	0.1	0.01	0

r 100 g
g/kg

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ASPECTS ON SOME PROBLEMS OF GEOTECHNICAL CHEMISTRY — PART III

By ROLF SÖDERBLOM

Söderblom, R.: Aspects on some problems of geotechnical chemistry — Part III. *Geologiska Föreningens i Stockholm Förhandlingar.* Vol. 92, pp. 452—468. Stockholm, 15th December 1970.

This report deals with results from an investigation in the Göta River Valley on the importance of salt content on the geotechnical properties of marine clays. Salt distribution in slopes is discussed and the method to determine slip surfaces in slides by means of salt soundings. The leaching theory has been studied both in the field and in the laboratory. No relation seems to exist between the total salt content in the pore water and the sensitivity. A relation seems, however, to exist between the chemical composition of the pore water salt and the sensitivity. Leached non quick clays contain relatively more divalent ions in the pore water than the quick clays. It can be shown that calcium and magnesium are complex bound in the quick clay system by means of organic material. The Donnan condition is thus valid for a quick clay system in spite of the apparent deviation. Ageing phenomena in quick clays are discussed. These properties seem to be in opposition to the classical leaching theory. Diffusion in natural slopes can be studied from the sharp salt gradient formed in a slide and some diffusion studies are reported. The connection between diffusion and electrical conductivity is also treated. The pure diffusion in Göta River clays seems to be too small for a commercial chemical stabilization. Other possible stabilization methods are also discussed.

Dr. R. Söderblom,

Salt distribution in slopes in the Göta River Valley

When studying the total salt content in undisturbed Swedish clay profiles one obtains curves of the type shown in Fig. 1. The salt content (and the conductivity of the clay) is highest in the middle of the profile. The curves are smooth and show no discontinuities.

As a rule, the slopes in the Göta River Valley have their saltiest clay near the river bank and the salt content decreases with increasing distance from the river, as shown in analyses given in Figs. 2, 3 and 4. The salt content in the vicinity of the river is about 3 %, about the same as in seawater.

These facts can be explained by diffusion both from the ground surface and from the bottom. Figs. 2 and 3 show that the diffusion has not yet been able to penetrate the deeper part of the section as thoroughly has been the case in the shallower parts. In the unleached parts of the clay section the ionic composition seems to correspond to that of seawater. In the leached parts two different compositions are found, both deviating

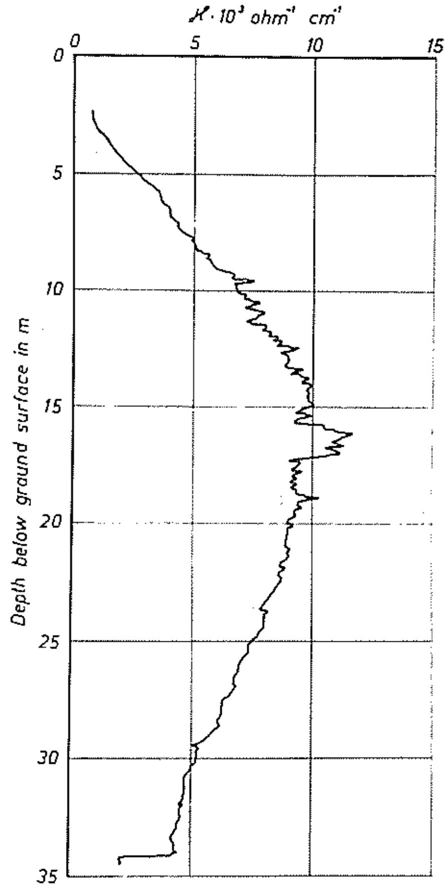

Fig. 1. Typical salt sounding curve (Utby Hole 602).

from that in seawater, due to partial leaching (cf. Rosenqvist, 1955). This will be treated in connection with the ionic composition of the pore water of quick clays.

The decrease in salt content with distance from the river makes it possible to localize slip surfaces in slides by means of electrical salt soundings. In a slide, clay from the upper part of the slope moves on the slip surface and comes to a halt nearer the river. This means that clay with a low salt content comes to rest directly upon clay with a high one, giving a sharp gradient in the salt content curve in the slip zone. Fig. 5 gives a curve from the Göta slide in 1957 (cf. Odenstad, 1958) showing a low salt content directly in contact with a higher one. Fig. 6 shows the appearance of such a slip zone where two different clays are in contact.

This opens a possibility to study the diffusion in clays in situ, because the sharp salt gradient tends to equalize with time.

