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**No. 22**

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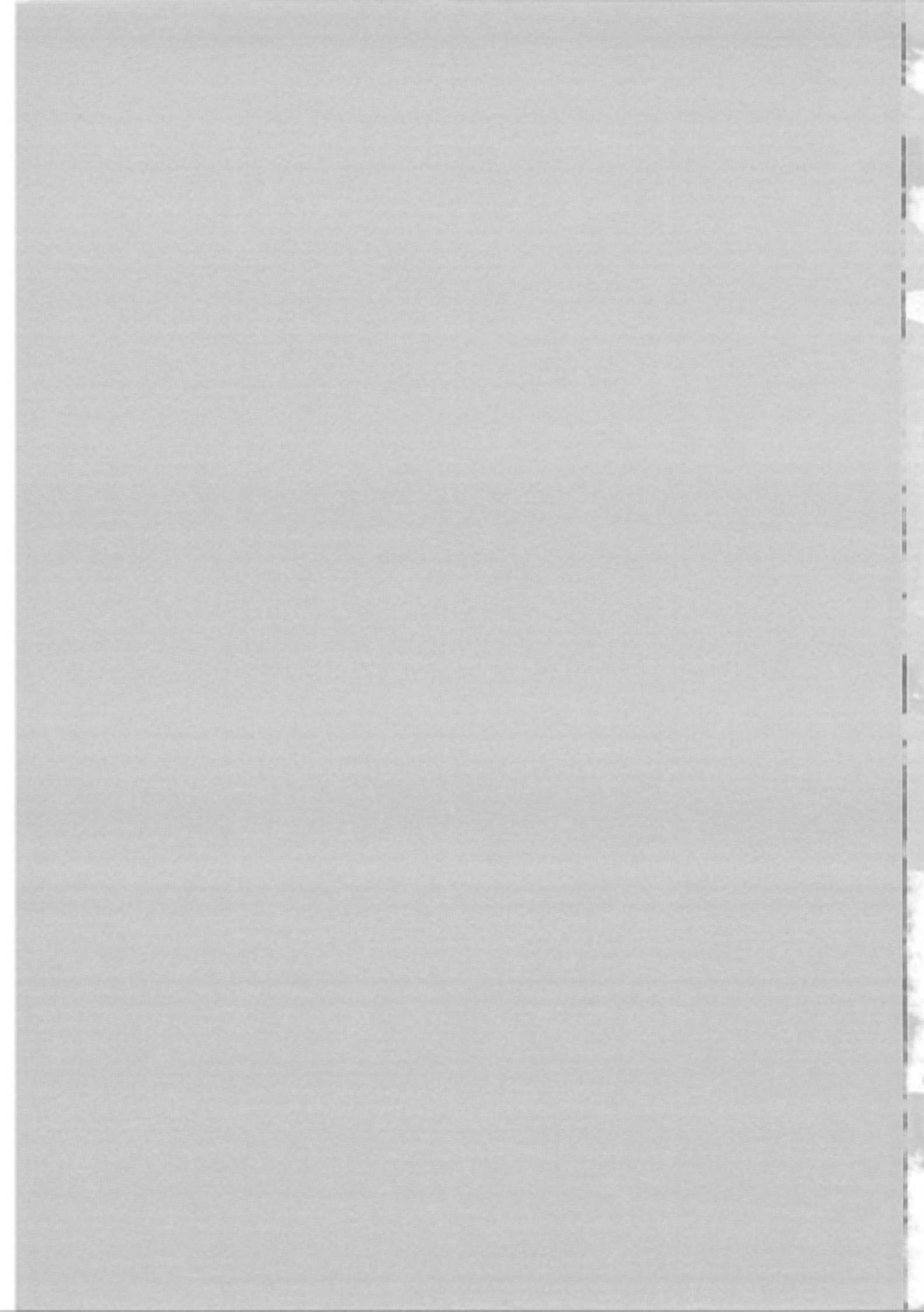
**SALT IN SWEDISH CLAYS  
AND ITS IMPORTANCE FOR  
QUICK CLAY FORMATION**

**Results from Some Field and Laboratory Studies**

**By  
Rolf Söderblom**

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**STOCKHOLM 1969**



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## PREFACE

Due to the many landslides, e. g. along railway lines and in river valleys, the slope stability problems have been studied extensively in Sweden. The first more systematic investigations were made by the Gothenburg Port Authority in the beginning of this century and by the Geotechnical Commission of the Swedish State Railways in 1914-1922. After the large slides at Surte in 1950 and at Göta in 1957 in the Göta River Valley the Swedish Geotechnical Institute has been investigating factors affecting the slope stability. An important factor in this connection has been the occurrence of quick clays.

Investigations have shown that both salt and organic materials are of great importance for the slope stability. They also indicate that the problems are very complex. The present report should therefore be regarded as a first attempt to study the factors affecting the long term stability of slopes.

The report deals with the salt content of clays and its importance for the formation of quick clays. Extensive field and laboratory studies have been made to investigate e. g. the validity of the salt leaching theory. The possibility to determine the slip surface in connection with salt investigations has been developed further. In this connection the diffusion and the ageing processes were studied. The paper chromatography method has been used in the study of the different chemical components in clay and has been further developed for this purpose.

The research work was planned and directed by Mr. R. Söderblom who also has prepared the present report. Part of the laboratory investigations was made by Mrs. I. Almstedt and Mr. Shanti Parekh.

The work was carried out at the Research and Consulting Department A of the Institute (Head: Mr. G. Lindskog) 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 Natural Science Research Council and from the Swedish Building Research Council.

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

A report on the factors of organic nature which influence the formation of quick clays is under preparation and will later be published in this publication series.

Stockholm, August 1969  
SWEDISH GEOTECHNICAL INSTITUTE



## SUMMARY

This report deals mainly with the importance of salt in Swedish clays. Especially the relationship between salt and sensitivity has been investigated. Methods have been developed by which the salt content in Swedish clays can be determined rapidly. A special instrument, "the salt sounding tool", has been used in the field to determine the approximate salt content in a clay. Rapid chromatographic methods have been developed and used to study the ionic composition of the pore water in clays.

The salt conditions in clays from different parts of Sweden are discussed. It has not been possible to correlate the sensitivity of Swedish clays with the total salt content. There exists, however, a correlation between the ionic composition of the pore water of a clay and the sensitivity. Quick clays have an ionic composition which is not in accordance with the simple Donnan effect condition due to the presence of organic material in the clay.

The investigation also shows that the strength properties of extracted samples of quick clay change with time.

A method has been developed to detect slip surfaces in slides from salt soundings. The report also includes a study of the diffusion processes in clays as well as a laboratory investigation of the leaching processes.

## 1. INTRODUCTION

Occasionally large landslides occur in Sweden causing great damage and sometimes loss of life. They have taken place in several parts of the country, especially in the Göta River Valley. A great slide there at Intagan in 1648 caused the death of 85 persons. In recent years large slides occurred at Surte in 1950 (Jakobson, 1952) and at Göta in 1957 (Odenstad, 1958). Not far from Göta River a slide occurred at Sköttorp in 1946 (Odenstad, 1951), in the eastern part of the country at Svärta in 1939 (Jakobson, 1952) and further to the north at Kramfors in 1959 (Jerbo & Sandegren, 1962).

These large slides often begin as rather small slides close to the river, which then are spreading over large areas. This spreading is linked to the occurrence of quick clay, which lowers its stability drastically when mechanically disturbed and in extreme cases may turn from a solid body into a liquid. The initial slide may be started by such effects as pile-driving, dredging, erosion or changes of the ground water table. The

general land elevation also affects the stability of clay slopes.

In the studies on quick clays many authors have stressed the importance of the salt content in marine clays and the transformation of "normal" clays into quick clays by a natural reduction of their salinity by leaching processes. Some of them maintain that a great reduction of the salinity of a marine clay sediment is necessary for its transformation into a quick clay, for instance from 3.5 % to 0.1 % or less, while others are of the opinion that the original salinity may be much smaller, so that a reduction from, say, 0.3 % to 0.1 % is sufficient. Still other authors have found that although clays with high salinity never seem to be quick, clays with low salinity sometimes are quick, sometimes not.

Similarly different opinions are found in the literature regarding the kinetics of the reactions in the ground

that influence the formation of quick clays. Some authors state that the change of the salt content in the ground is a rather rapid process, while others have found that geological lengths of time are required for significant changes.

It is therefore evident that further studies on the salt content in Swedish clays and its importance for their stability are necessary.

After the slide at Surte the Swedish Government organized an extensive investigation of the geotechnical and geological conditions in the Göta River Valley, which was carried out during the years 1952-60, mainly by the Swedish Geotechnical Institute and the Geological Survey of Sweden. The reports are, however, published only in Swedish (Tullström, 1961, SOU 1962:48).

The observations on the slide at Göta in 1957 indicated that additional basic research on the physico-chemical properties of the clay sediments in the valley were necessary for an understanding of the changes which take place in course of time. Therefore studies of the factors which may transform clays with normal sensitivity into quick clays were initiated at the Swedish Geotechnical Institute.

This report deals with factors of an inorganic nature which have been found to be of importance for the quick clay formation. A following paper will report on factors of organic nature. The two papers can be regarded as a continuation of two earlier papers "Aspects on some problems of geotechnical chemistry" by the present author (Söderblom, 1959, 1960).

## 2. GENERAL CONSIDERATIONS

### 2.1 Definitions

The following terms are used in this paper.

$H_1$ -value is a value of the relative strength determined by means of the Swedish fall-cone test on completely remoulded clay (Swedish State Railways Geotechnical Commission, 1922, Caldenius & Lundström, 1956, and Hansbo, 1957).

$H_3$ -value is a relative strength value determined by the same test on undisturbed clay.

A clay into which the depth of penetration of the 60 g - 60° cone is 10 mm was given by the Commission an H-number equal to 10. The Commission assumed that there is proportionality between the resistance offered by different clays and the amount of external work done by the cone weights when causing a constant depth of penetration. According to this assumption the H-number of a clay is obtained in the following manner. The clay is tested with the 60° cone. Its weight is then varied until a depth of penetration of 10 mm is obtained. This weight in grams divided by 6 g is the H-number of the clay.

Usually one does not vary the weight of the cone. Instead the penetration depth of suitable standard cones is measured and the H-value is taken from calibration tables. The most recent values are given in App. 1.

Transformation of the H-values into shear strength<sup>1)</sup> has been made by several authors, e.g. Skaven-Haug

1) The author has followed the units used by the International Geotechnical Society and not the SI-system, thus the unit  $t/m^2$  being used instead of  $newton/m^2$ .

(1931), Hansbo (1957) and Swedish Geotechnical Society (1963, cf. App. 2). The values proposed by them differ considerably and this transformation must be considered as very approximate. For this reason the H-values proper are used in this report.

Sensitivity is in this work defined as  $H_3/H_1$ .

Terzaghi (1944) defined the sensitivity as the quotient  $S_t = q_u/q_{ur}$  of the unconfined compressive strength of undisturbed soil  $q_u$  and the unconfined compressive strength of the remoulded soil  $q_{ur}$  at the same water content. It is not possible to carry out unconfined compression tests on remoulded quick clays since they are almost liquid. Therefore the sensitivity of quick clays is often determined by the cone method. This method has recently also been used outside Scandinavia in studies on quick clay, e.g. Penner (1965) and Kerr & Liebling (1965).

Skempton & Northey (1952) classified clays by their sensitivity as follows:

Table 1 Classification of clays by their sensitivity according to Skempton and Northey, 1952

Sensitivity $S_t$	Classified as
1	Insensitive clays
1-2	Clays of low sensitivity
2-4	Clays of medium sensitivity
4-8	Sensitive clays
8-16	Extra sensitive clays
>16	Quick clays

Rosenqvist (1953) modified this classification for the more sensitive clays:

Table 2 Classification of more sensitive clays according to Rosenqvist, 1953

Sensitivity $S_t$	Classified as
8-16	Slightly quick clays
16-32	Medium quick clays
32-64	Very quick clays
>64	Extra quick clays

Quick clay was originally defined as a clay whose consistency changed by remoulding from solid to viscous liquid. The English term "quick clay" was probably first used by Reusch (1901).<sup>1)</sup>

In the literature on quick clays there is a great confusion about the definitions. Most authors do not distinguish between "sensitive clay" and "quick clay". Some authors, e.g. Odenstad (1951), supplement the quick clay definition with a maximum value of the remoulded strength value ( $H_1 < 1$  or  $< 3$ ), but in this paper the sensitivity ratio ( $H_3/H_1$ ) alone is used as a criterion of a quick clay. The old Swedish definition of a quick clay ( $H_3/H_1 > 50$ ) is more rigorous than that used in Tables 1 and 2.

Swedish clays have normally a sensitivity between 10 and 20. Clays with sensitivity ratios between 1 and 4 are very rare in Sweden. However, many clays in the south-western region of the country have sensitivity ratios higher than 16 (cf. App. 3 and 4). With the definitions in Tables 1 and 2 most clays in Sweden should be regarded as slightly quick or quick, both the leached and unleached ones, whether they have been deposited in fresh, brackish or salt water. The definitions of quick clay in these tables are thus not suitable for Swedish conditions.

An important property of a quick clay which has not been considered earlier in the geotechnical literature is the amount of work required to remould the clay and transform it into the liquid state. Rosenqvist (1946) stated that Norwegian quick clays are very sensitive with respect to mechanical disturbances and that only small amounts of work is required to transform quick clays into a liquid. The same is also true for many Swedish quick clays, but often a large amount of work is required to remould them. The quick clays at Utby have a very high sensitivity ratio ( $H_3/H_1$  up to 450) but they require a great amount of work to be completely remoulded. Sometimes this remoulding will require

1) The Swedish term "kvicklera" was probably first used in literature by Törnsten (1767).

about 10 minutes of manual stirring. These clays thus behave quite different than the "rapid" quick clays mentioned above. The Utby quick clays may initially be classified as non-quick, but after several minutes of intense remoulding the  $H_1$ -values drop substantially. It is evident that quick clays of this type, here called "slow" quick clays, are not so dangerous in connection with slides as quick clays of the "rapid" quick type. Although the behaviour of quick clays of the two types are of importance for the understanding of the slide mechanism, no reference to them has been found in the literature, nor seems anybody have published any method to determine the mechanical work required to break down a clay. This important question is, however, outside the scope of this report.

Because the earlier definitions of clays is unsuitable to Swedish conditions the author suggests the nomenclature given in Table 3.

The semi-quick clays are to be regarded as a kind of transition clays being more or less affected by quick clay forming processes.

## 2.2 Theories on the Formation of Quick Clays

Several theories on the formation of quick clays have been proposed. Some authors have published detailed abstracts of these theories, e.g. Keinonen (1963) and Kerr & Liebling (1965), and they will not be repeated here. Only a short summary of the leaching theory will be given, since it is essential for an understanding of the present work.

The leaching theory was originally introduced by Rosenqvist (1946). In a review of the Norwegian quick clay research Rosenqvist (1966) describes the quick clay process as follows:

"Quick clays will form where clay minerals are rapidly added to salt water at such high concentration that even the finest fractions will flocculate and precipitate together with the coarser particles. The clay gel forming in saline water will be stable at comparatively high water contents, due to the thick water films surrounding each grain. Subsequent to the formation of the clay deposits the salinity in the clay gels is strongly reduced, as the ions of the salt are in the process of diffusing out into the ground water through sand and gravel layers. This may happen not only in those cases where clay deposits are lifted above sea level, but even in off-shore, subaquatic sediments, since the fresh ground water under and in clay deposits remains unmixed with sea water comparatively far from the shore. Provided the clay deposits remain unaffected by movement, the thick

Table 3 Proposed classification of Swedish clays by their sensitivity

Sensitivity $H_3/H_1$	Main groups	Dividing according to remoulding work	
		Small remoulding work	Great remoulding work
<20	Normal clays		
20-50	Semi-quick clays		
>50	Quick clays	Rapid quick clays	Slow quick clays

water films will continue to exist in an unstable condition around the clay particles even after the salts have diffused out, and the clays will retain a considerable strength in the undisturbed state. On remoulding, this unstable skeleton of hydrolised clay particles will be destroyed and the surface water will be liberated. Thus the clays will turn to liquid".

Rosenqvist mentioned also that remoulded saline clay after consolidation and subsequent leaching by dialysis attained a state of higher sensitivity. The "less" sensitive clays were supposed to differ from the highly sensitive clays due to the following reasons:

"(1) They are deposited in water of low salinity.

(2) They may be deposited from suspensions so diluted that the clay minerals are unable to flocculate, but sediment individually, thus producing a denser packing.

(3) The salt content has not diffused out of the flocculated clays.

(4) Quick clays can be transformed into clays of low sensitivity by a squeezing out of water caused by the consolidating effect of overlying soil masses".

Rosenqvist (1955) modified his original theory as follows. "... for the first time that in itself the salt or the leaching of salt was not the fundamental cause of sensitivity, but that we had to consider changes in the charge of the clay particle as measured relative to the fluid phase, as expressed by the Zeta potential. It was pointed out that provided clay minerals are sedimented under conditions of low mutual repulsion, i. e. a low double layer charge, the consolidated sediment will have a higher water content than if the same minerals are sedimented under conditions of a higher double layer charge. It was stressed that the degree of flocculation depends upon the charge of the minerals, and may still remain after subsequent chemical changes of the environment, even though this would lead to changes in the double layer repulsion. Thus it was shown that the addition of phosphate ions to the clay would give results comparable to those obtained by the leaching of salt."

In 1946 Rosenqvist showed "that a clay consolidated at a high salinity and subsequently leached by dialysis, exhibited a high sensitivity, and it was proved that

even addition of suitable ions such as phosphate ions would produce the same result, and the same mechanical properties".

### 2.3 Scope of Investigation

One purpose of the present investigation was a study of the applicability of the leaching theory to Swedish clays. Therefore determination of the salt content in the pore water of clays was of interest.

A clay with high sensitivity does not necessarily have a low unremoulded shear strength. Quick clays are not generally considered to be more dangerous with respect to slope stability than "normal" clays (cf. Tullström, 1961), but once a slide has started its consequences may be disastrous if the clay has a high sensitivity. Therefore it is important to recognize areas with quick clays and to prevent local slides in them. It was therefore considered necessary to develop a method for rapid determination of the salinity of clays. An instrument has been developed suitable to localize leached zones in large areas and thereby possibly determine the occurrence of the quick clays.

The test results from the Göta River investigation mentioned in the introduction have served as a background material for the theories presented in this paper. That investigation was, however, incomplete from a chemical point of view. For example the concentration of sodium and potassium ions in the pore water was considered, but not the concentration of calcium and magnesium ions. It was therefore necessary to supplement previous investigations.

In the present paper the following items are described:

- 1) Methods developed at the Swedish Geotechnical Institute for rapid estimation of salt in clays.
- 2) Studies of the salt content in clays.
- 3) Attempted localization of quick clay deposits in situ by salt soundings.
- 4) Localization of slip-surfaces by salt soundings.
- 5) Diffusion processes in clays.

Because of the large extent of this investigation it has

not yet been possible to investigate thoroughly every factor discussed in this paper. For instance the microbial action in soils has not been dealt with. The investigation of the salinity conditions is limited to the pore water. The adsorbed double layer has not been studied due to disturbances from some easily destroyed constituents in the clay.

In this paper the inorganic factors are studied. In a following report the organic factors will be treated.

## 2.4 Test Sites and Materials

The investigations deal with various parts of Sweden (cf. Fig. 1) and have been carried out both on places with marine and with non-marine clays. The most important investigations reported in this paper have, however, been carried out in the Göta River Valley. The places are enumerated in Table 4. The location of the places is seen in Figs. 1, 2 and 3.

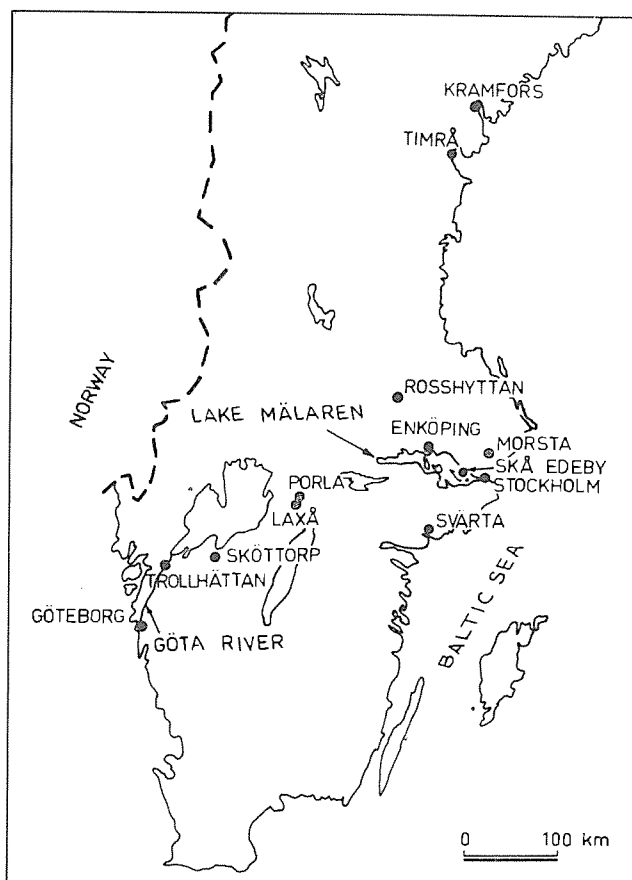


Fig. 1 Map of Sweden showing places investigated

The sites Utby, Lödöse and Ellesbo were studied in some detail. Both salt clays, leached quick clays and leached non-quick clays were found at Utby (See App. 3).

In many profiles here the change between clays of different sensitivity is very sharp.

Therefore this place was suitable for a study of the factors influencing the sensitivity. The geotechnical data of the clay profile investigated at Ellesbo are given in App. 4 and those from Lödöse are collected in Table 12. A varved quick clay which probably has been sedimented in fresh water was found at Rosshyttan (Fig. 1).