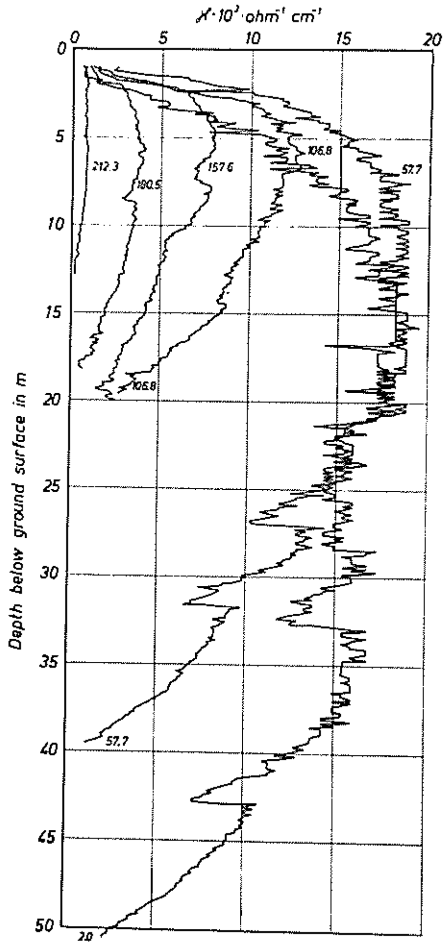

Fig. 2. Salt sounding curves from a section at Lödöse, showing salt distribution. Figures on the curves indicate distance from the Göta River in metres.

Field and Laboratory Studies of the Salt Leaching Theory

Bjerrum (1954) and Rosenqvist (1955) have found a relation between the pore water salinity and the sensitivity of Norwegian marine clays. This relation indicates a valuable practical application in localizing quick clays, and was studied both in the field in the Göta River Valley and in the laboratory.

The following results were however obtained.

A correlation between conductivity and sensitivity in clays from six points in the Göta River Valley is shown in Fig. 7. Clays with low sensitivity are found in the whole conductivity range. Quick clays on the other hand

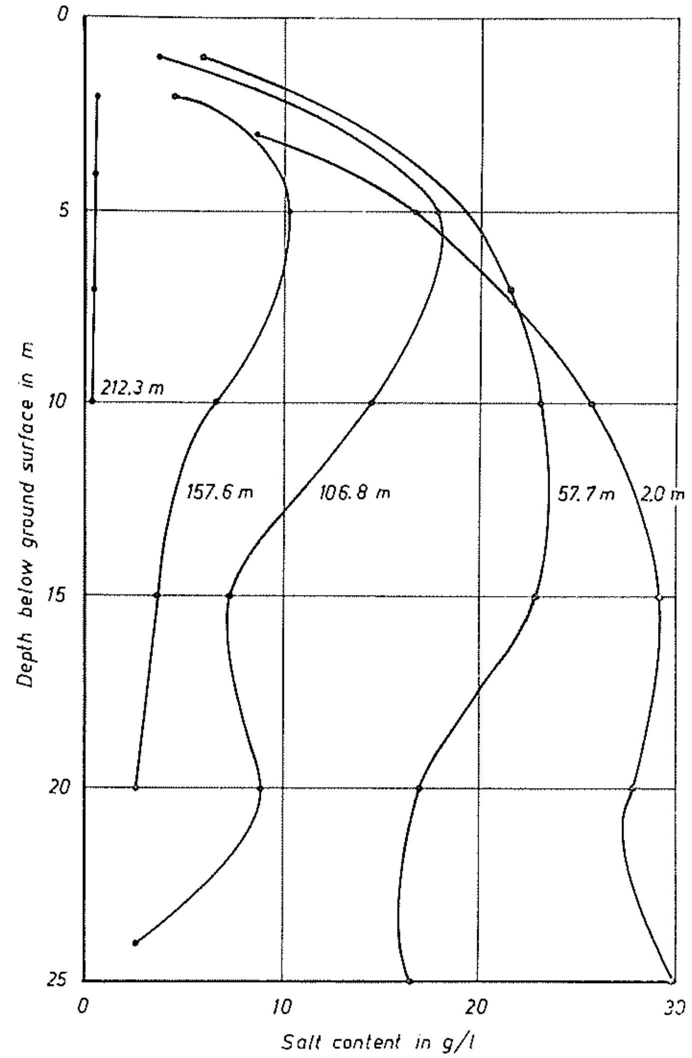

Fig. 3. Curves showing variation of pore water salt content with depth and distance from the Göta River in the profile at Lödöse.

are only found below a certain conductivity value. The relation shows an L-shaped point distribution (cf. Penner, 1965).

The conductivity curves had always the smooth course shown in Fig. 1, whether the profile contains quick clay or not. In contrast the sensitivity curves are mostly very irregular. A typical example is shown in Fig. 8.

The sensitivity thus seems to be caused by other factors than the salinity, which becomes smoothed out by diffusion.

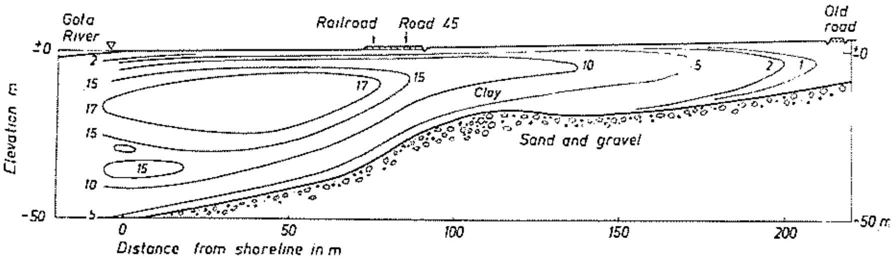

Fig. 4. Schematic view of the section examined at Lödöse showing variation in conductivity.

A stated by Penner (1964, 1965) and by Talme et al. (1966, 1968) the ionic composition of the pore water is of great importance in connection with quick clays. They stated that leached non quick clays contain more calcium and magnesium relative to sodium in the pore water than quick clays do. This connection seems to apply in the Göta River Valley and is illustrated by the chromatograms in Fig. 9. The quick clay has sodium as the dominating cation, while the non quick clay has calcium and magnesium.

The non saline marine clays in the Göta River Valley must have been leached. Leaching of a natural salt clay system having the cations Na^+, K^+, Ca^{2+} and Mg^{2+} in its pore water therefore seems to lead to two different systems, one with mainly divalent ions dominating and one with monovalent.

According to Rosenqvist (1955) the monovalent positive ions are easier to leach from a negatively charged clay colloid system than the divalent ones — "partial leaching" — as required by the Donnan effect. A normal leaching of a clay sedimented in seawater containing the cations mentioned above ought to result in a clay with mainly calcium and magnesium in the pore water, i.e. a non quick clay (see Fig. 9 and cf. Kamil and Shainberg, 1968).

Thus it would be in opposition to the Donnan effect if a clay system with a pore water composition of "quick clay type" could be formed by leaching alone. But if the divalent ions are precipitated or complexly bound by suitable substances, viz. dispersing agents it is very easy to explain clay systems with pore water of the quick clay type.

Recent experiments by the present author (Söderblom, 1966) have shown that certain types of organic material in quick clays act as dispersing agents. If this is the case calcium and magnesium will appear in the pore water if the quick clay is treated with hydrogen peroxide. The results of one such experiment are shown in Fig. 10. Calcium and magnesium are

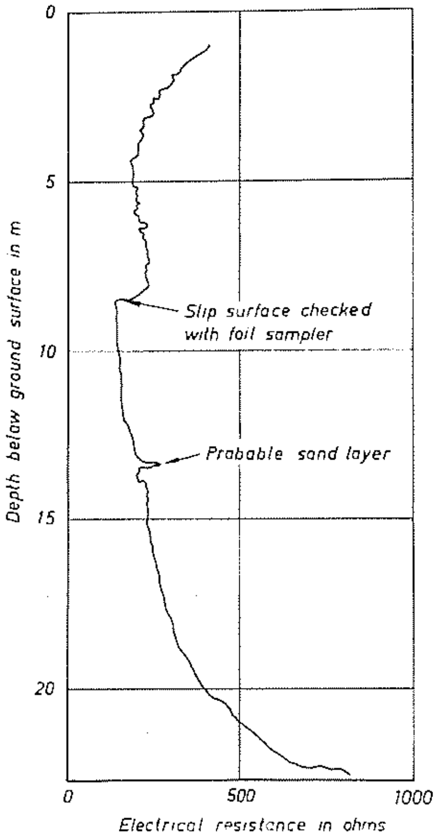

Fig. 5. Resistance curve from the Göta slide showing slip surface (from Söderblom, 1958).

dominant when the organic material has been destroyed. The chromatogram of the pore water from quick clay before treatment is shown in Fig. 9. The ionic composition of the pore water is thus changed by the H_2O_2 treatment. The hydrogen peroxide treatment destroys the quick clay properties. These properties can, however, be restored if a dispersing agent is added.

The pore water of aged quick clays is also rich in calcium and magnesium (see Fig. 11).

Studies on the leaching of Clays

In order to understand the natural leaching process a series of experiments were made on dialyses of clay samples. The method is described by Söderblom (1969) and will not be repeated here.