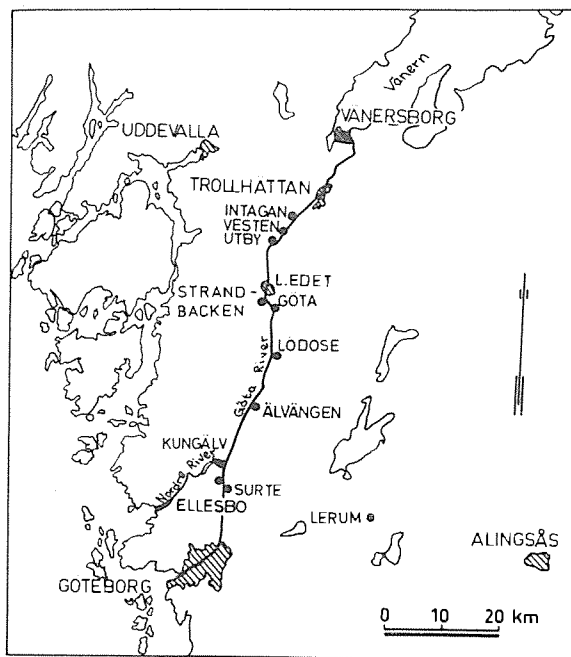


Fig. 2 Map showing places investigated in the Göta River Valley

The main constituent of Swedish clays is illite. Tentative attempts were made to use American illite as a reference material. Experiments were made with grundite from Gooselake, Illinois, and with Morris illite, also from Illinois. These two materials could, however, not be dispersed by normal dispersing agents, e. g.  $\text{Na}_4\text{P}_2\text{O}_7$ , without special pretreatment. The sensitivity properties of these clays thus were found to differ so much from those of Swedish clays so they could not be used as reference materials.

Pure kaolinites can be dispersed like normal Swedish clays as shown e. g. by Söderblom (1960). Some commercial kaolinites tested were, however, unaffected by normal dispersing agents and some others could also be dispersed by sodium hydroxide. According to van Olphen (1965) these clays are probably contaminated by such acids, whose anions act as dispersing agents.

Therefore four types of kaolin used at the pottery

factory of Gustafsbergs Fabriker, Sweden, were examined. A kaolin denoted "46" was found to be most suitable. This material could be dispersed by normal clay dispersing agents. It was hardly affected by sodium hydroxide. The material had almost reproducible properties.

Clays deposited in sea water - marine clays - will be discussed extensively in this report as well as different treatments of sea-water-affected sediments. It has turned out that the ratio divalent to monovalent ions has so great importance that it is not permissible to regard the sea water only as a simple NaCl solution.

Table 4 Test sites and indication of investigations made

Site	Location (cf. Figs. 1 and 2)	Material investigated				Sedimentation milieu	Examinations made		Remarks
		Quick clay	Normal clay	Peat	Water		Salt sounding	Sampling and lab. tests	
<u>Göta River Valley</u>									
Intagan	About 5 km SSW Trollhättan	x				Marine	x	x	Salt soundings in slide scar from 1648
Vesten	About 8 km SSW Trollhättan	x				"		x	
Utby	About 11 km SSW Trollhättan	x	x			"	x	x	
Strand- backen	Near Lilla Edet	x	x			"	x	x	
Göta	About 4 km SSE Lilla Edet	x	x			"	x	x	
Lödöse	About 12 km S Lilla Edet		x			"	x		
Älvängen	About 30 km NNE Göteborg		x			"	x		
Ellesbo	About 14 km N Göteborg	x	x		x	"	x	x	
Surte	About 13 km N Göteborg	x	x			"	x	x	
Tingstad	Near the center of Göteborg		x			"			Results from the Göta River in- vestigations
<u>Other sites</u>									
Kramfors	About 400 km N Stockholm					Marine			Slide in 1962
Rosshyttan	About 150 km NW Stockholm (On the railroad line Sala-Krylbo)	x	x	x	x	Non-marine		x	Distance accord- ing to the State Railway 147+500 V12
Kungsängen	In Uppsala	x				Marine	x	x	
Morsta	About 32 km NNE Stockholm			x	x	Non-marine		x	
Enköping	About 80 km WNW Stockholm		x			Marine and non-marine	x	x	
Skå-Edeby	About 18 km W Stockholm		x			"	x	x	On an island in Lake Mälaren
Svärta	100 km SW Stockholm					"			Slide in 1939
Porla	5 km NNE Laxå (half way Stock- holm-Göteborg)				x			x	Ochre from the "Old Spring of Porla" Berzelius
Sköttorp	About 40 km ENE Trollhättan					Marine			Slide in 1946



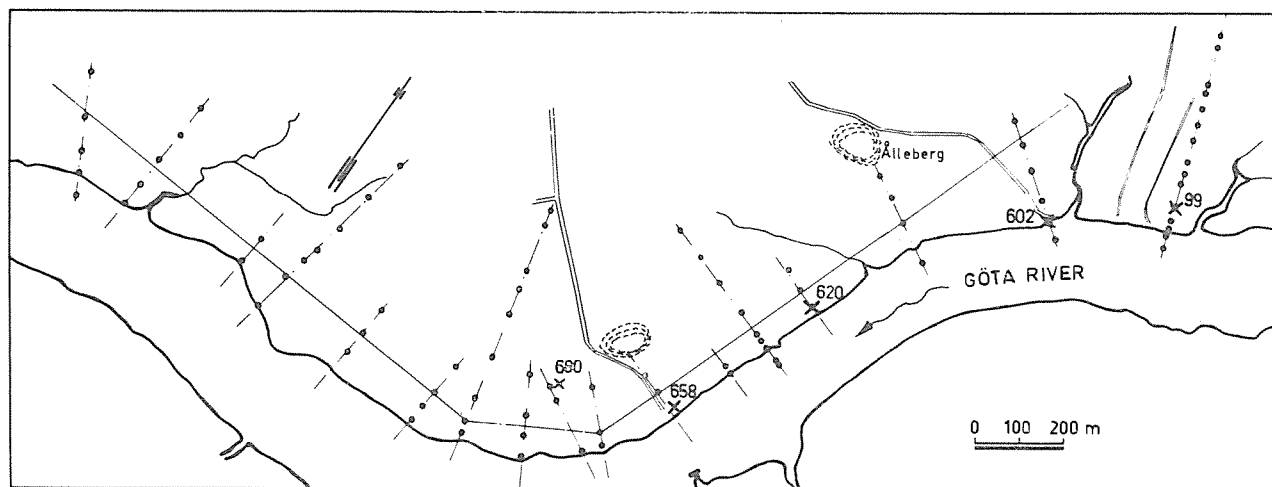


Fig. 3 Map of Utby showing places investigated

According to Sverdrup et al. (1942) the ionic composition of the sea water is very constant in the oceans. It is only the total salt concentration that varies. According to these authors 1 litre sea water contains

the amounts of different ions given in Table 5. For the present experiments the recipe for artificial sea water given in Table 6 was used (Lyman & Fleming, 1940), but with the three smallest constituents omitted.

Table 5 Main composition of sea water (after Sverdrup et al.)

Ion	Amount g/l	Ion	Amount g/l
Cl <sup>-</sup>	18.980	Mg <sup>2+</sup>	1.272
Br <sup>-</sup>	0.065	Ca <sup>2+</sup>	0.400
SO <sub>4</sub> <sup>2-</sup>	2.649	Sr <sup>2+</sup>	0.013
HCO <sub>3</sub> <sup>-</sup>	0.140	K <sup>+</sup>	0.380
F <sup>-</sup>	0.001	Na <sup>+</sup>	10.556
H <sub>3</sub> BO <sub>3</sub>	0.026		

Table 6 Recipe of artificial sea water (after Lyman & Fleming)

Salt	Amount g/l	Salt	Amount g/l
NaCl	23.476	NaHCO <sub>3</sub>	0.192
MgCl <sub>2</sub>	4.981	KBr	0.096
Na <sub>2</sub> SO <sub>4</sub>	3.917	H <sub>3</sub> BO <sub>3</sub>	0.026
CaCl <sub>2</sub>	1.102	SrCl <sub>2</sub>	0.024
KCl	0.664	NaF	0.003

### 3. DETERMINATION OF SALT CONTENT AND COMPOSITION IN SWEDISH CLAYS

#### 3.1 General

The standard method used in many geotechnical laboratories for the determination of the salt content of a clay is as follows.

20 g of dried and pulverized clay is leached with 80 g distilled water for one day. The slurry is then centrifuged and 50 cm<sup>3</sup> of the water is removed for analysis. The amount of salts are thereafter determined by evaporation and weighing, by conductivity, or by chemical or spectrometrical analysis.

Some authors, e.g. Benade (1928), have reported that the conductivity of soil and clay extracts is influenced by the leaching time and other factors. They also say

that organic material has an influence on the results and that the disturbance depends on the nature of the clay. Also Hammer (1949) has found that several factors will influence the results when dried clay powder is leached, e.g. solvent, time of leaching, temperature, filtering methods etc.

The evaporation and weighing method gives only an estimate of the total amount of salts, as also does the conductivity method. However, the ionic composition in the pore water is of great importance for the geotechnical properties, as discussed in Chapter 5.

Few laboratories seem to have studied the ionic composition in the pore water in clays. For the clays in the

Göta River Valley only one systematic investigation has been reported (Tullström, 1961). Talme et al. (1966) and Talme (1968) have investigated the ionic composition at a few places in Sweden. They have used flame spectrophotometrical methods for the cations and gravimetric, titrimetric and similar methods for the anions.

### 3.2 Development of a Method for Determination of Salt Content

#### 3.2.1 Experiments with Leaching Methods

Experiments were first made with the standard leaching method mentioned above. The salt content in a clay profile from Enköping (cf. Jakobson, 1954) as determined by this method is shown in Fig. 4. There is a maximum salt content at the depth of 12 m, which seems somewhat strange considering the diffusion in a natural undisturbed clay profile (cf. Chapter 7). Probably the analyses are affected by such disturbances as those observed by Hammer (1949) mentioned above. A series of experiments were therefore performed to investigate if such phenomena really occur in Swedish clays.

For this purpose a clay from Skå Edeby was examined. Suspensions of several concentrations of this clay were

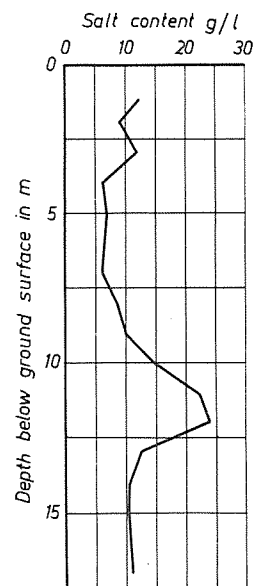


Fig. 4 Result of salt determination by means of the leaching and conductivity method (from Söderblom, 1957)

allowed to stand for one day. In some cases the suspensions were boiled for one hour. After this treatment the clay suspensions were centrifuged. The salt content in the clear solutions was determined by means of evaporation and weighing. The results are shown in Table 7. It is seen that they are affected by the concentration of the suspensions. The results are somewhat irregular, possibly due to disturbances from

Table 7 Studies on the leaching method for salt determination

Depth m	Natural water content w %	Salt content in squeezed pore water by evaporation g/l	Salt content according to the leaching method, g/l		Remarks
			Unboiled suspension	Boiled suspension	
1	70	2.95	13.6	17.2	2 grams of clay in 100 ml water. 10 ml evaporated
2	79.5	3.11	5.1		
2.5	63	2.89	14.3	12.7	
3	58	2.78	17.2	18.9	
3.5	56	2.89	22.3		
1	70	2.95	3.1	4.2	2 grams of clay in 40 ml water. 10 ml evaporated
2	79.5	3.11	4.5	6.5	
2.5	63	2.89	5.9		
3	58	2.78	5.0	6.2	
3.5	56	2.89	4.9	6.0	
3.5			5.3 x)		
1	70	2.95	10.7		5 grams of clay in 40 ml water. 10 ml evaporated
2	79.5	3.11	21.7		
2.5	63	2.89	14.9		
3	58	2.78	9.7		
3.5	56	2.95	14.7		
3.5			10.4 x)		

x) After squeezing of pore water.

the clay minerals. These methods do not seem to be suitable for Swedish clays. New methods were therefore developed.

### 3.22 Experiments with Pore Water

It was found suitable first to study the salt content of the pore water.

To obtain pore water from clay in a sufficient amount a filter press of the type used in the drilling mud industry as described by Rogers (1948) was first used. Compressed air was employed to squeeze out the pore water. From a sample with a thickness of 5 cm and a diameter of 5 cm about 25 ml of pore water was obtained which is common for an undisturbed Swedish clay with normal water content. The salt content can then be determined by evaporation, by conductivity tests or by chemical methods.

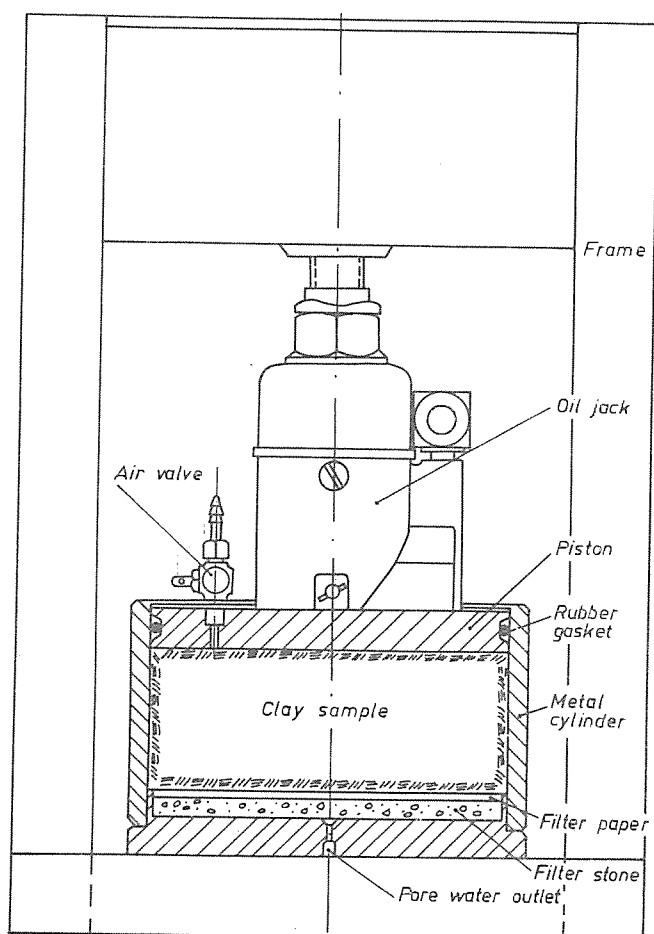


Fig. 5 Pore water press

For the systematic investigation two modified pore water presses were developed, one with a diameter of

19 cm for remoulded clay and one with a diameter of 5 cm for undisturbed samples. The design is shown in Fig. 5. A piston is used instead of air to squeeze out the pore water from the clay. The load on the piston is applied by a hydraulic jack.

Very often the water squeezed from postglacial Swedish clays contains a considerable amount of soluble organic substances. They can be destroyed either by hydrogen peroxide or by ignition before the inorganic salts are studied.

The results of a series of experiments on the same clay core from Enköping as in Fig. 4 are shown in Fig. 6. It should be noted that the salt maximum at 12 m seen in Fig. 4 could not be detected in the squeezed water (Fig. 6). These results indicate that for Swedish clays the leaching method is not reliable for the determination of the salt content in the pore water.

In Fig. 6 is also shown the electrical resistance of the clay. The resistance vs. depth curves are smooth without any maximum at the depth of 12 m.

Dakshinamurti (1960) has shown that the conductivity of a kaolin paste varies almost linearly with the clay content and is in a paste with constant kaolin content directly proportional to the concentration of the electrolyte added. Dakshinamurti found a critical concentration at which the adsorbed double layer influenced the conductivity. The same observations have been made by him for two Swedish clays. Similar results have also been reported by Letey & Klute (1960).

Penner (1964) has found an approximately linear correlation between  $\kappa$  in a clay sample and  $\kappa$  in its pore water. These results indicate that the conductivity of the clay can be used as a measure of the salt content of the pore water.

The conductivity of many hydrogels is nearly the same as the conductivity of the intermicellar liquid. This is not generally the case for clays because the clay particles impede the ion mobility. A clay sample has as a rule a lower conductivity than the squeezed pore water. The reduction in mobility has been expressed by the transmission factor  $\kappa_{\text{clay}}/\kappa_{\text{aq}}$  where  $\kappa_{\text{clay}}$  is the conductivity of the clay system and  $\kappa_{\text{aq}}$  the value in aqueous solution of the salts (cf. Gast & East, 1964). These authors, however, define the transmission factor as  $\lambda_{\text{clay}}/\lambda_{\text{aq}}$ , where  $\lambda_{\text{aq}}$  means the ionic conductivity at infinite dilution. This is in analogy with the behaviour in diffusion in clays where  $D_{\text{clay}}/D_{\text{aq}}$  is called the diffusion transmission factor (Porter et al.,

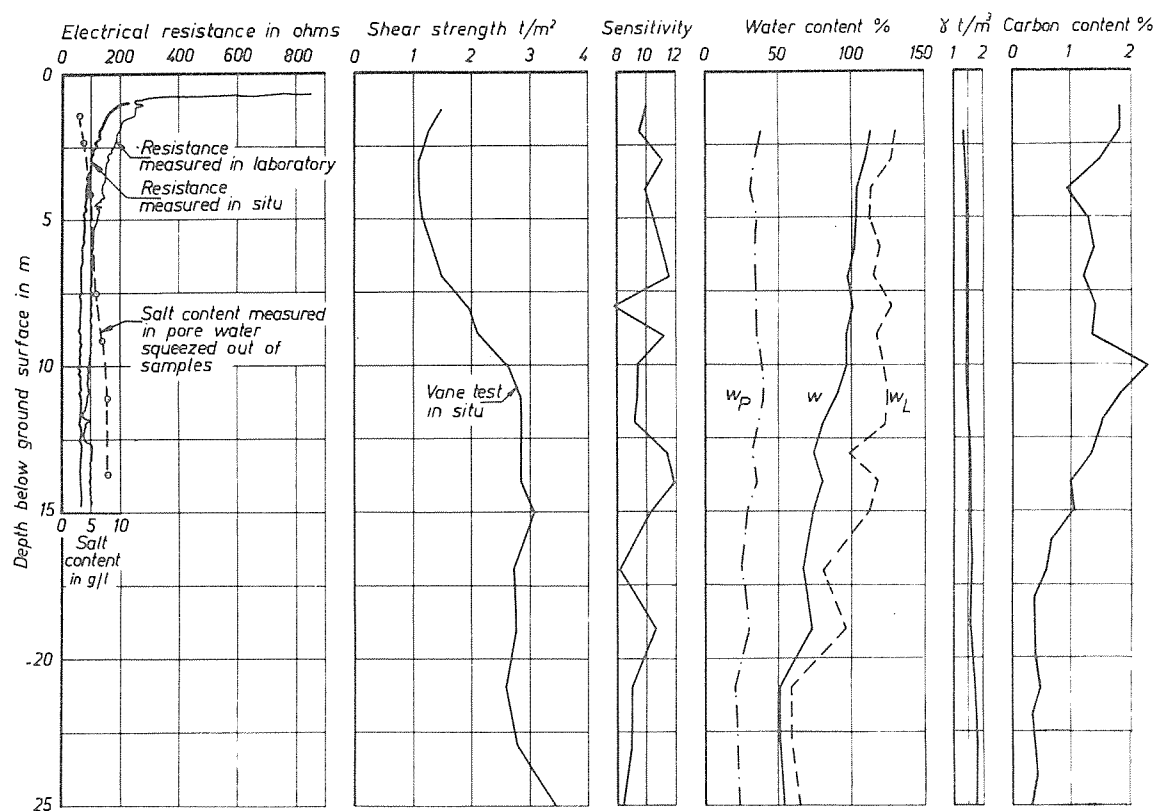


Fig. 6 Geotechnical data from a clay profile at Enköping including results of salinity determinations on pore water (from Söderblom, 1957)

1960), cf. Chapter 7. According to Gast & East (1964) the total reduction in mobility is of the same order of magnitude for both the conductivity and the diffusion transmission factors, indicating that the underlying mechanisms for the two processes are essentially similar. Sometimes they found higher values for the conductivity transmission factor than for the diffusion transmission factor and this has been explained as being due to electro-osmosis.

According to Cremers & Laudelout (1965) the conductivity transmission factor is  $<1$  when the conductivity is high, mainly depending on tortuosity effects in the gel, but at low conductivity, they have found values  $>1$  (cf. also Table 12) presumably due to conductivity effects in the double layers. When both effects balance each other, the conductivity of the clay mass is equal to the conductivity of the squeezed pore water. This case they called isoconductivity.

### 3.23 The Conductivity Method and its Application to Geotechnical Studies

In the previous chapter it was said that the conductivity method could be used to estimate the pore water salt content in a clay. For the theory of conductivity the

reader is referred to textbooks in electrochemistry. Here only a few principles will be mentioned which are necessary for an understanding of the present investigations.

A homogeneous conductor with the length  $L$  and the cross sectional area  $A$  has the electric resistance

$$R = \rho L/A$$

where  $\rho$  is the resistivity of the substance. The conductivity  $\kappa$  is defined as  $1/\rho$ . The unit of the resistivity  $\rho$  is  $\text{ohm} \cdot \text{cm}$  and that of the conductivity  $\kappa$   $\text{ohm}^{-1} \text{cm}^{-1}$ .

For an absolute determination of  $\rho$  the homogeneous substance must be enclosed in a vessel with exactly defined length and cross section. Investigations of this kind are difficult to perform and have only been made on some solutions and metals.

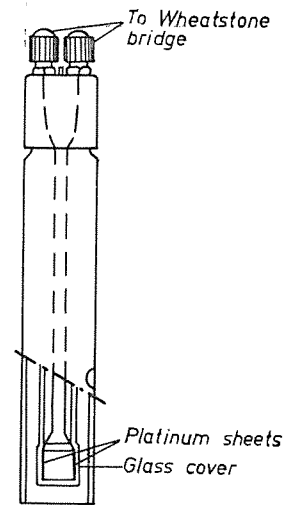
The common procedure to determine  $\rho$  or  $\kappa$  of a liquid is to use a relative method using resistivity vessels or dip electrodes of different kinds. One type is shown in Fig. 7 (dip electrode). The penetration electrode and the salt sounding tool described below are both instruments of this type.

When such a device is filled with or dipped into a liquid its electric resistance will be proportional to the re-

Table 8 Calibration of the penetration electrode in KCl-solutions

	Temp °C	R ohm	$\rho$ ohm·cm	1/k cm
1/50 N (1.491 g KCl/l)				
PW 9510	23.5	260	372.5	1.43
Penetration electrode	23.5	152	372.5	2.45
1/10 N (7.456 g KCl/l)				
PW 9510	25	54	77.6	1.44
Penetration electrode	25	31	77.6	2.50

Fig. 7 Principle sketch of a dip electrode (Philips PW 9510)



sistivity of the liquid. Thus

$$R = k \cdot \rho = k/\kappa$$

In this equation  $k$  is called the cell constant. The inverted value  $1/k$  is sometimes called multiplication factor. The same equation is valid for the penetration electrode and the salt sounding tool. Usually devices of this kind are calibrated by means of KCl-solutions with known  $\kappa$ .