Quick clay was dialysed against 3.5 % NaCl solution until the sample

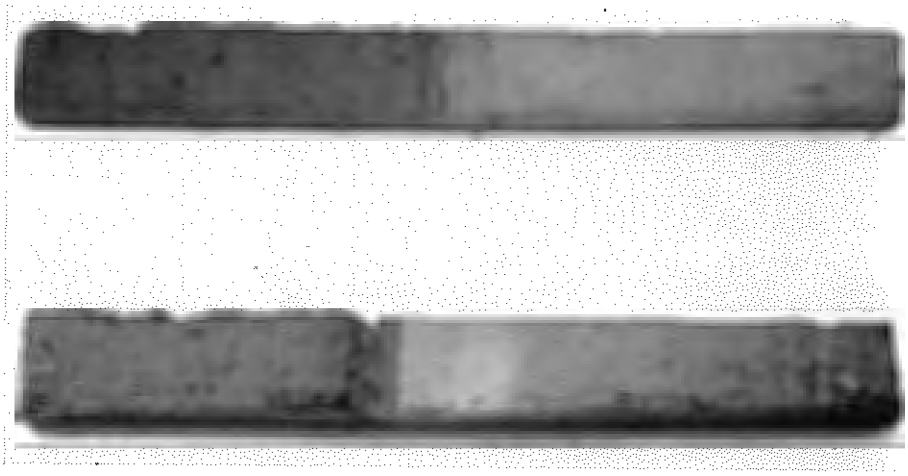

Fig. 6. Clay cores from Göta, Section I (Hole 352) and Section C (Hole 313) showing the slip zone, extracted in 1968, 11 years after the slide (Cadbro Foto, Lilla Edet).

obtained a conductivity $\varkappa \approx 5 \cdot 10^{-3}$ ohm^{-1} cm^{-1} similar to that of a natural salt clay. As expected, the salt-treated clay became non quick. The clay was then leached with distilled water. As shown in Table 1 the clay became quick again. Also the ionic composition of the squeezed pore water was almost unchanged by this treatment, viz. rich in Na^+.

These experiments in principle correspond to those made by Bjerrum and Rosenqvist (1956). They used quick clay material, introduced salt, leached and obtained quick clay again. Such experiments are referred to in literature as verifying the salt leaching theory.

The experiment was repeated with $CaCl_2$ instead of NaCl. In this case quick clay was not obtained after the leaching. The pore water contained Ca^{2+} but also considerable amounts of Na^+. The leaching water contained mainly Na^+.

The same experiment was made with synthetic seawater. Quick clay was obtained after leaching, and the pore water then had the composition of that of a quick clay.

Natural salt clays from Tingstad, Strandbacken and Älvängen in the Göta River Valley were leached in distilled water. None of these clays were transformed into quick clay and the ionic composition of the pore water became that of a non quick clay, i.e. in accordance with the Donnan effect. This indicates that one does not obtain quick clay by only leaching of natural salt clays having pore water compositions with the cations Na^+, K^+, Ca^{2+} and Mg^{2+} (cf. Kamil and Shainberg, 1968).

These salt clays had been stored for some months and the experiments were repeated with quite fresh salt clay samples from Älvängen and Strandbacken, transported to Stockholm by express train. The leaching experiments were started as soon as the samples arrived in Stockholm 10—20 hours after sampling. After leaching, the salt non quick clays had been transformed into quick clays with a sensitivity of about 100. In these cases the pore water had a dominance of monovalent ions. The leaching water contained only small amounts of calcium and magnesium. The water covering the sample within the dialyses membrane contained substances with very strong dispersing properties. The pH value of the system had increased from about 7 to 8, also indicating a Donnan hydrolysis. The presence of potassium and in some cases lithium indicates mineral weathering, as proposed by Kazda (1965).

Ageing phenomena in quick Clays

Ageing effects on the sensitivity of quick clay have been reported by Jerbo, Norder and Sandegren (1961). They found that samples of undisturbed quick clays after storing had been transformed into non quick clays. They also

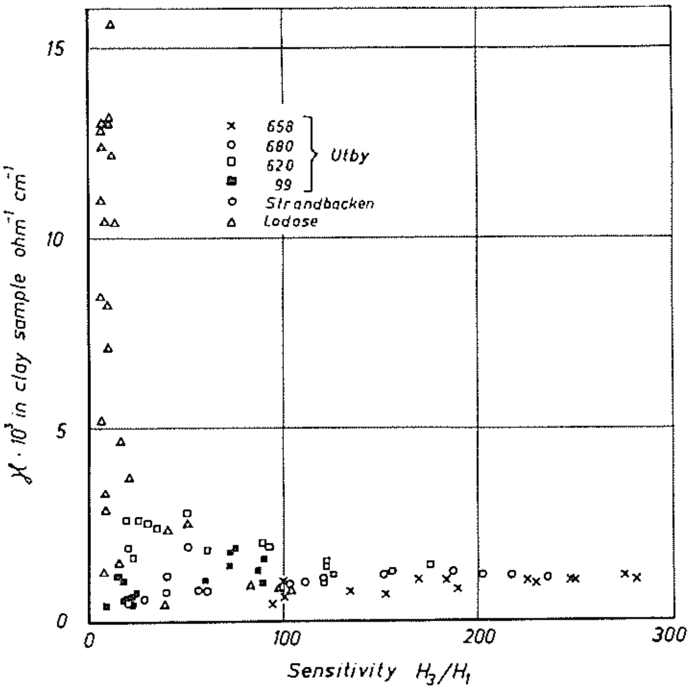

Fig. 7. Relation between conductivity and sensitivity for clay samples from the Göta River Valley.

TABLE 1. *Test Results from leaching Experiments in different Clays*

Site Hole Depth	Treatment	H_3	H_1	H_3/H_1 (S_t)	w %	Liquid limit, w_L		R ohm	$\varkappa \cdot 10^3$ ohm^{-1} cm^{-1}	pH	Ionic composition						Remarks
						Natural %	Predried %				Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	
Utby 658 15 m	Untreated	183	0.98	186	65	53	—	360	1.11	—	+ +	—	—	—	—	+	
	After dialysis against 3.5 % NaCl solution	208	13.5	15.4	—	—	—	37	10.8	—							
	After leaching of added salt	110	<0.33	>334	66.5	42	44	820	0.49	—	+ +	—	—	—	—	+	Double
Utby 658 15 m	Untreated	153	0.82	187	70	56	51	360	1.11	—	+ +	—	—	—	—	+	test
	After dialysis against 3.5 % NaCl solution	183	10.6	17.3	—	—	—	—	—	—							
	After leaching of added salt	101	<0.33	>306	82	43	50	710	0.56	—	+ +	—	—	—	+	+	
Utby 658 15 m	Untreated	163	0.384	425	66.5	44	41.8	330	1.26	7.6	+ +	—	—	—	—	+	
	After dialysis against 3.5 % $CaCl_2$ solution							31.5	12.7								
	After leaching of added salt	163	13.8	11.8	67.2	66.5	53.7	433	—	7.3	+	—	+	+	+	+	
Utby 658 15 m	Untreated	163	0.384	425	66.5	44	41.8	330	1.26		+ +	—	—	—	—	+	
	After dialysis against 3.5 % synthetic sea water							20	—								
	After leaching of added salt	141	<0.33	>427	65	46	45	850	0.47	7.5	+ +	—	—	—	+	+	

Utby 99	Untreated	145	13.8	10.5	52	59	41	390	1.02	—	—	—	+	+	—	+ +	
9 m	After dialysis against 3.5 % NaCl solution	104	13.5	7.7													
	After leaching of added salt	43	<0.33	>131	54	32	31	820	0.49	—	+ +	—	—	—	+	+	
Älvängen	Natural salt clay with about 2 % salt	50	7.17	7.0	93.2	95	64	36	11.07	—	+	—	+	+	+	+	Sample about 5 months old
7 m	After leaching of salt	27	2.05	13.2	96.2	99	62	830	0.48	—	+ +	—	+	+	+	+	
Strand-backen	Natural salt clay with about 2.3 % salt	153	19.2	7.9	49	55	—	54	7.4	—	+	—	+	+	+	+	Sample about 6 months old
20 m	After leaching of salt	98	6.93	14.1	51	48	—	400	1.0	—	+	—	+	+	+	+	
Strand-backen	Natural salt clay with about 2.3 % salt	281	26.8	10.5	70	78	61	52	7.7	7.4	+	—	+	+	+	+[1]	Fresh
20 m	After leaching of salt	66.2	0.60	110	84	63	50	430	0.93	7.8	+ +	—	—	—	—	+[1]	sample
Älvängen	Natural salt clay with about 2 % salt	120	10.4	11.5	86	90	54	31	12.9	7.5	+ +	—	+	+	+	+[1]	Fresh
14 m	After leaching of salt	68.0	0.60	113	91.5	63	—	460	0.87	8.4	+ +	—	—	—	—	+[1]	sample
Älvängen	Natural salt clay with about 2 % salt	69.8	9.09	7.68	85	90	56	27	14.7	7.2	+ +	—	—	—	—	+[1]	Fresh
15 m	After leaching of salt	69.8	0.44	157	92	65	57	435	0.92	8.2	+ +	—	—	—	—	+[1]	sample

[1] Contains phosphates

reported changes in the pH value. Similar effects in ceramic masses have been known since the beginning of this century. Baker and Glick (1936) attribute these phenomena to microbial action in the organic material.