The conductivity  $\kappa$  of a completely dissociated electrolyte is roughly proportional to the concentration if this is not too high.

As discussed in Chapter 4 the pore water of Swedish clays contains mainly  $\text{Na}^+$ ,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  as cations and  $\text{SO}_4^{2-}$  and  $\text{Cl}^-$  as anions. Pore waters from different clays show great variations in ionic composition. In the typical salt clays all the ions mentioned above are present with  $\text{Cl}^-$  as the dominating anion. Sometimes  $\text{Na}^+$  and  $\text{SO}_4^{2-}$  are the dominating ions but not  $\text{Cl}^-$ . In other clays  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$  and  $\text{SO}_4^{2-}$  sometimes dominate. In some weathered clays  $\text{K}^+$  also occurs in considerable quantities. In Chapter 4 it will be shown that the ionic composition in a clay profile may vary with depth. Because the ionic conductivities of the ions mentioned are somewhat different the salt content in the pore water of a clay cannot be determined with analytical accuracy by means of conductivity measurements. Several authors, who have systematically examined different clays and other soils are, however, of the opinion that the accuracy of the conductivity method is sufficient for most practical purposes (cf. Rosenqvist, 1955).

### 3.24 The Penetration Electrode

In order to determine the electrical resistance direct-

ly in clay samples the penetration electrode shown in Fig. 8 was designed by Söderblom (1957). This tool is a modification of Philips PW 9510 altered so that it is possible to insert the electrodes directly into a clay sample. The resistance between the two platinum electrodes (1.0 x 1.0 cm at a mutual distance 1.0 cm) is measured with a commercial Wheatstone bridge.

With this tool the conductivity can be determined at short intervals along the full length of an extracted clay core. It is thus possible to obtain an almost continuous registration of the conductivity conditions.

The tool was calibrated in KCl- and NaCl-solutions. The multiplication factor was first determined in 0.02 N and 0.1 NKCl-solutions. For comparison the dip electrode Philips PW 9510 was used. The results are shown in Table 8. The penetration electrode has a

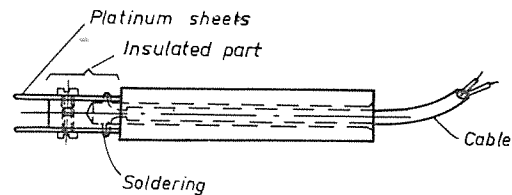


Fig. 8 Laboratory penetration electrode

multiplication factor of about 2.5 cm but the factor varies somewhat from tool to tool.

The electrodes in this tool can of course not be covered with platinum black because this cover would be rubbed off when the tool is inserted into the clay. Therefore polarization will disturb the measurements, but in a clay material no precision determinations can be made anyhow. For this reason the penetration electrode should only be used in clays (or other gels) where a

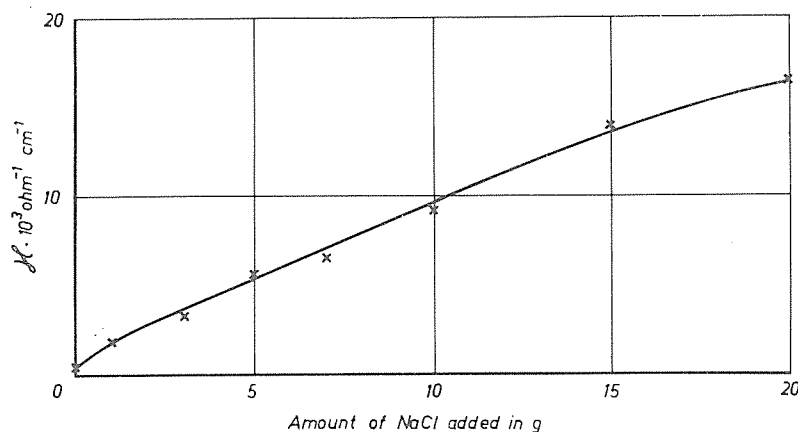


Fig. 9 Calibration curve for the penetration electrode showing change of conductivity  $\kappa$  in a kaoline mass by adding various amounts of NaCl

commercial dip cell with electrodes covered with platinum black cannot be used.

In order to study the influence of different amounts of salt on the conductivity of a clay the following experiments were made. Water was carefully added to 1 kg of dried "kaolin 46" until the  $H_1$ -value of the clay mass was equal to 10. The electrical conductivity of the clay mass was then determined with the penetration electrode. Thereafter 1 g of NaCl was added and the mass thoroughly homogenized. The conductivity was then determined again. The experiment was repeated and carried out with 1, 2, 3, 5, 7, 10, 15 and 20 g of salt per kg clay mass. The  $\kappa$ -values were plotted against the amount of added NaCl as shown in Fig. 9. The

relation is approximately linear with some scatter. Additional results will be given in a later paper (Söderblom, 1970) where the influence of different salts on the clay properties will be reported.

The change of the salt content in the pore water was studied by an experiment similar to that described above by squeezing out pore water from a small part of the clay mass after each addition of salt. The salt content was determined from evaporation and by the conductivity. An "expected" composition of the pore water was also calculated assuming no interaction between NaCl and the clay particles. The result is seen in Table 9 and in Fig. 10.

Table 9 Measurements on a Kaolin mass used for calibration of the penetration electrode (cf. Figs 9 and 10)

Amount of NaCl added to 1 kg clay mass g/l	Determination of salt content in squeezed pore water			"Expected" salt content g/l	Conductivity transm. factor x)	Remarks	
	By evaporation g/l	By conductivity (dip electrode)					
		R ohm	$\kappa \cdot 10^3 \text{ ohm}^{-1} \text{ cm}^{-1}$	Salt content g/l			
0	0.34	1800	0.38	0.21	0	0.24	The water contains $\text{Na}^+$ , $\text{Ca}^{2+}$ , $\text{Mg}^{2+}$ , $\text{Cl}^-$ and $\text{SO}_4^{2-}$ -ions
1	2.41	198	3.46	2.05	2.4	0.55	Besides $\text{Na}^+$ the water contains considerable amounts of $\text{Mg}^{2+}$
2	3.78	128	5.35	3.20	5.6	0.60	- " -
3	7.97	63	10.9	7.0	8.4	0.34	- " -
5	8.55	58	11.8	7.6	14.1	0.65	- " -
10	27.55	20.5	33.4	20.4	28.2	0.34	- " -
15	36.44	16.3	42.0	30	42.2	0.40	- " -
20	50.00	12.9	53.1	39	56.3	0.40	- " -

x) See p. 9

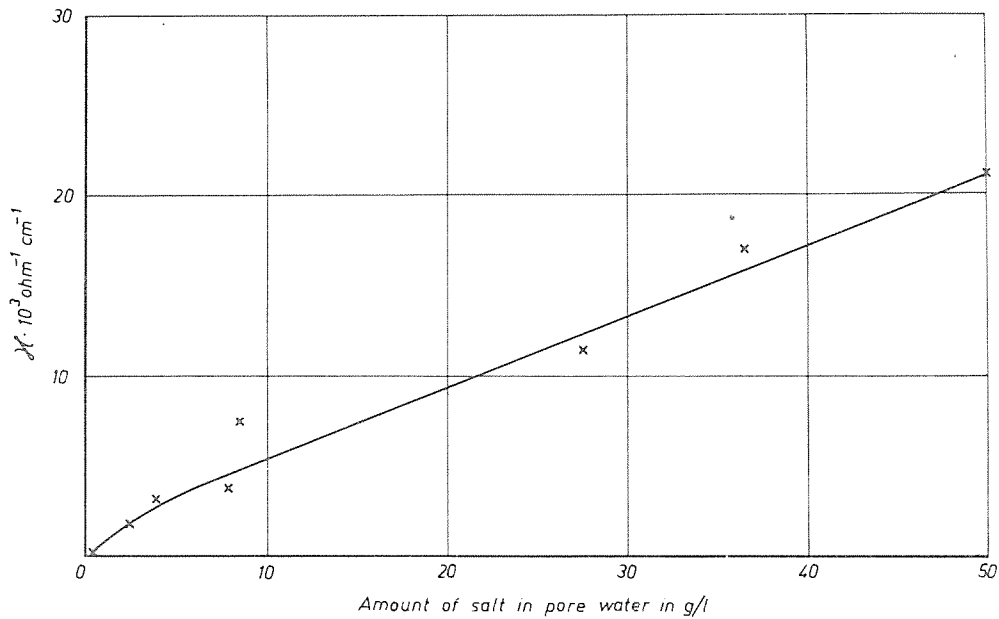


Fig. 10 Calibration curve for the penetration electrode showing the value of conductivity  $\kappa$  in a kaoline mass vs. pore water salt content determined by evaporation and weighing

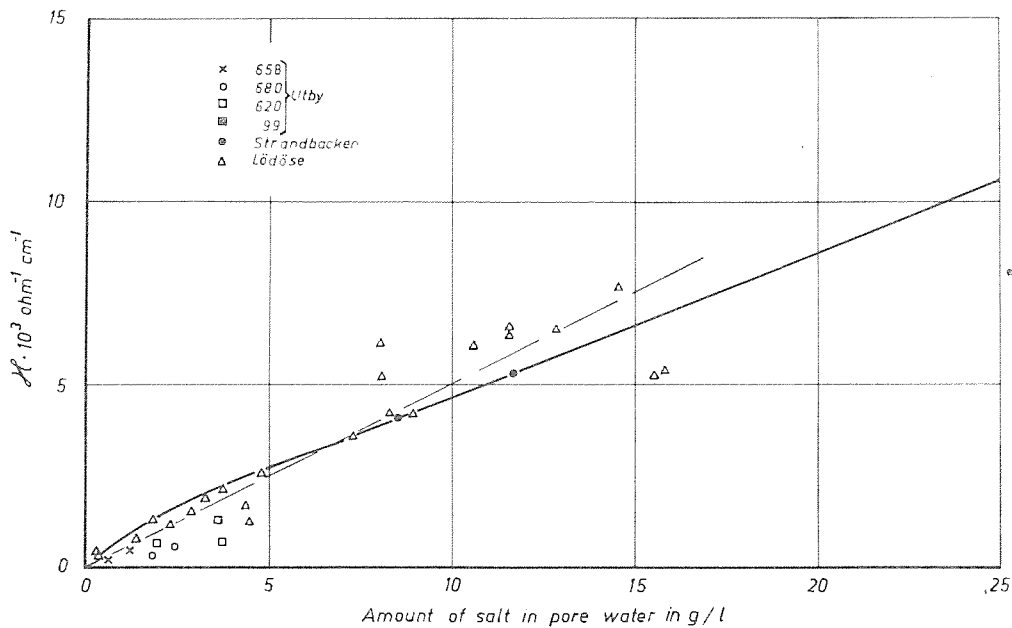


Fig. 11 Relationship between  $\kappa$  in sample and total salt content in pore water squeezed out from different clays in the Göta River Valley

The salt content in the squeezed pore water was lower than the "expected" value, indicating adsorption of salt. The salt content in the pore waters estimated from the conductivity shows lower values than those determined by evaporation.

The smoothed out curve (Fig. 10) gives values of the conductivity transmission factor of 0.32-0.36. At

lower concentrations the transmission factors are higher. The values mentioned are of the same order of magnitude as is often found in Swedish clays. The curve seems to be useful as a rough calibration curve for the penetration electrode.

In Fig. 11 the pore water salt content for clay samples from Utby, Strandbacken and Lödöse are plotted

against their conductivity. They are mostly deviating from the kaolin calibration curve from Fig. 10 and are in fact better represented by a straight line. These results show to which restricted extent the penetration electrode can be used to estimate the pore water salt content in clay. If more accurate values are required it is necessary to analyse the pore water itself. But the limited accuracy obtained by the penetration electrode (and the salt sounding tool) may be sufficient for several purposes.

### 3.25 The Salt Sounding Tool

The results with the penetration electrode suggested that it was possible to develop a tool which could be used to estimate directly the pore water salt content of clays in situ. With such a tool it would also be possible to study diffusion processes in nature.

Experiments with a tool suitable for determining the electrical conductivity in the ground have been undertaken by Rosenqvist (1956) who developed the so-called corrosion sounding tool. This instrument has a magnesium tip and, insulated from this, a ring-shaped electrode of steel. The resistance is measured between these two parts. Since the magnesium electrode always has an oxide cover the resistance measurements may be uncertain. It has a multiplication factor of about 4 cm, but this factor is said to vary somewhat from soil to soil.

The Norwegian sounding tool has been modified as shown in Fig. 12. The modified device is here called the salt sounding tool. Its body is of steel. The ring-shaped brass electrodes are insulated from the main part by glass fibre reinforced polyester plastic. The tool can be extended by the same tubes as are used for the Swedish Standard Piston Sampler. The tool is driven into the soil with standard equipment.

When making deeper holes a washing aggregate is placed between two extension tubes, about 1 m above the sounding tool. Water is pumped through by means of a highpressure pump. With this equipment it is possible to make soundings in the clay to depths more than 50 m below the ground surface. Readings with the salt sounding tool are made for every 10 cm. The measured resistances or the corresponding  $\kappa$ -values are plotted in a diagram as a function of the depth below ground surface.

The salt sounding tool has been calibrated in the same way as the penetration electrode. The accuracies of the two instruments are about the same.

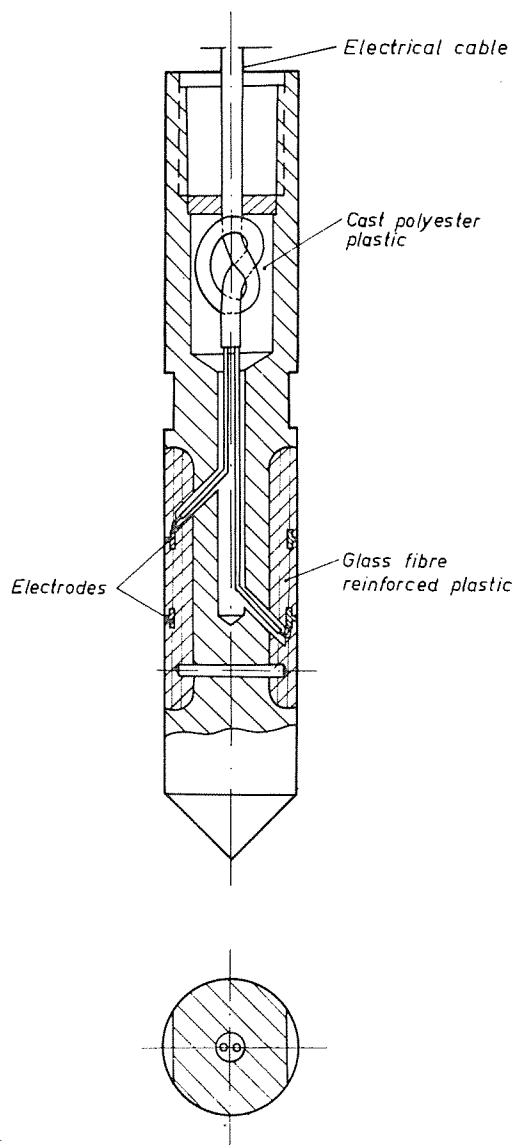


Fig. 12 Salt sounding tool for direct measurements of conductivity in soil

A modified device was later developed by Messrs. Orrje & Co., Göteborg, where a salt sounding tool has been combined with a vane borer. With this instrument it is possible to measure the sensitivity and the conductivity of a clay at the same time.

### 3.26 Chromatography

The dominating ions in sea water and in the pore water of clays deposited in salt water are  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Cl}^-$  and  $\text{SO}_4^{2-}$ . Therefore it was necessary to make determinations of mixtures containing these ions. A suitable rapid method was one-dimensional paper chromatography.

To estimate the composition of pore waters a method given by Long, Quayle & Stedman (1951) was employed.



The solvent used in this method is ethanol (95%) - ammonia (d = 0.81) - water (80:4:16). The pore water can be analysed untreated. About 3 to 5 mm<sup>3</sup> liquid are pipetted onto Whatman paper. Sodium chloride is mostly used as a standard substance.

The chromatograms are developed descending on a half-sheet of a Whatman I paper (23x57 cm) in a standard equipment for paper chromatography (Linskens, 1959). In most cases, however, it is sufficient to make small, rapid chromatograms which are developed ascending in the "Desaga" equipment for thin-layer chromatography (cf. Stahl, 1965). Instead of the plate used in thin-layer chromatography a glass frame covered with Whatman I paper was used. The papers had the dimensions only 10x20 cm. After development, which takes about 140 minutes, the chromatograms were dried for 5 minutes at 110°C and thereafter sprayed with bromophenolblue solution (cf. Linskens, 1959). In the solvent system used the ions will show the R<sub>F</sub>-values given by Long, Quayle & Stedman in Table 10.

Table 10 R<sub>F</sub>-values of different ions (after Long et al.)

Salt	R <sub>F</sub> -value	
	Cations	Anions
NaCl	0.26	0.43
NaBr	0.25	0.48
NaAc	0.26	0.52
Na <sub>2</sub> SO <sub>4</sub>	0.20	0.09
KAc	0.19	0.52
MgAc <sub>2</sub>	0	0.52
CaAc <sub>2</sub>	0	0.52

Systematic investigations on pore waters have shown that this method is suitable to distinguish between pore waters with sodium as the dominant cation and pore waters with Ca<sup>2+</sup> and Mg<sup>2+</sup> as the dominant cations. This difference in pore water composition is of great importance in a study of the relation between salinity and sensitivity (cf. Chapter 5). The method is well suited for field work.

The cations can be investigated in more detail by a method given by Seiler, Sorkin & Erlenmeyer (1952). The solvent is ethanol (95%) - 2 N acetic acid in water (80:20). The chromatograms are developed in the standard equipment for paper chromatography. With this method it is necessary to convert the salts into acetates before the analysis. This can best be made in an ion exchanger IRA 410 in its acetate form.

The chromatograms can be developed either with

bromophenolblue or still better with a 0.5 % solution of violuric acid. In the first method all cations appear as blue spots on a yellow background. In the second method characteristic colour reactions for alkali and alkaline earth ions will appear as given in Table 11 (Seiler et al., 1951).

Table 11 R<sub>F</sub>-values and colouring of alkali and alkaline earth ions with violuric acid (after Seiler et al.)

Ion	R <sub>F</sub> -value	Colour
K <sup>+</sup>	0.45	violet
Na <sup>+</sup>	0.56	violet-reddish
Ca <sup>2+</sup>	0.68	orange
Mg <sup>2+</sup>	0.76	yellow-pink
Li <sup>+</sup>	0.76	red-violet

It may also be mentioned that Zn is coloured red and iron blue by this treatment.

According to Seiler et al. (1951) it is possible to estimate the quantitative composition of a salt solution containing a mixture of alkali and alkaline earth ions with an accuracy of 10-15%.

The violuric acid reaction can also be used on the chromatograms first described. They are sprayed with 95% ethanol and kept for half an hour in the steam of conc. acetic acid. Thereafter the chromatogram is dried at 105°C for 5 minutes and sprayed with a 0.5% solution of violuric acid. The typical colourings of alkali and alkaline earth metals are then obtained.

In this work mainly qualitative examinations of the pore waters have been made. In Table 12 approximate values of the concentrations of the ions in pore waters from Lödöse are given. They are crude estimates from the small chromatograms mentioned above. Because of the irregular form of the spots it is hardly possible to estimate absolute ion concentrations directly from them. It seems safer first to estimate relative normalities, e.g. the salt in a water may have 40% Na<sup>+</sup>, 10%  $\frac{1}{2}$  (Ca<sup>2+</sup> + Mg<sup>2+</sup>), 35% Cl<sup>-</sup> and 15%  $\frac{1}{2}$  SO<sub>4</sub><sup>2-</sup>. From the total salt content obtained by evaporation it is then possible to estimate the absolute normalities of the ions.