These ageing phenomena have hitherto only been qualitatively studied. The strength values were determined by the present author immediately in the field, after storing of the samples in the field for some time, and after transportation to the laboratory.

The shear strength of an undisturbed quick clay with a high H_1 value decreased by up to 40 % after storing for 24 hours in field (at 22°C).

The change in strength values after transportation to the laboratory is shown in Fig. 12, showing a typical quick clay profile from the Göta River Valley. The undisturbed shear strength is reduced at every level and mostly at the levels where the strength is high (Fig. 12). The remoulded shear strength shows a decrease at higher values. At lower values there is, however, an increase. The sensitivity also shows a change, except in the low-sensitive part (Fig. 8). In one case at Utby, the H_1 value in the transported samples showed such a decrease that the clay changed from non quick in the field to quick in the laboratory.

The ageing phenomena are accompanied by changes in the pore water composition of the clay. It seems that they are dependent on changes in the organic material and its complex binding capacity. However, systematic investigations of this very important question have not yet been carried out.

It is very remarkable that a quick clay, being a typical lyophobic colloid, can exist for centuries, as is the case at Intagan in the Göta River Valley. Most textbooks in colloid chemistry stress that lyophobic colloids cannot exist in nature due to their instability. Some process must go on in the ground which prevents these ageing processes.

Diffusion and its influence upon geotechnical properties and chemical stabilization

Diffusion is a very important factor for an understanding of the geotechnical properties. Generally these are considered to be relatively independent of time in nature. In recent years, however, some authors e.g. Jerbo (1969), Talme et al. (1966, 1968) have discussed "secondary changes" which they consider to occur relatively rapidly. These changes are due to the transportation of reaction products and therefore diffusion has to be taken in consideration.

As mentioned before, salt diffusion in natural clay slopes can be studied at the slip surface of slides. By the movement of the clay masses two clays

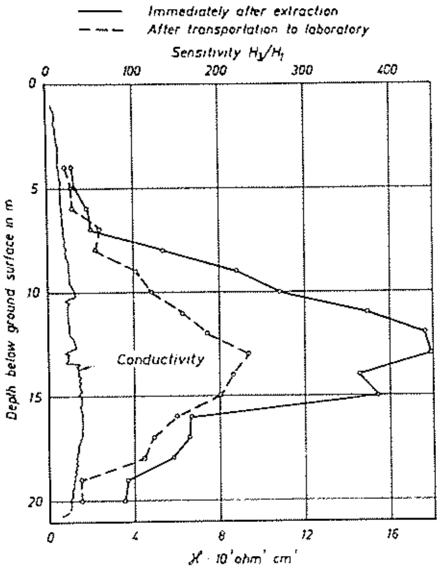

Fig. 8. Sensitivity and salt sounding curves from Hole 680 Utby.

with different salt contents may come into contact with each other. In the Göta slide in 1957, for example, a sharp gradient was formed in the salt content curve (Fig. 5). The corresponding curve in 1967 is shown in Fig. 13. A calculation using Fick's diffusion law gives D $\approx$ 0.23 cm^2/day. Diffusion constants varying between 0.1—0.3 have been obtained in the Göta slide area by this method.

The same applies to the Surte slide area (from 1950). In one case (Surte 42, Järnefors, 1958) it has been possible to make measurements at two different times after the slide. The smoothed out curve 7 years after the slide gave a value D $\approx$ 0.14 cm^2/day, and after 11 years D $\approx$ 0.11 cm^2/day. The two values are in reasonable agreement. This seems to indicate that Fick's diffusion law can be used for calculation of salt diffusion in a clay profile.

The diffusion coefficients found in these studies are too small to permit a commercial strengthening in reasonable time based on diffusion. The short-time experiments on stabilization in clays hitherto made in Scandinavia have been carried out with plugs of salt or concentrated solutions. Moum et al. (1968) report a diffusion coefficient of KCl of 0.7 cm^2/day. Talme (1969) considers the salt diffusion coefficient in quick clays to increase with increasing salt concentration.

Letey and Clute (1960), by combined conductivity and diffusion measurements, have found that in charged soil systems Fick's diffusion laws must be used with a concentration dependent diffusion coefficient. Dutt and

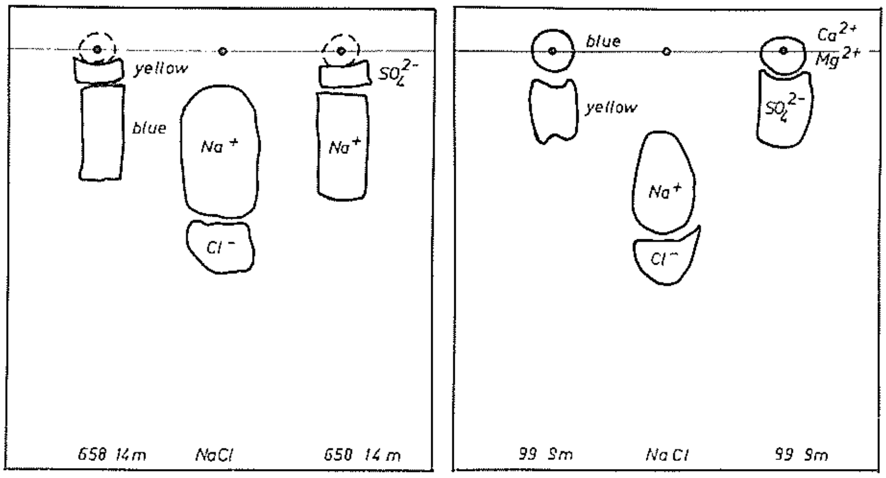

Fig. 9. Small-paper chromatograms of pore water of a clay from Utby Hole 658, 14 m and Hole 99, 9 m.

Low (1962) have found that the diffusion coefficients of LiCl and NaCl in Li- and Na-clays respectively decreased with increasing salt concentration. Gast (1966) has on the contrary found that the diffusion coefficient increases with increasing concentration.

Diffusion in soils thus seems to be a process which is hitherto insufficiently studied and understood. Especially diffusion combined with ion exchange which occurs when, for example, $CaCl_2$ is added to a sodium clay has not been taken into consideration. According to Gast and East (1964) sodium ions have about ten times higher self diffusion coefficient than the divalent strontium ions.

The diffusion transmission factor is defined as the ratio of the apparent diffusion constant D_p in the clay and D_0 in water (Porter et al., 1960). This factor must at least be larger than 0.5 to allow an economical chemical stabilization of a clay. The findings from Göta and Surte gave quite lower factors, (about 0.1).

Controlled diffusion experiments in the field are as a rule time consuming and expensive. It is therefore desirable to work out simpler methods to estimate the diffusion rate in a clay slope, which seems to vary from point to point. One possible way is to use the conductivity transmission factor, which according to Gast and East (1964) should depend on principally the same factors as the diffusion transmission factor. The possibility of estimating diffusion from conductivity is very important in the strengthening technique and must be studied in detail.

Possible methods of chemical stabilization of quick clays

As mentioned above, quick clays are rich in complex bound divalent ions which are liberated if the clay samples are stored for some time. In the ground the quick clays are stable and some processes, probably of microbial nature, must go on in situ. These processes are hitherto incompletely understood. If they are prevented, however, the Ca^{2+} and Mg^{2+} content in the pore water of the quick clays will spontaneously increase, giving rise to a chemical stabilization independent of slow diffusion processes. One method may be to sterilize the clay mass, for example with formaldehyde. This substance might also react with the organic material forming bridges between the different molecules. Before any discussion of methods of this kind can be made, the influence of organic material on the strength properties of clays must be understood. It should be noted that a natural quick clay system is not an inorganic sterile mass (Jerbo, 1969 and cf. Bell, 1968).

The properties of quick clay and their dependence on time are so incompletely understood that not much can be said concerning the possibilities of changing their properties artificially in situ. In addition to the factors mentioned above one must consider the importance of artesian water, and the possibility of diminishing its flow.

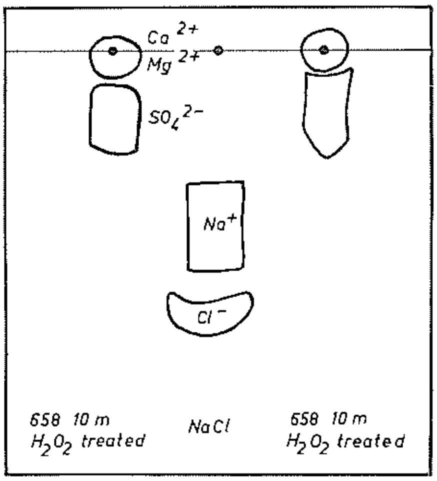

Fig. 10. Small-paper chromatogram of pore water of a clay from Utby Hole 658, 10 m treated with H_2O_2.