### 3.3 Discussion

As stated in (2.3) the main purpose of the present investigation was to develop methods for a study of the influence of electrolytes on the geotechnical properties and especially a field study of the leaching theory. Kerr

Table 12 Data from the section investigated at Lödöse in the Göta River Valley

Hole Depth m	R in pore water ohm	$\kappa \cdot 10^3$ $\text{ohm}^{-1}$ cm	Salt	Salt	Salt	R in sam- ple ohm	$\kappa \cdot 10^3$ $\text{ohm}^{-1}$ cm	Salt	Ionic composition, meq/l <sup>5)</sup>					$H_3/H_1$ ( $S_t$ )	Natural water content w %	Liquid limit w <sub>L</sub> %	Conduc- tivity transm. factor		
			cont. in pore water 1) g/l	cont. in pore water 2) g/l	cont. in pore water 3) g/l			cont. in pore water 4) g/l	Na <sup>+</sup>	Ca <sup>2+</sup> Mg <sup>2+</sup>	Cl <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	H <sub>3</sub>					H <sub>1</sub>	
<b>Hole 1</b>																			
2	810	0.93	0.52	0.65	0.50	532	0.80	1.2	4	0.4		0.4	33.6	<0.33	>102	88	65	0.85	
4	790	0.96	0.54	0.70	0.43	460	0.92	1.3	3.3	0.4		0.4	27.0	<0.35	>82.0	91	59	0.96	
7	1200	0.63	0.35	0.49	0.26	540	0.79	1.2	2.2			0.2	44.1	0.45	99.0	87	57.2	1.25	
10	1650	0.50	0.25	0.34	0.30	980	0.43	0.6	2.6			0.3	40.0	1.02	39.2	50	37.6	0.95	
<b>Hole 2</b>																			
2	138	5.5	3.3	4.61	4.42	180	2.2	2.8	40	10		35	15	90.6	10.0	9.6	67	67	0.40
5	51	14.9	9.0	9.77	9.27	78.5	5.1	9.0	63	18		63	18	51.1	10.8	4.7	72.4	73.6	0.34
10	74	10.2	6.6	6.43	6.23	108	3.7	5.6	48	5		51	2	61.5	3.08	20.0	84	64.5	0.36
15	130	5.82	3.6	3.76	3.65	160	2.5	3.7	30	1.2		30	1.2	73.5	1.45	50.7	84	65.0	0.43
20	175	4.33	2.5	2.57	2.54	300	1.33	2.3	20	2		20	2	49.0	3.57	13.7	33.5	37	0.31
<b>Hole 3</b>																			
1	178	4.27	2.6	3.36	2.79	260	1.54	2	19	5		21	3	86	15.4	5.6	56	60.6	0.36
5	29	26.2	18	20.02	17.87	48	8.35	17.5	147	37		166	18	110	12.0	9.2	68.5	71	0.32
10	36	21.0	14.5	15.45	14.27	56.2	7.13	14.6	85	37		110	12	120	13.2	9.1	72.4	76	0.34
15	64.3	11.8	7.8	7.55	7.20	86	4.68	7.6	49	12		60	1	81.5	4.66	17.5	81.9	72	0.39
20	54	14.0	9.2	9.67	8.81	170	2.35	3.1	53	22		68	7	141	3.57	39.6	77.7	64.8	0.17
23	170	4.5	2.7	2.80	2.63	268	1.49	2	20	2		20	20	61.5	4.39	14.0	44	40	0.33
<b>Hole 4</b>																			
1	80	9.5	6.1	6.61	5.85	140	2.85	6	40	10		45	5	79.4	8.25	9.6	58.6	57	0.30
7	24.8	30.5	21.5	24.01	21.31	33	12.1	27.2	127	55		164	18	141	12.3	11.1	67.7	69.1	0.40
10	22.8	33.2	23.5	26.08	23.02	30.5	13.1	29.6	138	59		177	20	141	13.8	10.0	60.3	64.4	0.36
15	23.5	32.4	23.5	25.67	22.94	31.2	12.8	28.8	137	58		185	10	120	19.7	6.1	52.2	59.8	0.40
20	30	25.3	17.9	18.78	16.85	32.5	12.3	27.6	104	43		141	6	149	19.7	7.5	72.8	84.5	0.49
25	30.5	25.0	17.3	18.16	16.40	38.8	10.4	23.0	98	42		140		163	12.3	13.2	56	58	0.42
<b>Hole 5</b>																			
3	55.8	13.6	9.0	9.15	8.57	121	3.3	4.8	59	15		71	3	141	16.6	8.5	61.4	67.5	0.24
5	31.5	24.0	17.6	17.88	16.55	47.9	8.4	17.6	113	28		136	5	117	19.7	5.9	70.6	82.0	0.35
10	21.5	35.2	26.0	27.81	25.70	30.8	13.0	29.6	154	66		211	9	141	15.4	9.2	57.8	62.7	0.37
15	20.0	37.9	28.0	31.29	29.01	26	15.4	35.4	176	76		242	10	189	18.2	10.6	66.1	76.0	0.41
20	21.0	36	26	29.33	27.63	38.7	10.3	22.6	165	71		212	24	189	19.7	9.6	67	77.5	0.29
25	20.0	37.9	28.0	31.56	29.65	36.8	10.9	24.0	189	81		216	54	141	19.7	7.2	72.5	84	0.29

- 1) Calculated from the conductivity of pore water
- 2) " " " evaporation residue of the pore water
- 3) " " " ignited evaporation residue of the pore water
- 4) " " " conductivity of the clay
- 5) The samples in Hole 1 contain organic anions and HCO<sub>3</sub><sup>-</sup>

& Liebling (1965) mean that it is necessary to reduce the salt content in the pore water of a clay from e.g. about 3.5% to about 0.1% to obtain a quick clay. If their opinion is correct there must be large differences in salt content between quick clays and non-quick clays. Quite crude methods seem to be sufficient to detect such large differences.

One might expect the sensitivity to vary inversely to the salt content. To test such a relationship one cannot use e.g. the method where dry clay powder is leached, as that method is uncertain and may give false peaks in the salt content curve. As seen in (3.21) the salt content found by this method is dependent on the concentration of the suspension, treatment, etc. The method usually gives a higher total pore water salt content than a direct analysis of the squeezed pore water, because

varying amounts of ions from the adsorbed double layers are extracted.

A pore water salt content of about 0.4% in quick clays as found by some authors gives a  $\kappa$ -value of about  $4 \cdot 10^{-3} \text{ ohm}^{-1} \text{ cm}^{-1}$  for the clay if NaCl is the dominating electrolyte. This salt content, at which a quick clay system flocculates, is about the same as that in the "salt clay" at Kungsängen (cf. Fig. 21). In order to understand the disturbances by leaching methods some chromatographic studies were made of the leachates. Such a chromatogram from a clay sample from Hole 620 Utby 13 m is shown in Fig. 13. If compared with the chromatogram from the pore water of an adjacent clay (Fig. 32) it is seen whereas sodium chloride is present in both cases, there are only traces of calcium and magnesium in the leachate but much

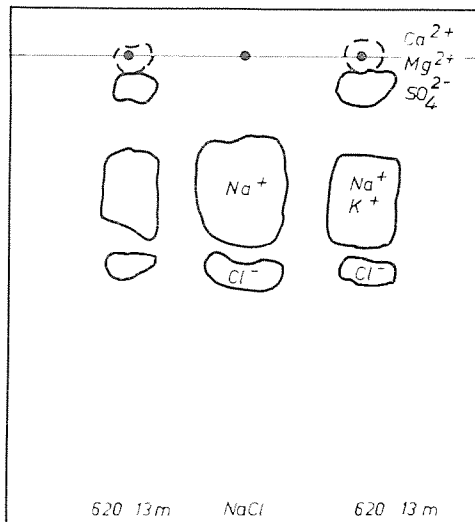


Fig. 13 Small-paper chromatogram of a leachate from a pulverized dry clay from Utby Hole 620, 13 m

more in the pore water. Sulfate ions are present both in the leachate and in the pore water. Organic matter is also present in the yellow leachate. Thus the water obtained by the leaching method had another composition than the squeezed pore water. It may therefore be concluded that the leachate is inadequate for studies of the pore water salt content.

Accurate values of the total salt content of the pore water cannot be obtained from its conductivity because the composition of the salt content is varying. But because the ionic conductivities of the several ions are not too much at variance, the method may yield results accurate enough for geotechnical purposes (cf. Rosenqvist, 1955). As seen from Table 12 the salt content derived from the pore water conductivity agrees reasonably well with the content obtained by evaporation.

The conductivity in the ground is often determined by the "four probes method" developed by F. Wenner (1915). In this method four steel probes are inserted into the ground with equal spacing along a straight line. A potential is applied between the two outer probes.

By measuring the potential difference between the two inner probes the average resistivity of the soil within a depth of the same order of magnitude as the distance between the electrodes can be calculated. If this distance is varied some authors believe it to be possible to determine the resistivity variations with depth.

These values are, however, at best mean values of the conditions between the probes. In the present investigation the local variations of the resistivity in a profile were of interest and therefore Wenner's method was not adequate.

Rosenqvist (1955) has found that the ratios of the sev-

eral ions in the clays investigated differ from those in sea water. The sulfate to chloride ratio was lower in an in situ unleached clay than in sea water, but in a quick clay this ratio was much higher than in sea water. Also the percentage of magnesium in the leachate water salt was higher in quick clays than in sea water, probably due to partial leaching in nature. Penner (1964, 1965) has found relatively more divalent cations in the pore water of a "normal" clay ( $S_t \ll 50$ ) than in that of a quick clay. Talme et al. (1966) and Talme (1968) have found similar differences.

## 4. STUDIES OF SALT CONTENT IN CLAYS

### 4.1 General

The knowledge of the distribution of salt clays in Sweden and of leaching processes in them is very limited. Only few investigations have been carried out. Mostly clay river slopes have been studied, as a part of the Göta River Valley investigation (cf. Chapter 1).

A systematic investigation of the salt conditions in Swedish clay soils is of importance since most geotechnical properties are dependent on the salt conditions of the clay. Also the rate of corrosion in the clay is in many cases dependent on the salt content.

Arrhenius (1954) has published maps showing the salt content in ground water springs at several places in Sweden. He reports relatively low salt contents in the spring waters. As a rule they have much lower salt content than the pore water in the surrounding clays.

An investigation of the salt content in the ground has been made in Australia by Lightfoot, Smith & Malcolm (1964).

### 4.2 Clay Examinations with the Salt Sounding Tool

When salt soundings have been made in Sweden curves of the type shown in Fig. 14 are usually obtained. The clays have as a rule a leached zone near the ground surface. The salt content gradually increases with depth and reaches a maximum value in the middle of the profile. At greater depths the salt content slowly decreases again. In the bottom layers the salt content is usually very small.

The salt sounding curves hitherto obtained by the present author (and also salt content curves of the pore

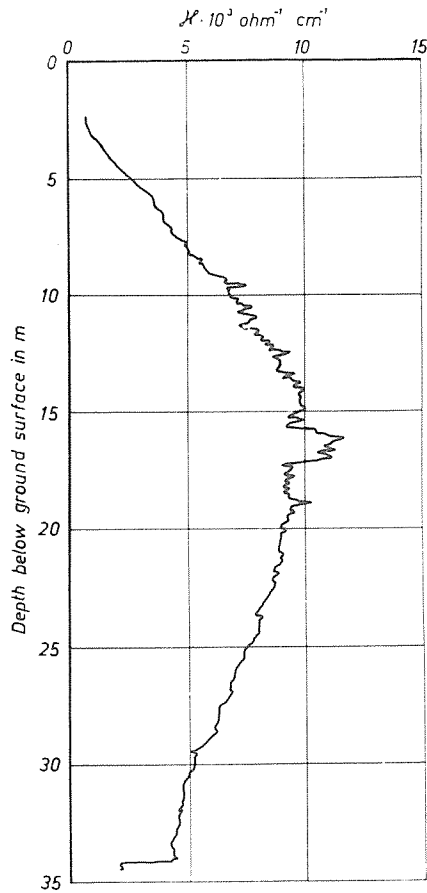


Fig. 14 Typical salt sounding curve (Utby Hole 602)

water by chemical analysis, cf. Tullström, 1961) are usually smooth in undisturbed clay profiles. It seems reasonable to assume that diffusion is a major cause of this fact. As a rule only small "ripples" are observed such as those shown in Fig. 14 (cf. Chapter 7).

As mentioned in Chapter 4, 1 most measurements of salt distribution have been made in slopes in the Göta River Valley. The salt distribution in them is notable. The saltiest clay is generally found near the river. The salt content decreases gradually with increasing distance from the river bank. A typical series of salt determinations in such a slope at Lödöse, where the ground surface is gently sloping (1 vertical to 55 horizontal) towards the river, are shown in Fig. 15 and Table 12. Six soundings are shown at different distances from the river, the nearest 2 m and the most distant 212 m from the bank. Sampling was made with the standard piston sampler (Swedish Geotechnical Institute, 1961) at the points examined, with the exception of the point at 180 m from the river. Samples were studied at about every 5 m down to 25 m. Their geotechnical properties were investigated in the laboratory and their pore water squeezed out and examined. The results are given in Table 12. The Lödöse section is shown in Fig. 16 in which the curves are connecting

points with equal conductivity. The salt content is shown in Fig. 17. The saltiest clay is found in the middle part of the deepest profile quite near the river and the salinity is there almost the same as in sea water ( $\approx 3\%$ ).

The conductivity determined with the penetration electrode in an extracted core from Tingstad, Göteborg, and corresponding results from spectrophotometric salt content determinations are shown in Fig. 18. The clay core was about 90 m long. It is seen that below the depth of about 20 m the salt concentration of the

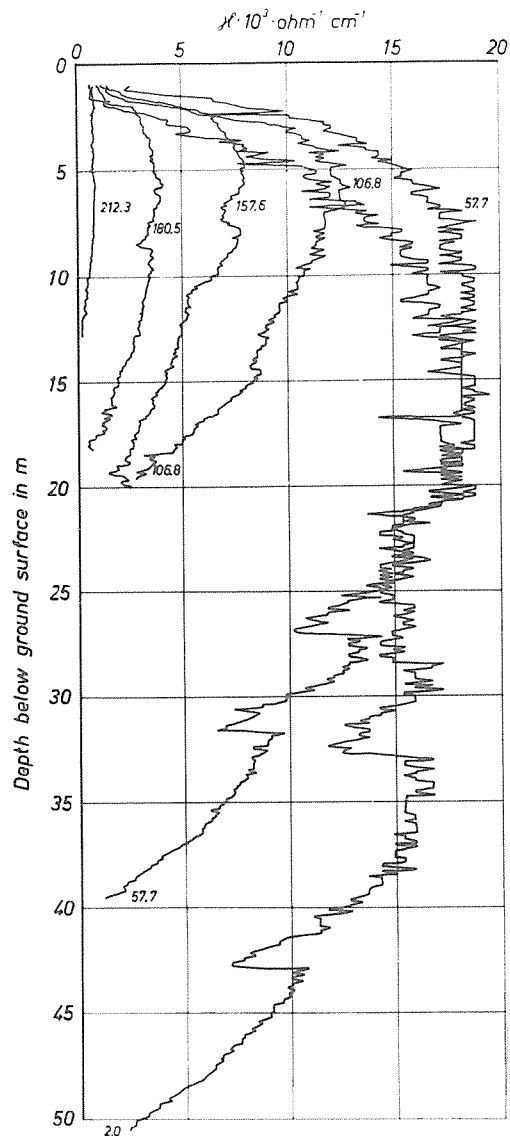


Fig. 15 Salt sounding curves from a section at Lödöse, showing salt distribution (Figures on the curves indicate distance from the Göta River in metres)

pore water is 3.5%, i. e. about the same as that of the sea water in the oceans. (The present sea water off Göteborg has a salt content of about 2.3%.) Similar relations from Olskroksmotet, Göteborg, are shown

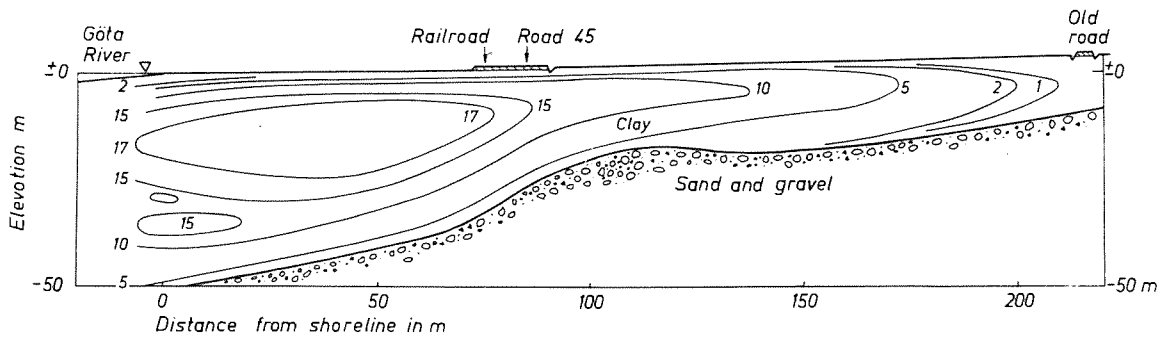


Fig. 16 Schematic view of section examined at Lödöse showing variation in conductivity

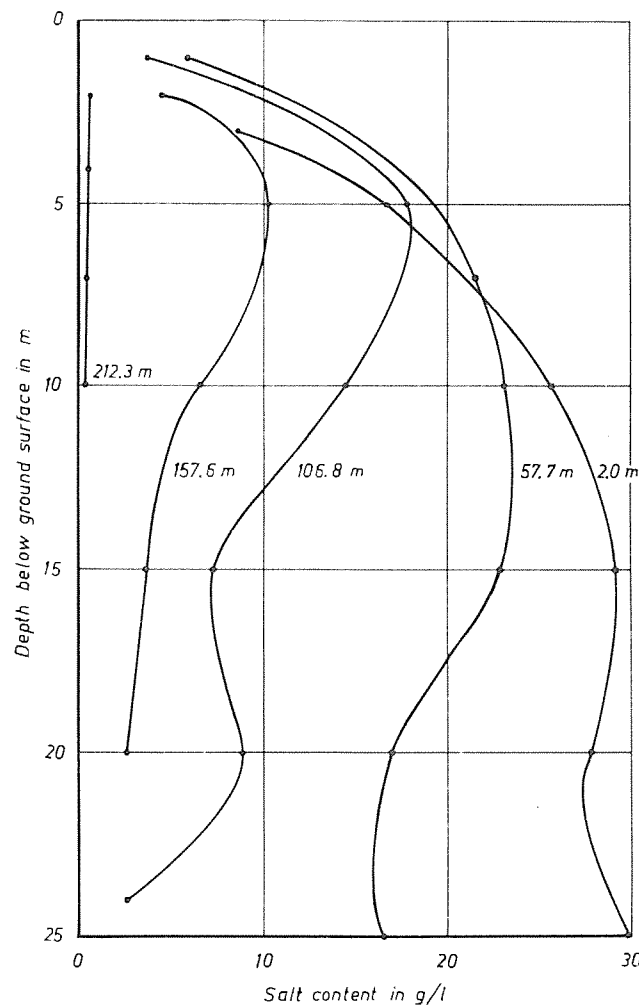


Fig. 17 Curves showing variation of pore water salt content with depth and distance from the Göta River in the profile at Lödöse

in Fig. 19. Also in this case the pore water has a salt content which is about the same as that in ocean water.

Salt sounding curves from the Enköpings River are given in Fig. 6. The soil conditions at this place are shown in Fig. 20. The pore water salt content does not

exceed 0.8‰ in the 30 m deep profile. The same general distribution as that at Lödöse was also noticed here, i. e. the salt content decreased with increasing distance from the river.

A salt sounding curve from Kungsängen, Uppsala, near Fyrisån (Kallstenius, 1958) and results from salt con-

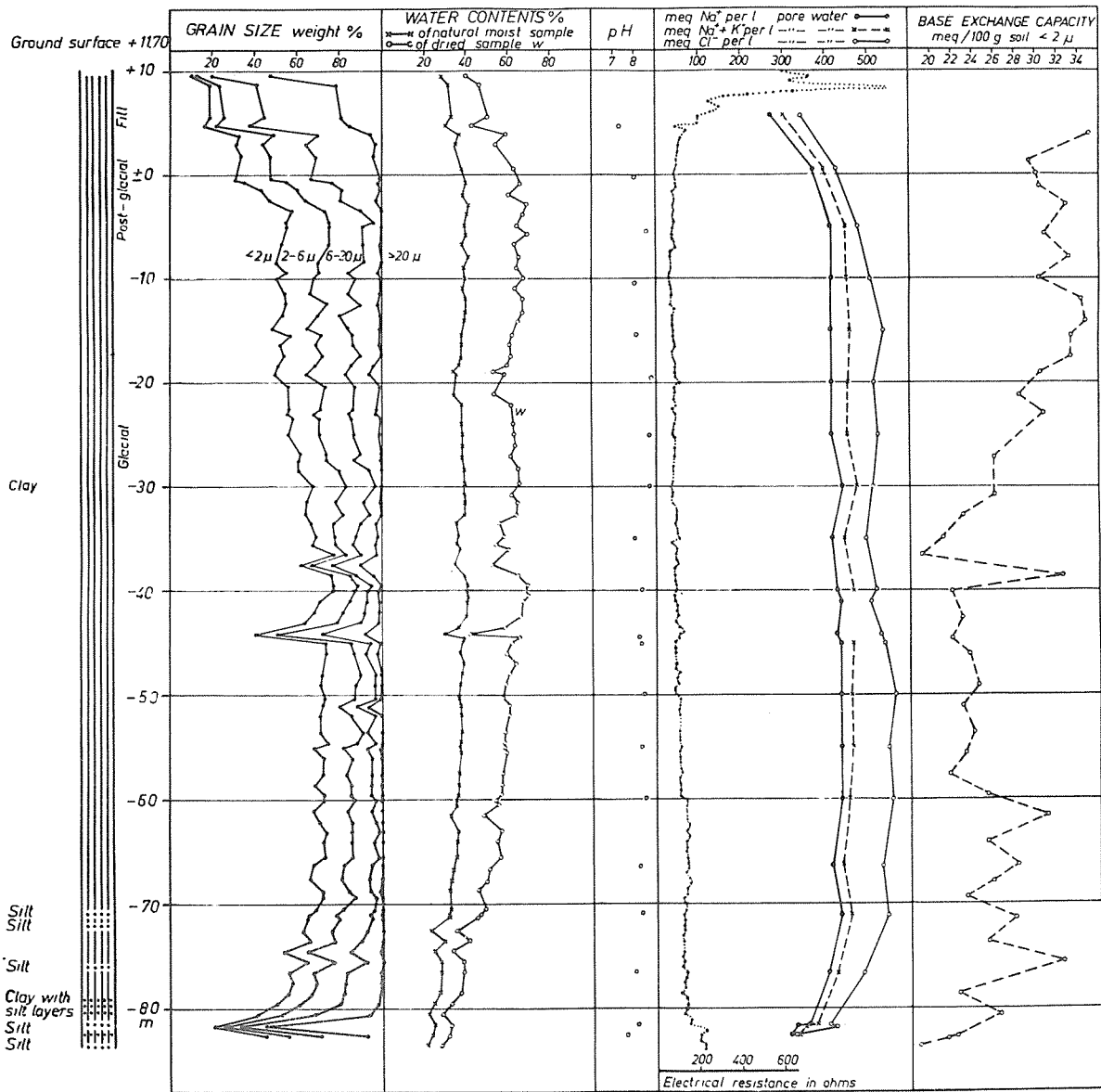


Fig. 18 Geotechnical data from a clay profile at Tingstad, Göteborg, including results of salinity determinations on pore water (from Tullström, 1961)

tent determinations by evaporation or squeezed pore water are given in Fig. 21. The total salt content in the soil profile does not exceed 0.3%.

From these last two profiles it seems that the salt sounding curves in central Sweden are of the same general type as those in the Göta River Valley in spite of the different geological conditions during their deposition, e.g. differences in salinity.

#### 4.3 Discussion of Test Results

Curves of the type shown in Fig. 14 seem to be typical in Sweden. Their shapes can be explained if one assumes that leaching has occurred from both the top

and the bottom of the profile. Rain water of course will leach the salts from the upper parts of the profile (the "dry crust") and then salts will move by diffusion upwards from the more saline parts of the profile. This process can explain the shape of the upper part of the curves.

The clays are usually deposited on a bottom layer of coarse material with high permeability which was laid down during the glacial period. Through this bottom layer there is a flow of ground water of low salinity. This water will leach salt from the overlying clay layer. As a result the salt content curves have the shape as shown in Fig. 14.

Theoretical calculations based on the normal diffusion

laws do not contradict the hypothesis that the salts in the clays are residues from the marine milieu in which they were originally deposited (Chapter 7).

The salt content in the clay pore water from Tingstad and Olskroksmotet is about the same as in ocean water. These clays are believed to have been sedimented in rather undiluted sea water and after that remained mainly unchanged.

In central Sweden the clays were deposited under very varying salt conditions. During Holocene time the

salinity of the Baltic Sea has varied. About 10,000 years ago it was an inland basin with fresh water, the so-called Baltic Ice Lake. When the ice gradually melted a passage was formed in central Sweden and the Baltic Sea received salt water, the so-called Yoldia Sea (about 9,500 to 8,500 years ago).