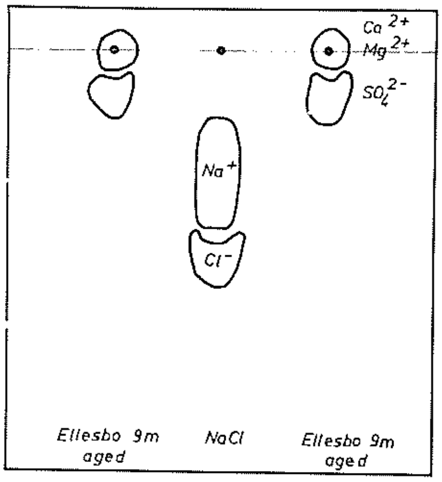

Fig. 11. Small-paper chromatogram of pore water of an aged, formerly quick clay from Ellesbo, 9 m (the sample about 2 years old).

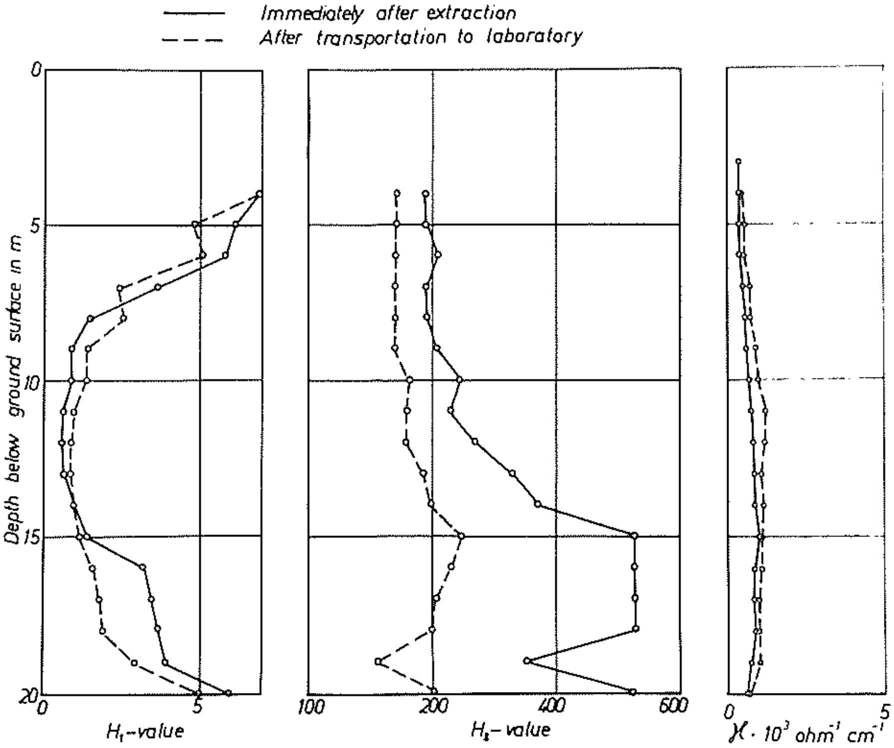

Fig. 12. Strength values and conductivity curves from Hole 680 Utby.

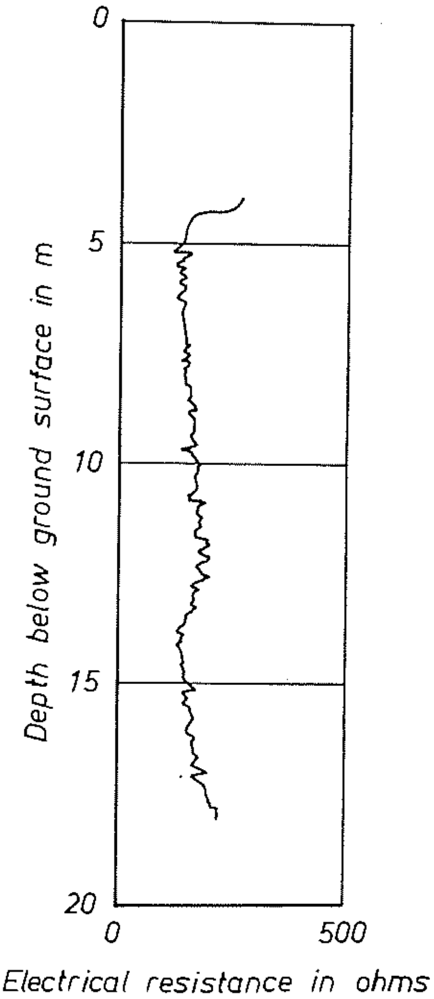

Fig. 13. Salt sounding curve from Göta in 1967 showing the equalizing of the former sharp gradient in salt content by diffusion.

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