During this time the sedimentation conditions in central Sweden and in the Göta River Valley seem not to have been very different.

Later this passage was closed when the land raised

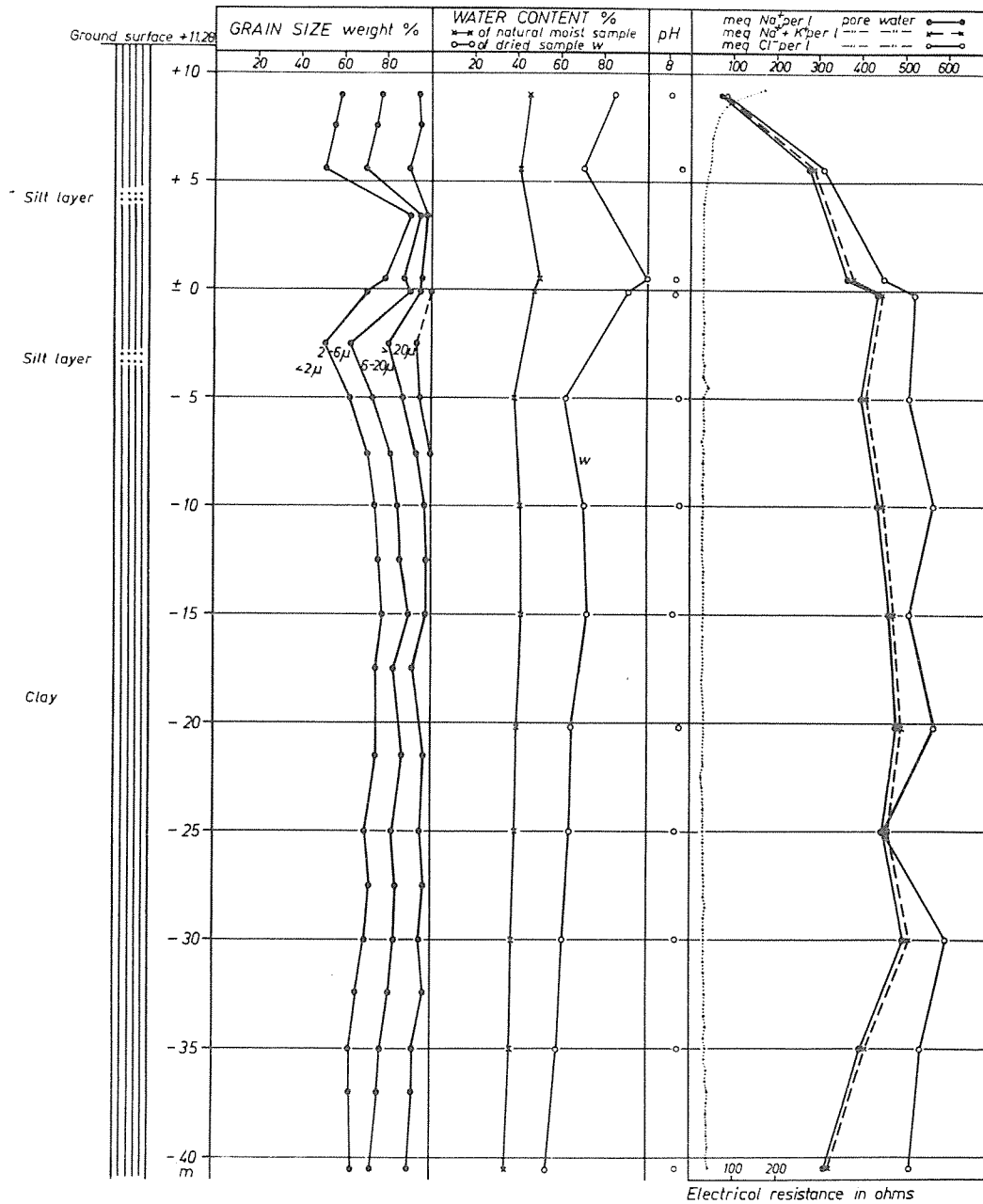


Fig. 19 Geotechnical data from a clay profile at Olskroksmotet, Göteborg, including results of salinity determinations on pore water (from Tullström, 1961)

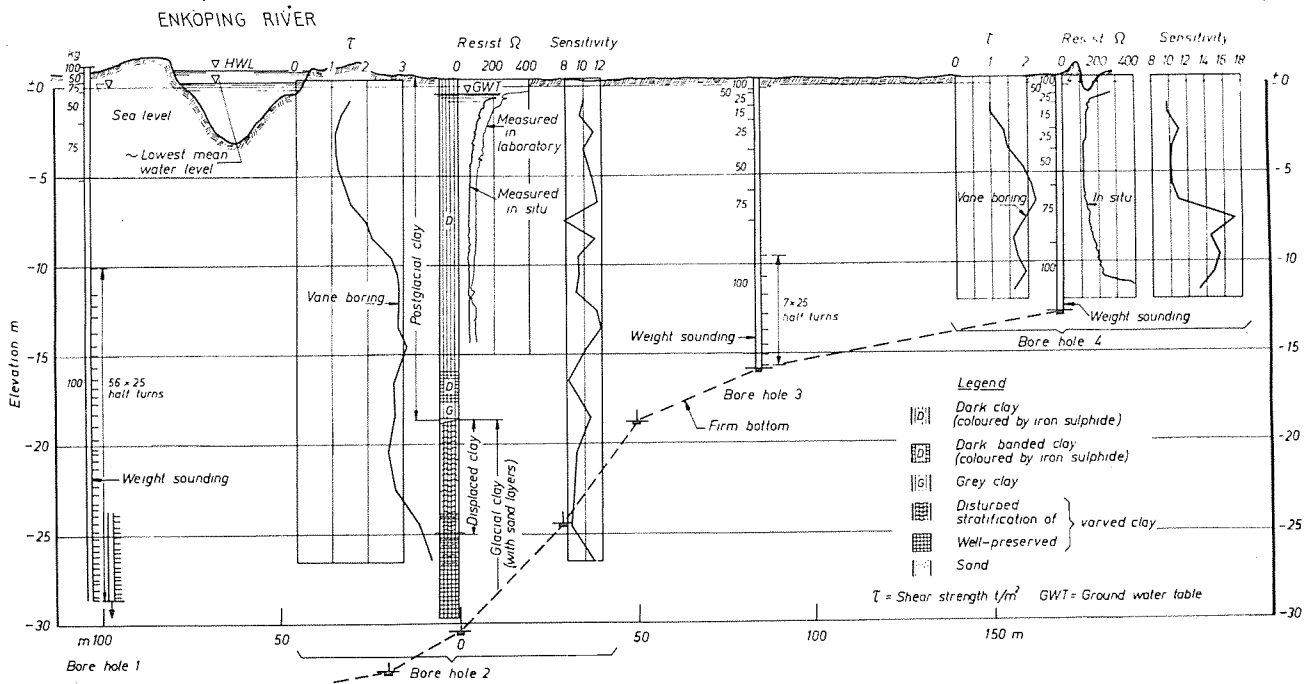


Fig. 20 Result of investigations of a clay profile at Enköping (from Söderblom, 1957)

and the Baltic again became a fresh water lake, the so-called Ancylus Lake.

About 7,000 years ago the still existing passages were formed south of Sweden and the Baltic Sea became even more salt than now, the Litorina Sea. During this time Lake Mälaren was still part of the Baltic Sea and hence carried salt water. The present lowland around Mälaren was below the sea level. The Litorina

Sea is believed to have had a salt content of about 1.6%.

During these periods clays were deposited in central Sweden. These clays are called Yoldia Clay, Ancylus Clay and Litorina Clay, respectively.

The salt sounding curves from Enköping and Kungsängen give no indications that these clays have been deposited under varying salinity conditions. The conductivity curves show a leached zone at the ground surface, a higher salinity in the middle of the clay layer and a leached zone close to the bottom. This indicates that diffusion or equalizing in other ways has taken place since deposition.

The salt in the Enköping clay may be a residue from the Litorina Sea. The salinity of the pore water is about 0.8%, i. e. only half of the assumed salinity of the Litorina Sea water. The salinity of the clay at Kungsängen located in the same part of Sweden is 0.3%. These values approach the present salt content in the Baltic Sea (0.6% east of Stockholm).

Clays with a salt content approaching that in the ocean (3.5%) are scarce in Sweden. They have hitherto been found only at some places in the vicinity of Göteborg. Clays with lower salt content (0.3 to 2.5%) are found at several places.

At first it was unexpected to find the saltiest clay close to the river and that the salinity decreased with increasing distance therefrom. If pure diffusion has

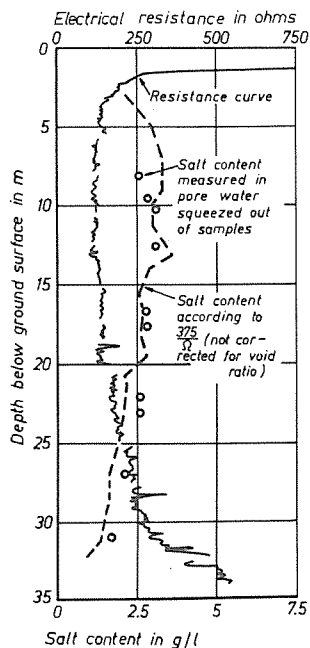


Fig. 21 Result of salt investigations of a clay profile from Kungsängen, Uppsala (from Kallstenius, 1958)



occurred from top and bottom of the clay, the saltiest clays will be found approximately in the middle of the deepest part of the profile, as was the case in the profiles investigated at Lödöse. The maximum salt content was located somewhat nearer to the ground surface than to the bottom. This distribution suggests a slower diffusion to the surface than to the bottom but can also be explained if a convection occurs from the bottom towards the surface in addition to the diffusion. It must be noted that in the profile at Lödöse the salt sounding gave no exact picture of the salt distribution in the clay, because of variations in the conductivity transmission factor.

It is not probable that the diffusion coefficient is constant throughout the whole slope. As seen in Table 12 the conductivity transmission factor varies considerably in different parts of the slope. The diffusion transmission factor is of the same order of magnitude as the conductivity transmission factor, because the same factors which affect the diffusion also affect the conductivity (cf. Chapter 7). Thus it is probable that

the diffusion constant varies with both the depth and the distance from the river.

The ionic distribution in the profile (Table 12) is of interest. In the most leached part, away from the river, no chlorine was found in the chromatograms. Sodium was the dominating cation. When the salt content of the clay increased towards the river, the ionic composition of the pore water gradually approached that of sea water. This is in accordance with the theory of partial leaching advanced by Rosenqvist (1955).

Hutchinson (1961) has found similar salt distributions at the Namsen Valley in Norway and used this distribution to localize slip surfaces. He believed that the distribution is caused by a more intense leaching in the parts of a clay deposit lying high above the river level than in the lower parts close to the river. A similar distribution seems also to occur in the Cauca Valley, Colombia (Borrero, 1956).

## 5. ATTEMPTS TO LOCALIZE QUICK CLAYS BY SALT EXAMINATIONS

### 5.1 General

It is of great geotechnical interest whether it is possible to localize quick clays by means of salt soundings or not. In a slope there may exist zones of quick clay which can affect the extent of a slide considerably. A small initial slide due to e.g. erosion that has started close to the river may then develop into a large slide.

As mentioned in Chapter 3.1 Rosenqvist (1955) has found a correlation between salinity and sensitivity in Norwegian clay deposits. This was expected from the salt leaching theory. Penner (1965) found in the Ottawa-Hull area no such correlation between salinity and sensitivity. The conductivity of clays with low sensitivity varied here within the whole conductivity range found in nature but the conductivity of quick clays was always below a certain limiting value. If sensitivity is plotted versus conductivity an L-shaped point distribution was obtained, cf. the conditions in the Göta River Valley, Fig. 31.

The map in Fig. 22 shows that quick clays are common in the area where the salt water channel covered central Sweden during the Yoldia period. The points represent 80 cases of quick clay found in about 1500 consecutive works carried out at the Consulting Department of the

Swedish Geotechnical Institute (mainly from the years 1960-1965).

What is said above could suggest that the salinity of the water where the clay was deposited might have something to do with the formation of the quick clays. However, about half of the quick clays reported are varved quick clays, which have been sedimented in rather fresh water. Electron micrographs indicate that the structure of clays is not influenced by the salt content of the pore water (Pusch, 1968). Experiments have also shown that most Swedish clays can be transformed into quick clays by a treatment with dispersing agents, e.g. sodium diphosphate (Söderblom, 1970). Both the electron micrographs and the experiments with dispersing agents indicate that most Swedish clays have a structure which is sufficiently loose to allow the transforming of a clay with low sensitivity into a quick clay.

A thorough examination of the salt leaching theory is difficult and requires much field work. It will be necessary to ascertain the salt conditions under which the clay sedimented; for this purpose it seems necessary to make diatom analyses. In addition the present salt content in the pore water must be determined. Such an investigation has been attempted by e.g. Keinonen (1963). In four cases in Finland he found

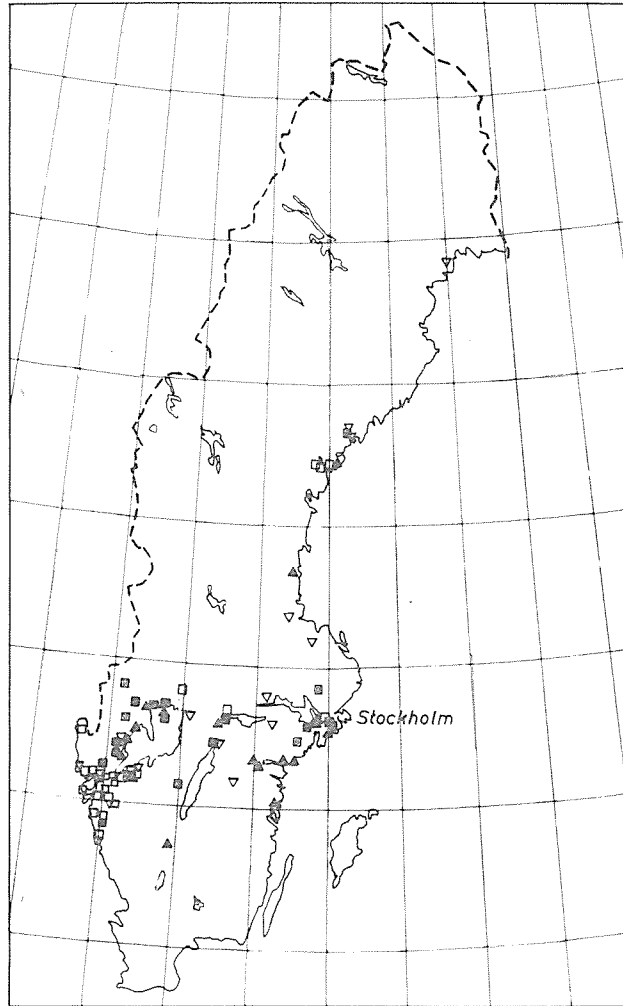


Fig. 22 Map showing the occurrence of different types of quick clays in Sweden  
 ▽ non-varved quick clays in connection with peat or other organic materials  
 ▲ varved quick clays in connection with peat or other organic materials  
 □ other non-varved quick clays  
 ■ other varved quick clays

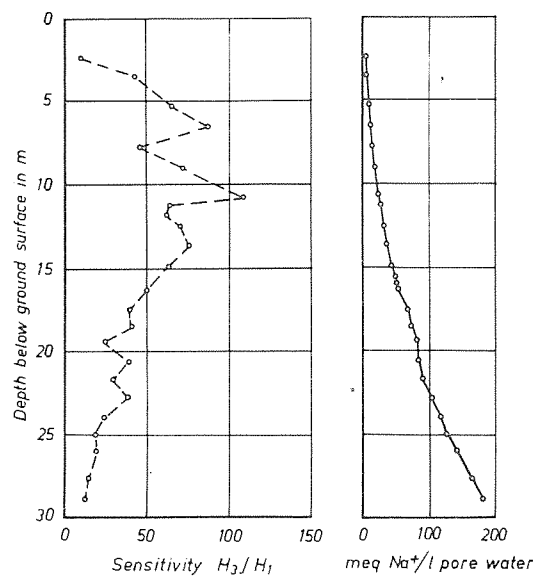


Fig. 23 Sensitivity and Na-content curves from Strandbacken, Göta River, showing a marked correlation between salinity and sensitivity (from Tullström, 1961)

quick clays which have been sedimented in almost fresh Ancylus water with the present salt content of the pore water only little deviating from that prevailing during the sedimentation.

## 5.2 Studies with the Salt Sounding Tool

Salt soundings and vane borings have been made concurrently in the Göta River Valley. The salt soundings have been supplemented by sampling. The samples have been examined geotechnically and chemically. The combined vane borer and salt sounding tool (cf. Chapter 3.25) developed by Messrs. Orrje & Co. has also been used.

As mentioned in Chapter 4 the conductivity curves usually have the general smooth shape shown in Fig. 14, whether the profile contains quick clay or not. In contrast, the sensitivity - depth relation is often highly irregular. One would expect corresponding jumps to be found in the conductivity curves, but they are generally not found.

Rosenqvist (1955) has presented data for two clays from Tøyen and from Studenterlunden in Oslo. In these cases the total salt content was inversely correlated to the sensitivity of the clays. Sometimes one can find similar conditions also in the clays in the Göta River Valley. Fig. 23 shows a profile from Strandbacken, Lilla Edet. The sensitivity of the upper part of the clay layer was high while the sensitivity was low towards the bottom where the  $\text{Na}^+$ -content increased. A few hundred metres from this place the  $\text{Na}^+$  and sensitivity curves, however, have quite different appearances as shown in Fig. 24.

Some typical measurements from Utby on the Göta River

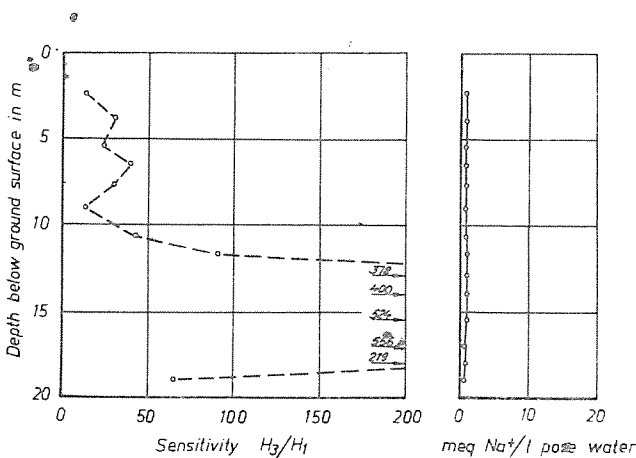


Fig. 24 Sensitivity and  $\text{Na}^+$ -content curves from Strandbacken, Göta River, showing no visible correlation between salinity and sensitivity (from Tullström, 1961)

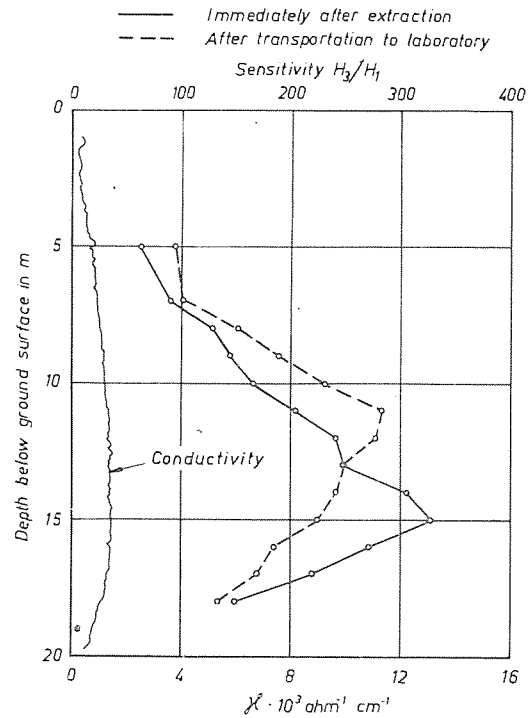


Fig. 25 Sensitivity and salt sounding curves from Hole 658, Utby

are shown in Figs. 25 through 27. The conductivity curves are smooth while the sensitivity curves have distinct peaks. It should be noticed that the clays in Figs. 25 and 26 have the highest sensitivity at the levels where the measured conductivity reaches a maximum. Another type of curve is shown in Fig. 28 (Hole 99 at Utby). The clay is of normal sensitivity (cf. App. 3) down to the depth of 14 m in spite of the clay being leached in the whole profile. At 15 m quick clay was found, but at the depths of 16 and 17 m the sensitivity was normal again. As seen in Table 13 the total salt content of the pore water was about the same for both the quick and non-quick clay.

Some results obtained with the combined tool of Messrs Orrje & Co Ltd are shown in Figs. 29 and 30. These measurements were made at Intagan in the Göta River Valley. The results agree with those obtained from other investigations. The resistance curves are smooth without discontinuities. The sensitivity curves, on the other hand, are more or less irregular.

In most cases it was not possible to find a correlation between conductivity and sensitivity. If any general conclusion can be drawn from these results, it must be that the conductivity method turned out to be quite unsuitable for localizing quick clays. The passing over from normal sensitive clay to quick clay in an undisturbed profile was never associated with a deviation or jump in the conductivity curve. Instead, the con-

Table 13 Data from clays from Utby and Strandbacken

Site Hole Depth m	Determination of salt content in pore water						By evaporation of squeezed pore water Dried 105°C g/l	After ignition g/l	Conductivity transm. factor	Natural water content w %	Type of clay
	By conductivity			In squeezed pore water <sup>2)</sup>							
	In Sample <sup>1)</sup>			R	$\kappa \cdot 10^3$	Salt cont. g/l					
ohm	$\text{ohm}^{-1} \text{cm}^{-1}$	g/l	ohm	$\text{ohm}^{-1} \text{cm}^{-1}$	g/l	ohm	$\text{ohm}^{-1} \text{cm}^{-1}$	g/l			
<u>Utby 99</u>											
9	550	0.8	1.2	83	8.2	5.1	7.78		0.09	52	Normal
17	280	1.4	2.0	80	8.6	5.4	10.70	9.39	0.16	53	Quick
<u>Utby 620</u>											
4	280	1.43	2.0	96	7.1	4.5	8.37	7.56	0.20	77	"
15	155	2.58	3.7	78	8.8	5.6	7.55	7.02	0.28	62	Normal
19	310	1.3	1.8	145	4.7	2.8	5.23	4.85	0.28	47	"
<u>Utby 658</u>											
5	1100	0.36	0.7	370	1.85	1.05	1.90	1.22	0.19	71	Quick
8	620	0.65	0.8	515	1.53	0.8	1.28	0.58	0.42	73	"
14	390	1.03	1.4	215	3.18	1.8	3.71	-	0.32	65	"
17	380	1.05	1.5	205	3.34	1.9	3.11	-	0.31	59	"
19	420	0.9	1.2	255	2.78	1.6	2.70	2.38	0.32	61	"
<u>Utby 680</u>											
4	960	0.4	0.7	209	3.27	1.9	4.57	-	0.12	58	Normal
5	680	0.6	0.8	210	3.26	1.9	4.15	3.59	0.18	58	"
14	350	1.14	1.6	140	4.9	2.9	5.26	4.76	0.23	57	Quick
<u>Strand- backen</u>											
15	50	8	16.8	36	19	13	18.9	16.9	0.43		Normal
20	37	10.7	23.8	27	25.4	19.0	25.4	23.5	0.46		"

1) Penetration electrode

2) Dip electrode

ductivity curves have the appearance they theoretically should have in a profile where diffusion has occurred during a very long period. This is not remarkable from a physico-chemical point of view. The irregular shape of the sensitivity curves must be developed by a process whose main cause is some other reaction than simple salt diffusion.

In Fig. 31 the conductivity of samples from six boreholes in the Göta River Valley is plotted against the sensitivity. The salt content of clays with low sensitivity can vary between wide limits but the salt content of quick clays is always low. This relation is similar to that reported by Penner (1965).

### 5.3 The Ionic Composition in some Clay Profiles

The ionic composition of a profile from Utby, Hole 620 has been studied chromatographically as described in Chapter 3.

The salt content of the clay was high, except close to the ground surface where the clay had been leached. A chromatogram of the pore water salts at a depth of

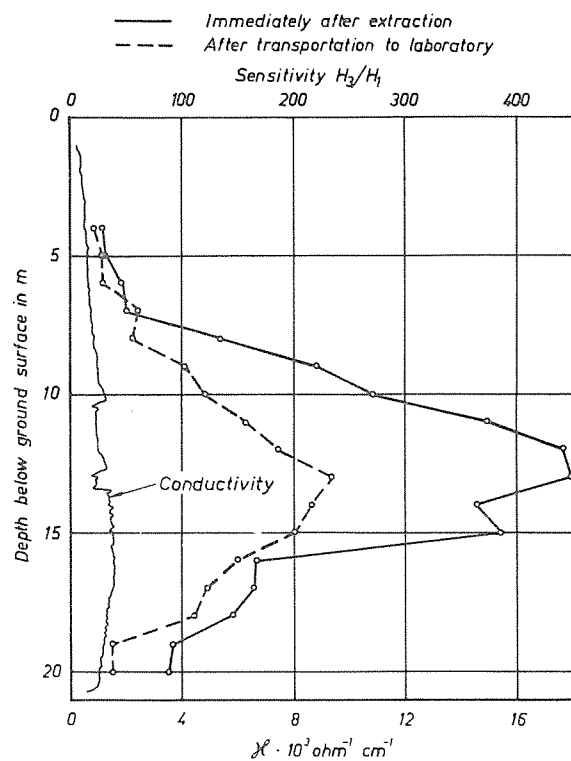


Fig. 26 Sensitivity and salt sounding curved from Hole 680, Utby

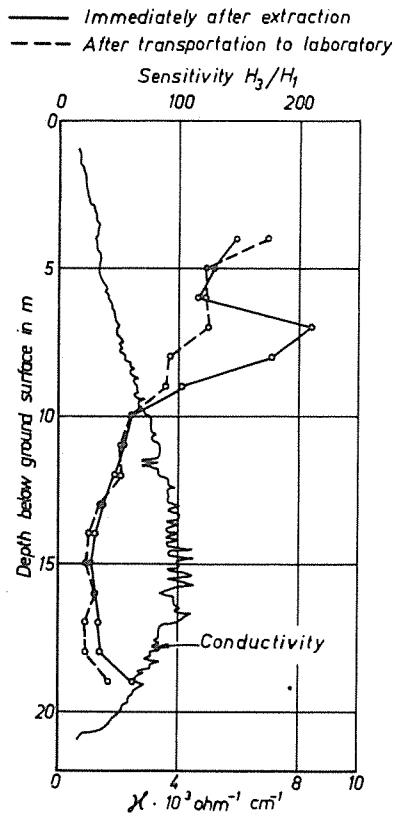


Fig. 27 Sensitivity and salt sounding curved from Hole 620, Uthv

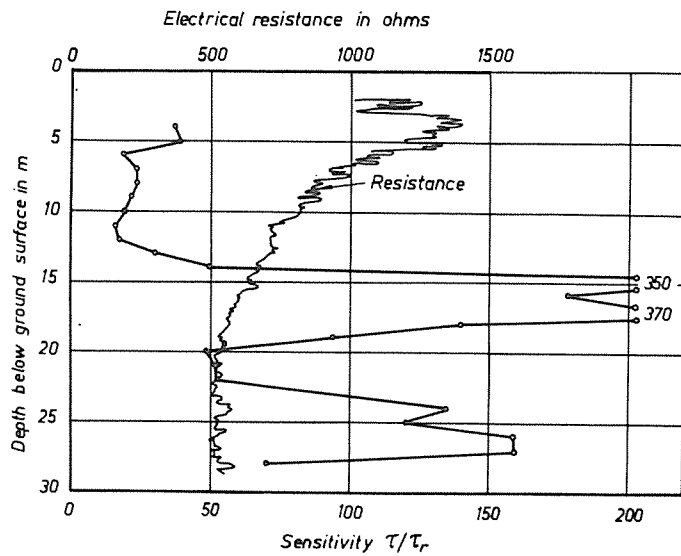


Fig. 29 Relationship between electrical resistance and sensitivity obtained by the combined vane borer and salt sounding tool

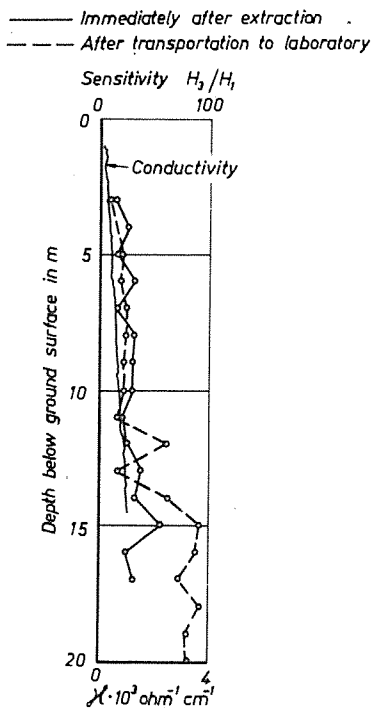


Fig. 28 Sensitivity and salt sounding curves from Hole 99, Utby

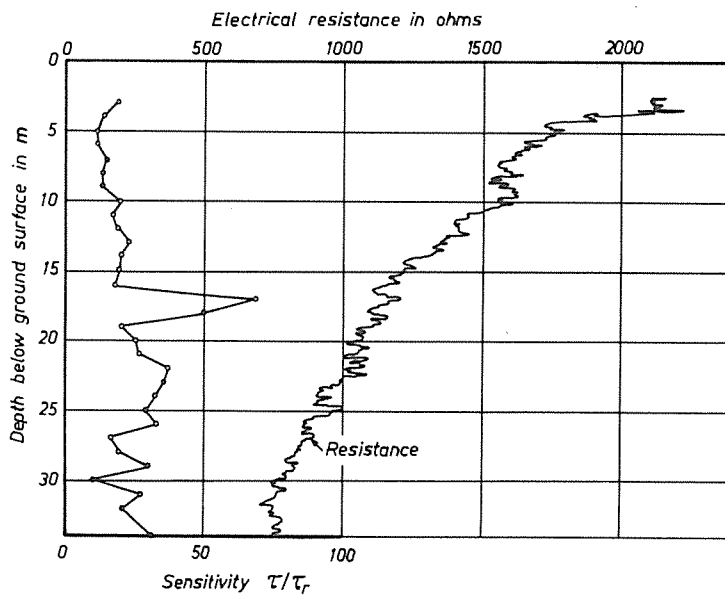


Fig. 30 Relationship between electrical resistance and sensitivity obtained by the combined vane borer and salt sounding tool

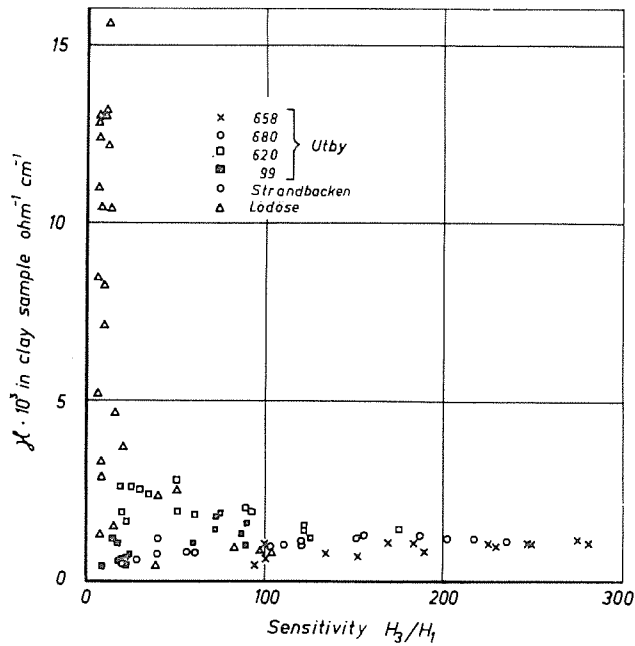


Fig. 31 Relationship between conductivity and sensitivity for clay samples from the Göta River Valley

14 m below the ground surface is shown in Fig. 32. The chromatogram indicates that the anions are mainly chloride, but some sulfate can also be detected. The cations are mainly sodium and calcium + magnesium. A chromatogram of acetates is seen in Fig. 33. This pore water has approximately the same ionic composition as sea water.

A chromatogram from the quick clay part of this profile at a depth of 4 m is shown in Fig. 34. This indicates that calcium and magnesium are almost lacking, whereas sodium is the dominating cation. Sulfate is now the dominating anion. The ionic composition of the pore water of the quick clay thus differs from that of the salt clay.

In Hole 680 at Utby the clay is non-quick from the ground surface to a depth of 7 m. Below this depth the sensitivity increases rapidly to very high values,  $H_3/H_1 \approx 400$ . The conductivity is increasing from the ground surface in the low sensitive part but the conductivity curve shows no jumps at the transition between the non-quick and quick clays (Fig. 26). A chromatogram from the low sensitive part (4 m) (Fig. 35) does not indicate any sodium; the dominating cations are calcium and magnesium. The dominating anion seems to be sulfate. No chloride could be detected. The chromatogram from the quick clay part (8-17 m) was almost identical with that in Fig. 34 from Hole 620. The composition of the pore water thus differed from that of the quick clay.

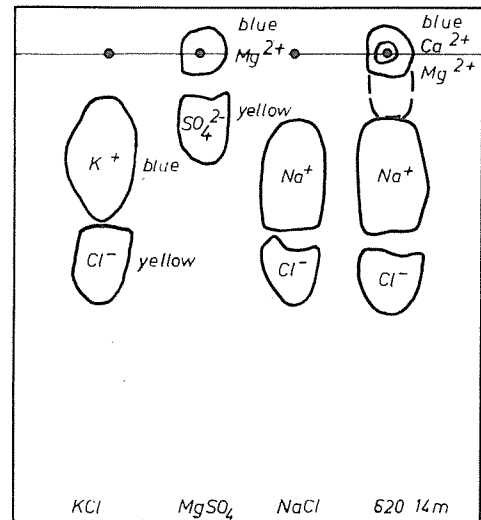


Fig. 32 Small-paper chromatogram of pore water of a clay from Utby Hole 620, 14 m. Standards KCl,  $MgSO_4$  and NaCl

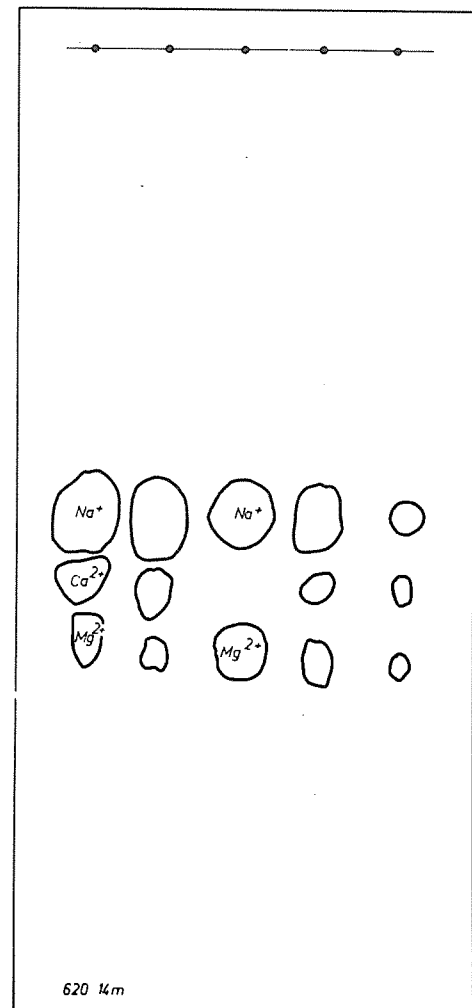


Fig. 33 Paper chromatogram according to Seiler et al. of pore water of a clay from Utby Hole 620, 14 m. Standards NaAc and  $MgAc_2$

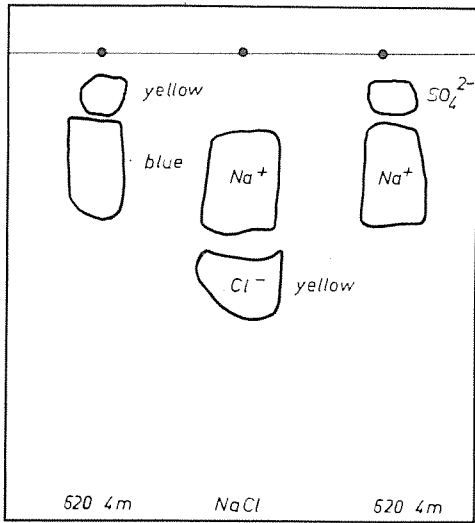


Fig. 34 Small-paper chromatogram of pore water of a clay from Utby Hole 620, 4 m

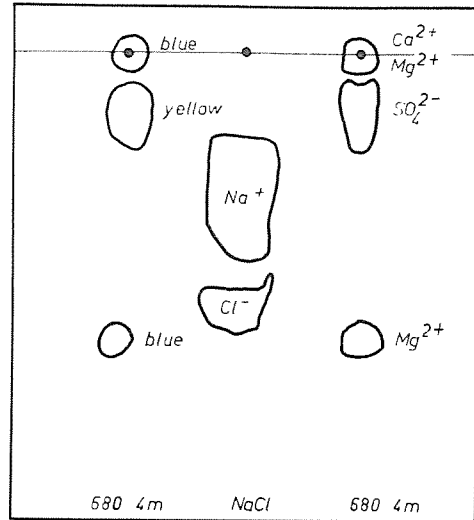


Fig. 35 Small-paper chromatogram of pore water of a clay from Utby Hole 680, 4 m

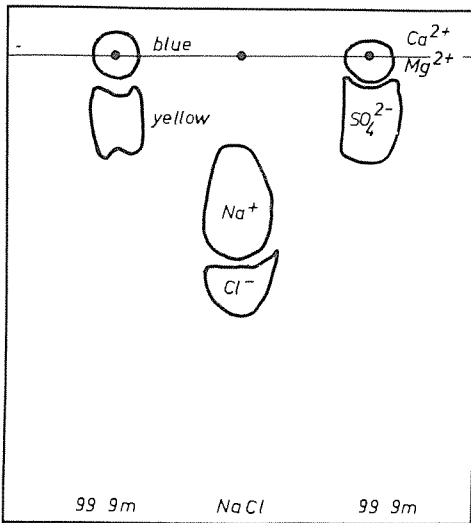


Fig. 36 Small-paper chromatogram of pore water of a clay from Utby Hole 99, 9 m

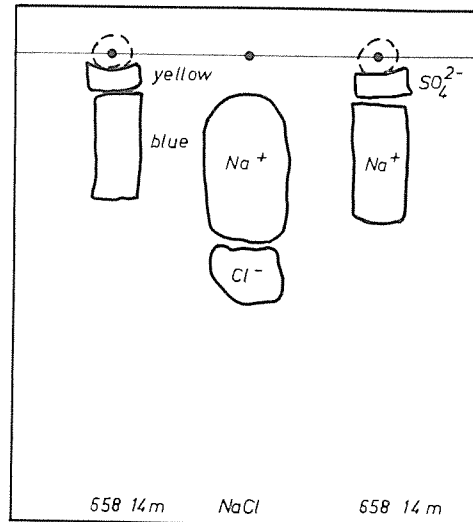


Fig. 37 Small-paper chromatogram of pore water of a clay from Utby Hole 658, 14 m

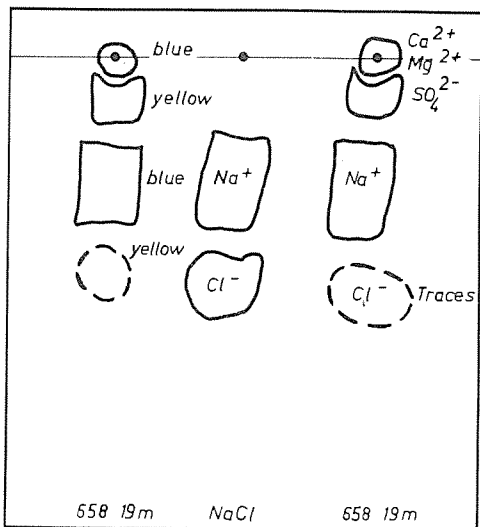


Fig. 38 Small-paper chromatogram of pore water of a clay from Utby Hole 658, 19 m

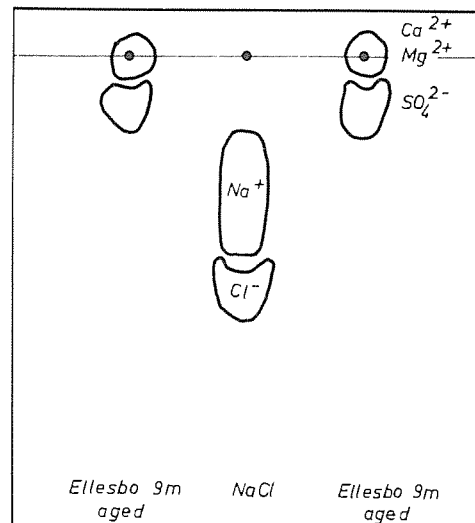


Fig. 39 Small-paper chromatogram of pore water of an aged, formerly quick clay from Ellesbo, 9 m (the sample about 2 years old)

In Hole 99 at Utby no quick clay was found from the ground surface down to a depth of 14 m. The  $\alpha$ -value was very low, Fig. 28. A chromatogram of the salt composition at 9 m is shown in Fig. 36. Calcium and magnesium but no sodium were detected. The anions seem to be sulfate. The pore water has a composition similar to that of the low sensitive part at Hole 680 above.

Fig. 37 shows a chromatogram of the squeezed pore water in Hole 658 from a depth of 14 m where the clay is quick (Fig. 25). The pore water has a similar composition as the pore water of the quick clay in Hole 620. The dominating cation is sodium whereas calcium and magnesium are almost lacking. Chloride could not be detected, the dominating anion seems to be sulfate. A similar chromatogram is obtained from a depth of 17 m.

The chromatogram in Fig. 38 was obtained from Hole 658 at a depth of 19 m, where the sensitivity is decreasing ( $H_3/H_1 \approx 100$ ) and the total salt content is low (see Fig. 25). The dominating cation is still sodium but distinct amounts of calcium and magnesium could be detected. The dominating anion seems to be sulfate, but distinct amounts of chloride were also found. The pore water thus seems to have changed from a "sodium water" to a water with calcium and/or magnesium.

Investigations were made on the pore water composition of samples stored for relatively long times. The chromatogram from a sample from Ellesbo, originally quick and stored for two years in the laboratory, is shown in Fig. 39. Its sensitivity had decreased during storing

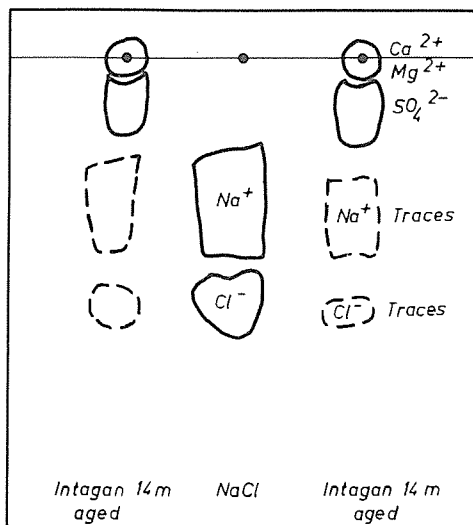


Fig. 40 Small-paper chromatogram of pore water of an aged, formerly quick clay from Intagan, 14 m (the sample about 4 years old)

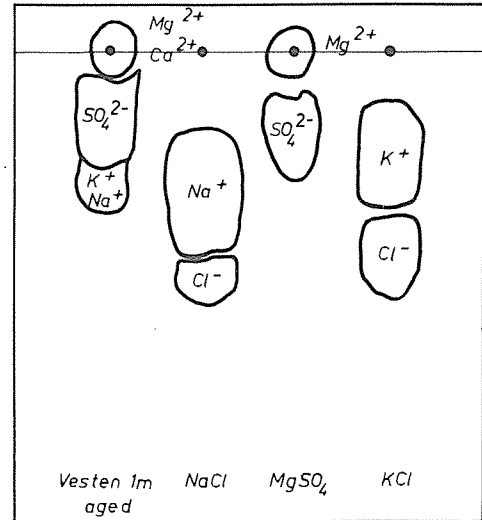


Fig. 41 Small-paper chromatogram of pore water of an aged, earlier quick clay from Vesten, 1 m below the slip surface. Standards  $\text{NaCl}$ ,  $\text{MgSO}_4$  and  $\text{KCl}$

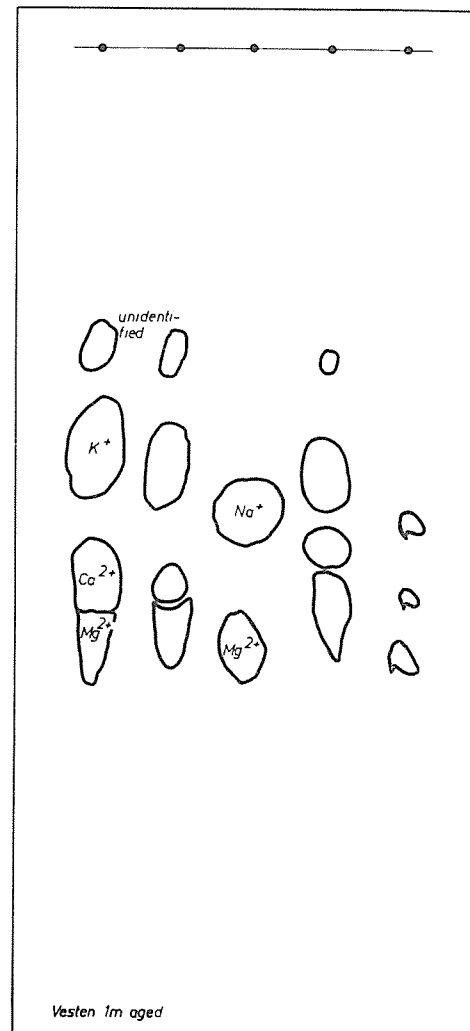


Fig. 42 Paper chromatogram according to Seiler et al. of pore water of an aged, earlier quick clay from Vesten 1 m below the slip surface. Standards  $\text{NaCl}$  and  $\text{MgCl}_2$



to that of a normal clay. Only a very weak spot of sodium was noticed, not reproduced in the figure. The dominating cations are calcium and magnesium. No chloride could be detected, but the dominating anion is sulfate. A chromatogram from a four year old sample of an initially quick clay from Intagan is shown in Fig. 40. Sodium is seen in the chromatogram as well as a distinct spot of calcium and magnesium. The dominating anion is sulfate, but a weak spot of chloride is also seen. This ageing effect is further discussed in Chapter 5.4. Clay was taken in 1967 at a depth of 1 m below an exposed slide bottom of the 1960 slide at Vesten. In the meantime this clay had lost its quickness. A chromatogram (Fig. 41) indicates the presence of potassium (cf. below) and distinct amounts of calcium and magnesium. Sulfate is the dominating anion but no chloride could be detected. The pore water of this clay was also chromatographed according to Seiler et al. The result is shown in Fig. 42. The cations are potassium, calcium and magnesium, but only very small amounts of sodium are present. An unidentified cation with a  $R_F$ -value  $\approx 0.39$  could be detected by spraying with bromophenolblue, but violuric acid did not colour this cation.

The pore waters from all the quick clays examined contained only small amounts of calcium and magnesium. In waters from aged clays whose sensitivity had decreased the amounts of these ions were considerable.

The chromatogram of the pore water from "kaolin 46" mixed with water to  $H_1 \approx 10$  is shown in Fig. 43 (cf. Chapter 2). This indicates sodium but also calcium and magnesium. The dominating anion is chloride. When this clay was dispersed by  $\text{Na}_4\text{P}_2\text{O}_7$  until the strength value reached a minimum ( $H_1 < 0.33$ ) the pore water gave the chromatogram shown in Fig. 44. Sodium (and potassium) is now the dominant ion. Calcium and magnesium could of course not be detected now because they had been precipitated, nor could chloride be observed. A phosphate ion with  $R_F \approx 0$  is the dominating anion. Thus the chromatogram for the "kaolin 46" is similar to the chromatogram obtained from the pore water of a quick clay (cf. Fig. 37).

The kaolin-diphosphate suspension was coagulated with NaCl. The pore water was squeezed out and examined. The result is shown in Fig. 45. Sodium and chloride are now the dominating ions.  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  could of course not be detected, as the diphosphate precipitate is not expected to be dissolved by NaCl.

A quick clay from Hole 658 12 m Utby, with a typical quick clay composition of its pore water, was treated with NaCl until it became stiff ( $\kappa \approx 10^{-2} \text{ ohm}^{-1} \text{ cm}^{-1}$ ).

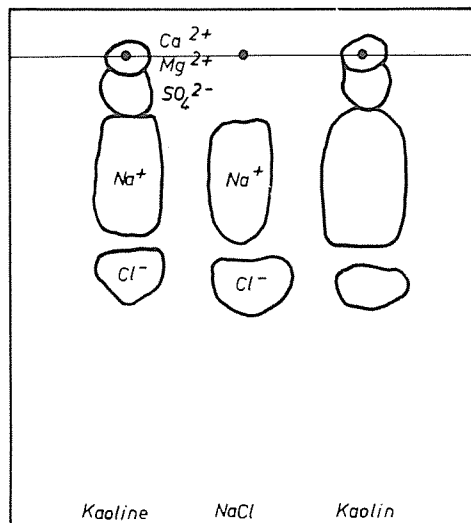


Fig. 43 Small-paper chromatogram of "pore water" of a paste of "kaolin 46" with an H-value of about 10

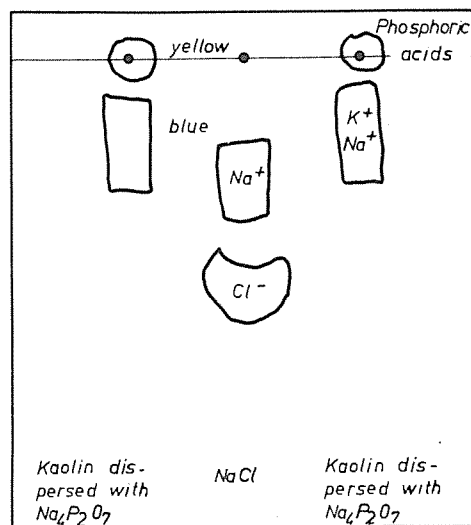


Fig. 44 Small-paper chromatogram of "pore water" of a paste of "kaolin 46" dispersed to minimum viscosity by  $\text{Na}_4\text{P}_2\text{O}_7$

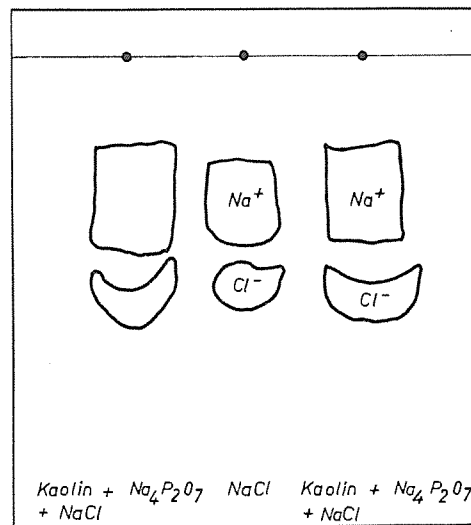


Fig. 45 Small-paper chromatogram of "pore water" of a paste of "kaolin 46" dispersed to minimum viscosity by  $\text{Na}_4\text{P}_2\text{O}_7$  and afterwards coagulated with NaCl

After that the pore water gave the chromatogram shown in Fig. 46. Naturally the pore water now showed spots of sodium chloride, but distinct amounts of calcium and magnesium were also present. Thus the calcium complex in a natural quick clay is weaker than the calcium diphosphate complex, since addition of salt to the quick clay liberates calcium and magnesium ions from the system. These results indicate that the stiffening of a natural quick clay by salt is a more complicated colloid chemical reaction than a simple salt coagulation such as those studied by Freundlich (1922) and his collaborators at the beginning of this century.

#### 5.4 Changes of Quick Clay Samples with Time. Ageing Phenomena

In the study of the quick clay problems it is very important to pay attention to the changes which take place in quick clay samples during transportation to and storage in the laboratory.

Ageing effects in quick clay samples have been reported by Jerbo, Norder & Sandegren (196f). They found that if an undisturbed sample of quick clay is extracted and the sample is carefully stored it gradually changes its sensitivity during a few months to a clay with a lower sensitivity. A similar phenomenon is known in general colloid chemistry as the ageing of gels.

Kallstenius (1963) also noticed such an ageing effect. He found that the strength value  $H_3$  of samples extract-

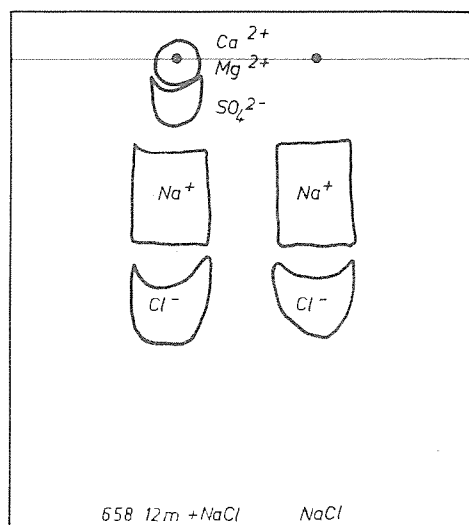


Fig. 46 Small-paper chromatogram of pore water of a quick clay from Utby Hole 658, 12 m. Coagulated with NaCl

ed with a standard piston sampler decreased with as much as 28 per cent over a 3 months period. He also studied the influence of the transport to the laboratory.

The process of ageing in ceramic clays has been known since the beginning of this century. An aged clay has normally a higher plasticity than a freshly extracted clay mass. According to Glick (1936) and Baker & Glick (1936) bacterial activity plays an important role in these ageing processes. The combined action of oxygen, carbon dioxide, water and bacteria under atmospheric conditions is according to Hammer (1949) known as "weathering", "ageing" or "souring" of the

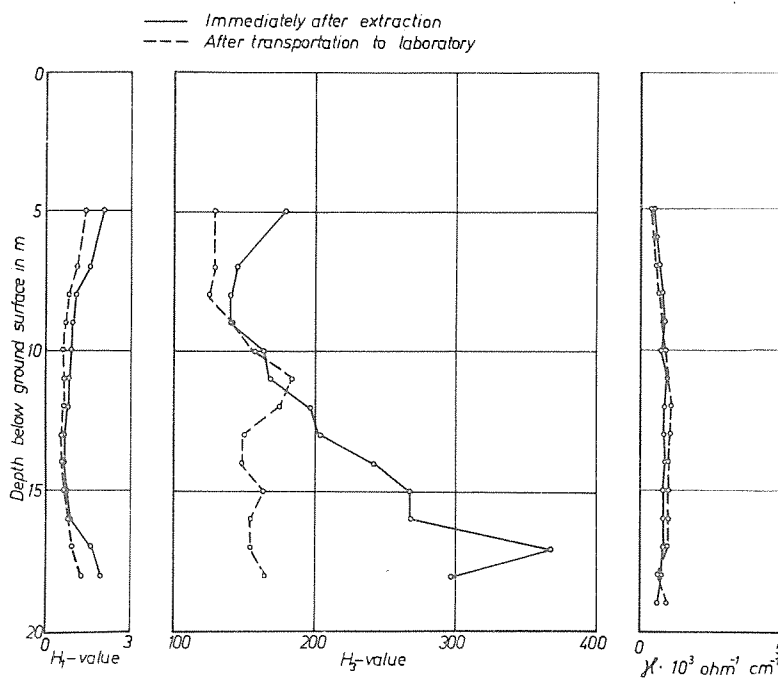


Fig. 47 Strength values and conductivity curves from Hole 658, Utby

clay. During the weathering several processes take place which increase the quantity of soluble salts. Among these, the oxidation of sulfides and the decomposition of such silicates as biotite, chlorite and the feldspars should be mentioned.

In the investigation at Utby mentioned in Chapter 5.2, the undisturbed and the remoulded strength of extracted clay samples were measured by the fall-cone tests a few minutes after the extraction of the sample. The conductivity of the samples was measured at the same time with the penetration electrode. Thereafter the samples were transported by bus and railway about 500 kilometres to the laboratory in Stockholm where they were re-examined. The time lapse between the two measurements was between 1 week and 1 month. The results are shown in Figs. 25 through 28.

The strength values from Hole 658 are shown in Fig. 47. It is seen that both the undisturbed and the remoulded shear strength have changed more or less at almost all levels. The undisturbed shear strength decreased with time at each level investigated with the exception of a part in the middle of the profile (9 through 10 m) where it was practically unchanged. Towards the coarse bottom layers and at the surface layers the decrease was large. Thus the greater shear strength towards the bottom layers determined in the field investigation was lost after the transport. The remoulded laboratory shear strength values were lower than the field values at each level, with a maximum difference near the ground surface and the bottom. The shear strength was almost unchanged at the depths 13 to 16 m.

In Hole 658 the sensitivity immediately after sampling was lower than the sensitivity determined in the laboratory for the samples between 5 and 13 m (Fig. 25). In the upper part the original sensitivity was higher. The sensitivity measured in field reached a maximum at 15 m depth and the laboratory sensitivity at 11 m. The two sensitivity curves thus intersected. But this unchanged value of sensitivity at 13 m is the unchanged ratio between two different pairs of changed strength values!

The corresponding electrical conductivity curves are shown in Fig. 47. It is seen that the conductivity has changed a little but with a regularity indicating that it cannot reasonably be due to experimental errors. In the upper parts of the profile down to 9 m depth the conductivity measured in the laboratory was lower than that determined in the field immediately after extraction of the samples. At greater depths the conditions were reversed. As seen in Chapter 5.3 changes in the ionic composition of the pore water of a quick clay

sample were also noticed.

The strength values from Hole 680 are shown in Fig. 48. The undisturbed shear strength obtained in the field was at laboratory tests considerably lower at all levels. The undisturbed shear strength in the field increased with depth in a normal way. This increase was lost at the laboratory tests, just as in Hole 658. The remoulded shear strength increased in the middle part of the profile where the remoulded values were the lowest and decreased at the top and bottom. The sensitivity in the low sensitive part down to 8 m below the ground surface was practically unchanged with time (Fig. 26). In the high sensitive part a large decrease was noticed at all levels. The electrical conductivity increased at all levels during the ageing process (Fig. 48).

In Hole 620 the undisturbed shear strength decreased at all levels except at a depth of 6 m as well as the remoulded shear strength did, except at 17 and 18 m as shown in Fig. 49. The sensitivity was high in the upper part of this profile with a maximum at 7 m depth. The sensitivity values of the most sensitive parts decreased considerably after transport to the laboratory but in the other parts of the profile the change was small (Fig. 27). However this unchanged sensitivity represents the ratio between two changed strength values (Fig. 49). The measured electrical conductivity of the samples in this profile was almost unchanged after the transportation (Fig. 49).

The clay in Hole 99 at Utby (Fig. 28) is of special interest in this connection. In spite of being strongly leached the profile contained almost no quick clays in its natural state according to the field measurements. After transportation to the laboratory the clay samples from the deep layers surprisingly increased their sensitivity so much that they had to be regarded as quick clays ( $H_3/H_1 > 50$ ), cf. App. 3. In the upper part of the profile the sensitivity was almost unchanged (Fig. 28.). The undisturbed shear strength decreased during the ageing process at almost all levels, and also the remoulded shear strength decreased at most levels as seen in Fig. 50. Below a depth of 14 m the remoulded shear strength decreased remarkably and it is this decrease which makes the clays quick according to the laboratory tests although they were "normal" in the field.

The electrical conductivity increased after ageing at all levels. Because changes of this kind were not expected at the time of the investigations, no measurements were made in the field on samples from levels above 9 m depth and below 17 m (Fig. 50).

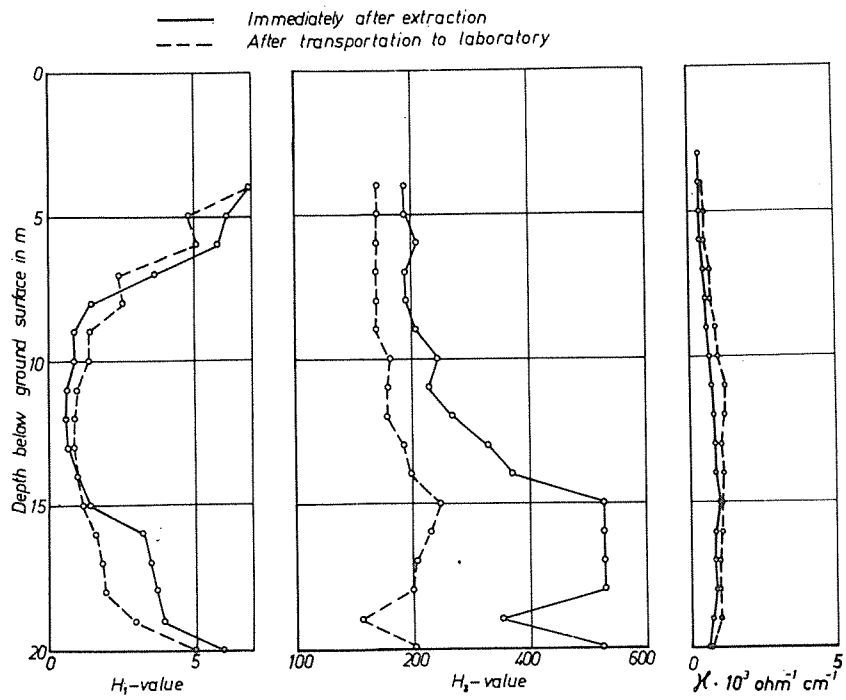


Fig. 48 Strength values and conductivity curves from Hole 680, Utby

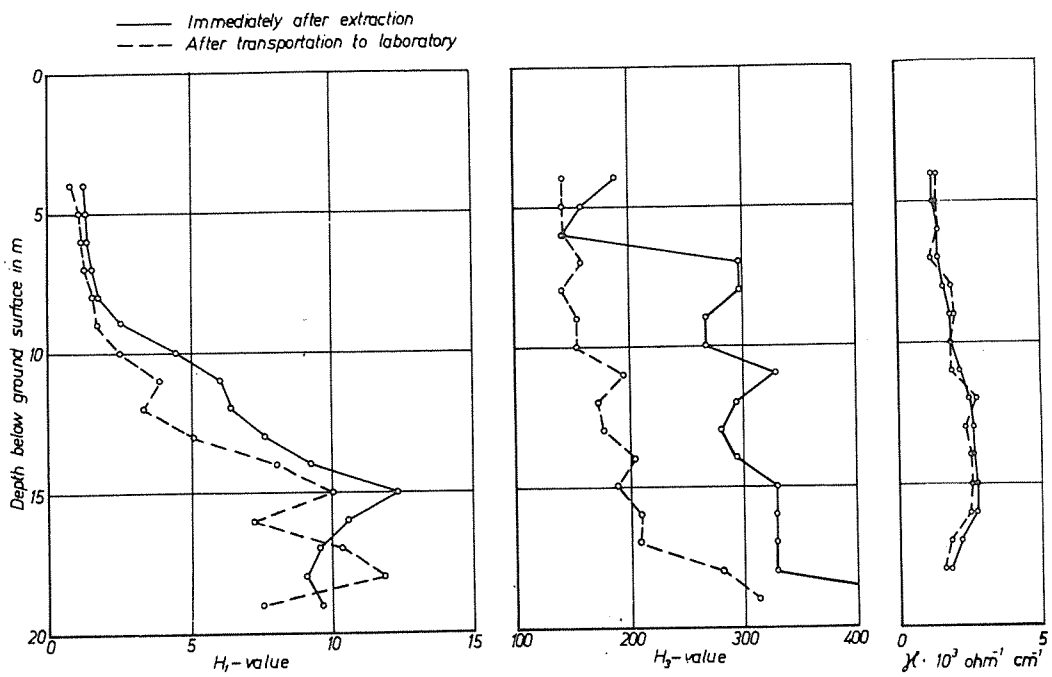


Fig. 49 Strength values and conductivity curves from Hole 620, Utby

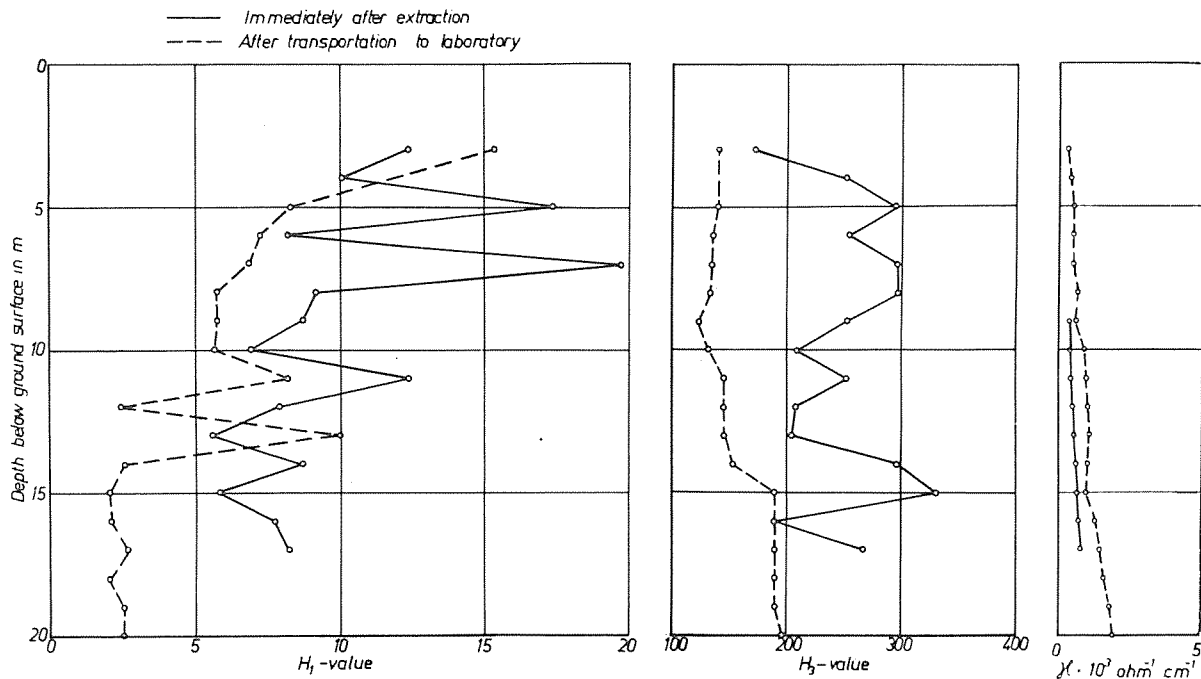


Fig. 50 Strength values and conductivity curves from Hole 99, Utby

### 5.5 Discussion of Test Results

The examinations of the salt conditions in the Göta River Valley indicated that no systematic relationship between salt content and sensitivity existed. The sensitivity therefore seems not to be caused only by a simple salt coagulation of the colloidal part of the clay.

Several authors have found that the laws which govern negative colloids in general can be applied to the clay-water system. This suggests that parallels can be drawn between the salt leaching in clays and the behaviour of colloids in general when their electrolyte content is reduced.

Lyophobic colloids will flocculate if the electrolyte concentration exceeds a certain value. If the salts are removed the colloid often deflocculates. Electrolytes can be removed from a colloid system by the dialysis procedure introduced by Graham (1861).

Dialysis of a flocculated colloid results in a deflocculated system only when electrical charges are formed on the surfaces of the particles. In many cases it is necessary to add small amounts of foreign substances to the solution. A prolonged dialysis of a colloid will, on the other hand, cause the adsorbed ions to leave the system more completely and the charge of the particles will then decrease. Picton (1892) thus found that  $As_2S_3$  particles will lose their adsorbed  $S^{2-}$ -ions so that they become discharged and then flocculate. This

observation indicates that a low electrolyte content is an indispensable condition for the clay system to be quick, but it is also necessary that the clay particles have suitable surface conditions. Otherwise, the system will be "non quick" for all prevailing salt contents, and this is found in many cases. A low pore water salt content is a necessary, but not a sufficient condition for a high sensitivity of a clay system.

On the other hand, the ionic composition of the pore waters, as found above, is different for quick clays than for non-quick clays. Where the sensitivity changes in a profile, the pore water composition is also changed. Calcium and magnesium ions seem to be the dominating cations in the non-quick system pore waters and sodium in the quick ones. According to Penner (1965) exceptions can, however, be found.

The ageing and salt stiffening experiments show that calcium and magnesium ions have not been removed from the clay system by leaching and that these ions can be liberated by suitable treatment. This indicates that calcium and magnesium are complexly bound ("masked") in a quick clay. This is in accordance with Rosenqvist's theories, which demand that the univalent ions are easier to leach away than the bivalent ones as required by the Donnan effect. Leaching thus causes an accumulation of  $Ca^{2+}$  and  $Mg^{2+}$ . A normal leaching process carried out on a clay sedimented in sea water will give a pore water mainly containing  $Ca^{2+}$  and  $Mg^{2+}$ -ions. The leached clay will then become a non-

quick clay.

On the other hand, it is very easy to transform a normal clay into quick clay by complex-binding or precipitating  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ . The substances known as dispersing agents have these properties. From Fig. 44 it is seen that sodium diphosphate removes the  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  -ions from the solution, and that the pore water obtains a composition corresponding to that of a quick clay. Many substances are known to have these properties and it is questionable whether a clay can be

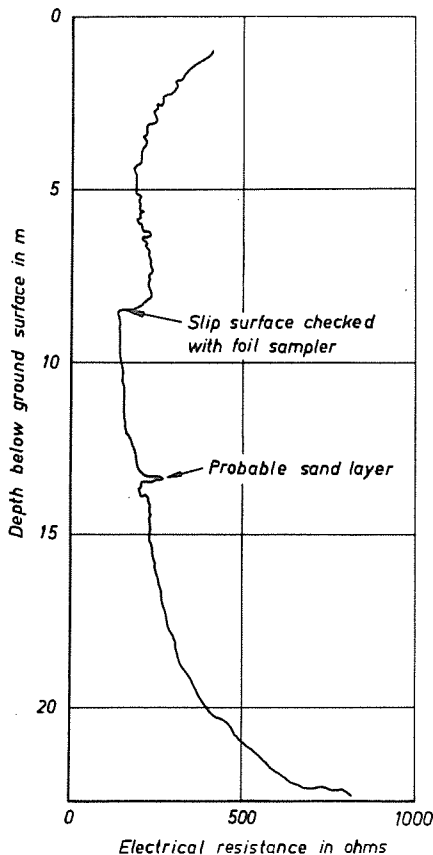


Fig. 51 Resistance curve from the Göta slide showing slip surface (from Söderblom, 1958)

transformed into a quick clay without the influence of such dispersing agents.

Of course, the change in the composition of the pore water in equilibrium with the colloid particles is only a result of a change in the colloid chemical state of the particles. A study of these changes is a more complicated task than a study of the easily removable pore water and shall not be treated here.

The results described above are in accordance with results from systematic leaching experiments by Quirk (1952) and Emerson (1954). They found that

various British soils behave differently when leached. In some cases a deflocculation occurred, but in other cases, especially "grass land crumbs" soils with organic materials forming bridges between the clay "crystals", resisted dispersion by salt leaching. If the soil crumbs, on the other hand, were mechanically disaggregated before the leaching the result was different. The organic molecules now acted as a kind of dispersing agent and the "disturbed crumbs" could easily be deflocculated. Leaching experiments carried out by the present author on different types of Swedish clays gave results similar to those reported by Quirk and Emerson, as discussed in Chapter 7 and in a later report (Söderblom, 1970).

In this connection the question of positive edge charges of the clay particles is of importance. Several authors, e.g. van Olphen (1965), have found that the clay particles may possess positively charged sites at the edges of the flakes besides the normal negative charges. The positively charged edges are responsible for "edge-to-face" flocculation occurring in neutral or acid solutions. These authors base their statements on the work by Thiessen (1942). His electron microphotographs showed that negatively charged gold is deposited on kaolinite platelet edges.

Similar experiments have been made at the Shell Development Company (cf. Marshall, 1964 and van Olphen, 1968). These experiments show that the edge effect is obtained only in very pure kaolinite systems at a pH-value of 4 to 5. Organic substances impede the adsorption of the gold. Michaels (1958) has suggested that the dispersion effect by polyphosphates might be used as a measure of edge surface.

Van Olphen (1965) has shown that polyphosphate reverses the particle charges in a positive alumina sol or in a quartz sol which has been made positive by the addition of traces of aluminium salts. According to this theory a deflocculation can only occur below the isoelectric point for  $\text{Al}(\text{OH})_3$ , i. e.  $\text{pH} = 6.7$ .

Swedish clays are in general somewhat alkaline,  $\text{pH} \approx 8$ , but they are nevertheless strongly affected by diphosphates and other dispersing agents. The dispersing mechanism seems to be uncertain. But the occurrence of edge charges gives a good explanation of the card-house structure theory of quick clays.

The Swedish clay colloids contain substances forming positive colloids, e.g.  $\text{Fe}(\text{OH})_3$  (cf. Løken, 1968) which cause a mutual coagulation with the negative clay particles. This might possibly partly explain the strong reaction with polyphosphates of the Swedish clays.

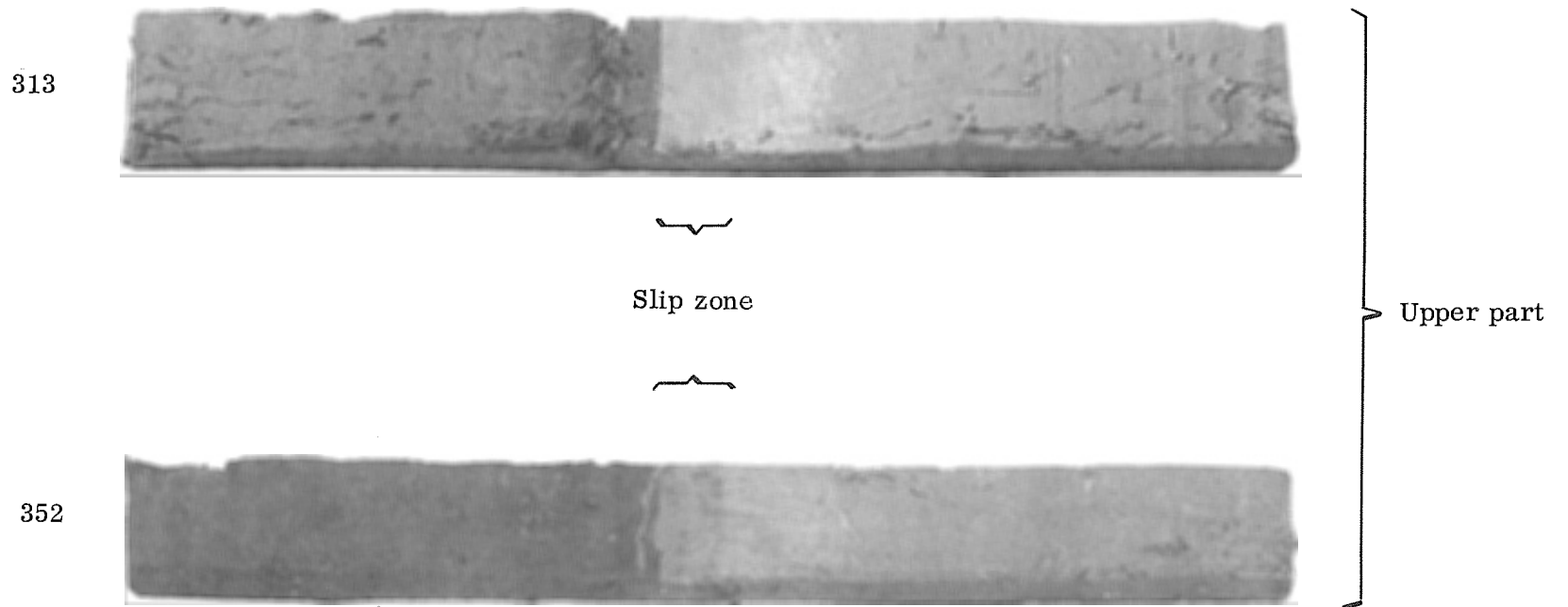


Fig. 52 Clay cores from Göta Section I (Hole 352) and Section C (Hole 313) showing the slip zone, extracted in 1968, 11 years after the slide (Cadbro Foto, Lilla Edet)

Van Olphen's investigations may give new aspects on the question of salt leaching, but according to him the usefulness of a gold sol to show positive sites in colloidal material is limited.

If the gradual changes of the composition of the pore water and of the sensitivity are indications of dispersing effects according to the "classical" colloid dispersion theory, or if these observed effects are secondary phenomena is too early to discuss. According to van Olphen the changes in the pore water are only of minor importance. Further studies of this question are therefore desirable.

Similar ageing effects have also been observed in colloids in general. Both freshly prepared gels and sols change with time. The viscosity of linear colloids can either increase or decrease with time. The viscosity of long-chained linear colloids, e.g. solutions of cellulose, usually decreases with time. The cause of this phenomenon is believed to be the rupture of the long molecules by the oxygen of the air. An increase in viscosity with time occurs e.g. in sols of vanadium pentoxide. This increase is explained by linear aggregation. The particles in this sol are long rods which tend to combine to longer aggregates. A similar increase in viscosity occurs in all cases of gelation when clusters and irregular networks of the fibrous particles are formed. The latter effect is analogous with observations on clays and is also in agreement with theories on influence of organic material proposed e.g. by Emerson (1954). In clays with a high remoulded strength there is a possible influence of organic gels, e.g. of the "gyttja" type, giving the clay high water binding properties and a high liquid limit. The gels may, however, be destroyed during storage by e.g. microbial action. The remoulded strength thus decreases, but in clays with low  $H_1$ -value where the organic material forms dispersing agents, complexly binding  $Ca^{2+}$ - and

$Mg^{2+}$ -ions, the remoulded strength tends to increase. These dispersing substances may change chemically.  $Ca^{2+}$ - and  $Mg^{2+}$ -ions are then liberated causing changes of the colloidal clay system. As a result the remoulded shear strength of the clay is increased. Systematic experiments on the reaction of  $Ca^{2+}$ - and  $Mg^{2+}$ -ions with different organic materials are required for a thorough understanding of this problem.

The reason why the clay samples are ageing rapidly after they are extracted is not understood at present. In undisturbed clays in situ no similar processes are known. It is obvious that the sampling procedure disturbs the clay appreciably and also changes the stress conditions. An extracted clay sample behaves in some respect very much as a freshly precipitated colloid, in spite of the fact that the clay is many thousand years old. The change from anaerobic to aerobic state and accompanying changes in the microbial activity may be the most important factor.

Most textbooks in colloid chemistry are stressing the fact that lyophobic colloids hardly exist in nature because of their instability. Quick clay is a typical lyophobic colloid which exists in such large amounts that it creates big problems. It is stable in situ. If extracted the samples behave as ordinary lyophobic colloids. Not much is known about the long time stability of lyophobic colloids, and from a chemical point of view it seems strange that the quick clays at Intagan can still remain quick such as they were in 1648 (cf. Järnefors, 1957). Some chemical processes must occur in the ground which prevent the ageing.

These ageing processes (disregarding transport effects) will as a rule lower the undisturbed shear strength of clays as mentioned above. Geotechnically this is of great importance when the strength properties of clays are studied.

## 6. DETERMINATION OF SLIP SURFACE BY ELECTRIC SOUNDINGS

### 6.1 General

The salt distribution conditions in the Göta River Valley allow of an interesting application of the salt sounding technique. As mentioned earlier in this paper the analytical salt curves and the salt sounding curves are generally smooth in undisturbed clay profiles and show no abrupt changes between different clay layers. Irregularities seem to have been partly equalized, main-

ly by diffusion.

In Chapter 4.2 it was stated that the conductivity of the clay and the salt content of the pore water decrease with increasing distance from the river, see Figs. 15, 16, 17 and the corresponding analytical values in Table 12. If a slide occurs in a section with such a salt distribution, clays from the upper part of the slope with low salinity may be placed upon clays with high salt



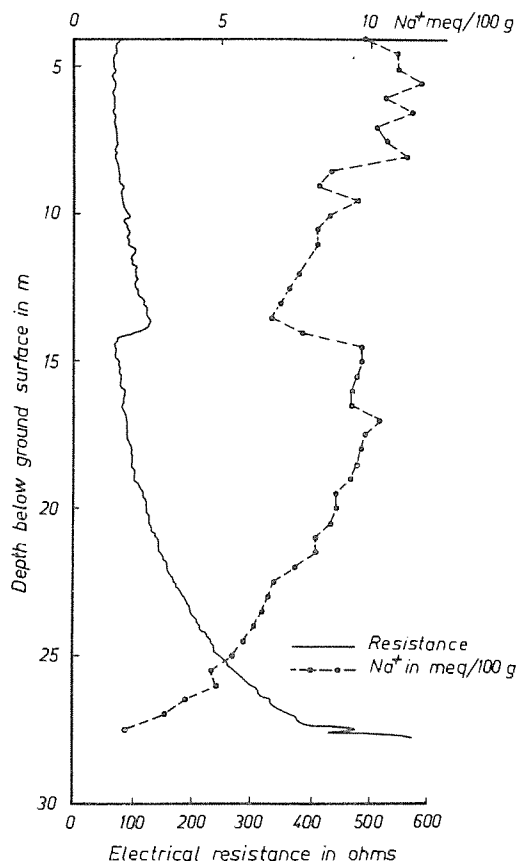


Fig. 53 Electrical resistance of a clay core from Göta and its sodium content, showing the sudden jump at the slip surface (from Järnefors, 1958)

content. The resistivity will then change abruptly at the slide bottom as shown in Fig. 51. This resistance curve was obtained at Göta 14 days after the slide in 1957. The fact that the jump in the curve really occurs at the failure surface was checked with the penetration electrode on clay cores (Fig. 52) which were extracted with the Swedish foil sampler (Kjellman et al., 1950). The sudden change in salt content was moreover checked by chemical analysis of the clay (Järnefors, 1958). The concentration of sodium ions in the clay varied inversely to the electrical resistance of the clay as seen in Fig. 53.

## 6.2 Application of the Method

The slip surface of the slides at Göta (Söderblom, 1958) and at Surte (Järnefors, 1958) have been examined. The test results of the present author from Section C at Göta are shown in Fig. 54. This section is situated in the secondary slide area and was convenient to investigate because of the relatively large displacement of the sliding masses. Salt soundings were made at the points marked in Fig. 54. Several points were checked with cores obtained by the Swedish foil sampler. It is seen

that the failure surface is almost plane except close to the river. A typical resistance curve for Section C is shown in Fig. 55. The failure surface and related geotechnical problems in the Göta slide have been discussed by Odenstad (1958).

In most soundings at Göta distinct jumps were found in the resistance curves. The resistance differences decreased with decreasing distance from the river because the slide masses had piled up near the river, where the movement was very small. Close to the river the clays were in most cases only slightly leached and therefore showed only small differences in salt content.

Close to the river the conductivity jump was reversed in some cases, which is explained if the salt distribution was similar to that found at Lödöse (Figs. 15 and 16). Clays with a relatively low conductivity were in some cases found close to the river. Clays with high conductivity were then placed above clays with low conductivity, as shown in Fig. 56.

The slip zone in an extracted core is shown in Fig. 52. The lower part of the core consisted of a dark sulfide clay. There was a sharp transition into an oxidized pale zone of remoulded clay. The thickness of the remoulded zone is about 1 cm. Above this zone there is a gradual transition of the pale clay into a darker one.

The salt sounding method was used at Surte by Järnefors (1958) to locate the failure zone when the slide was 7 years old. The curves showed gradual transitions of the resistance due to diffusion. Typical resistance curves reported by Järnefors are shown in Fig. 57. It is seen that the thickness of the transition zones is about 1 m. Järnefors says that cores extracted with the Swedish foil sampler contained slip surfaces just as the samples from Göta in Fig. 52.

Measurements were also made in the old slide area at Intagan by Järnefors in 1957 and by the present author in 1967. It was not possible to detect any jump in the salt content curve from chemical analyses, neither from resistance measurements. The profile showed a resistance curve and salt content curve which were similar to those in an undisturbed clay profile. If there have been any irregularities, they have been equalized by diffusion during the 319 years which had elapsed since the slide happened in 1648.

The salt sounding method was used for further studies in the slides at Göta and at Surte by the present author in 1968. Salt soundings and salt determinations were compared with studies on cores extracted with the

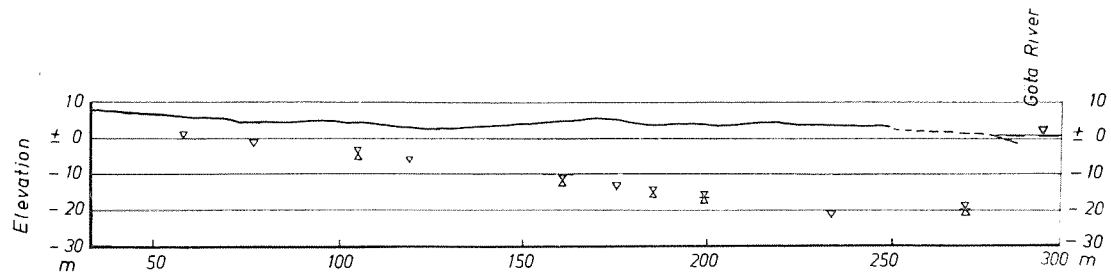


Fig. 54 Slide bottom at the Göta slide, Section C, determined by measurement of electrical resistance in situ  $\nabla$  and in extracted cores  $\triangle$  (from Söderblom, 1958)

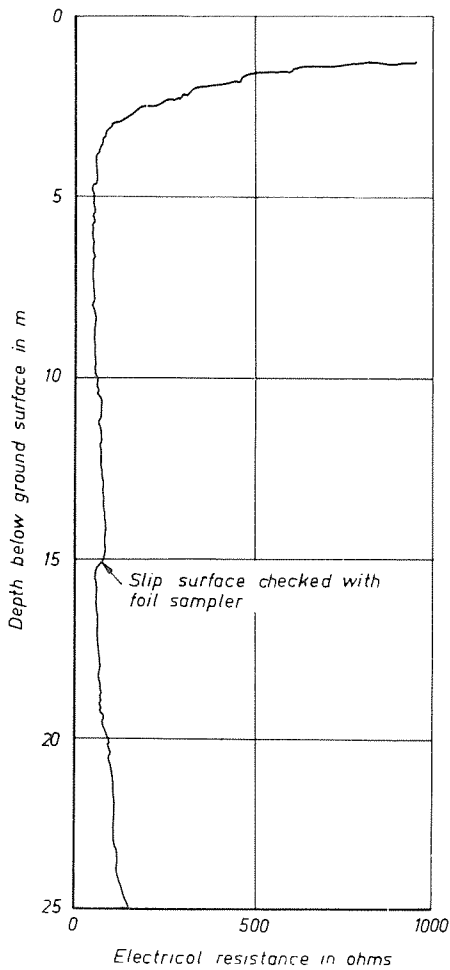


Fig. 55 Typical resistance curve from the Göta slide, Section C (from Söderblom, 1958)

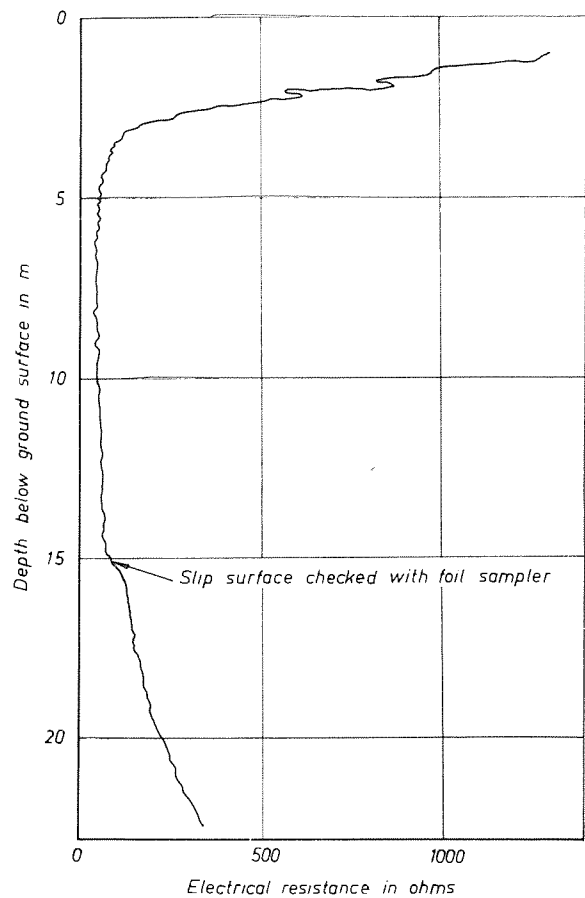


Fig. 56 Resistance curve from the Göta slide with the reverse resistance condition in comparison with Fig. 51 (from Söderblom, 1958)

Swedish foil sampler.

At Göta the appearance of the failure surface as seen in Fig. 52 was almost the same as in 1957 (Söderblom, 1958). However the jump in the salt sounding curves had partly been equalized. Such a curve from a point located close to Hole 313 in Section C is shown in Fig. 58. It is seen that the length of the jump is about 1.4 m

11 years after the slide. Corresponding measurements on an extracted core are given in Fig. 59. It should be noted that the slip surface is now not located in the middle of the resistance jump. The jump seems to have moved upwards, reasonably due to convection in the clay pore water, caused by artesian water pressure (cf. Odenstad, 1958). It was possible to find the slip surface by salt soundings 11 years after the slide.

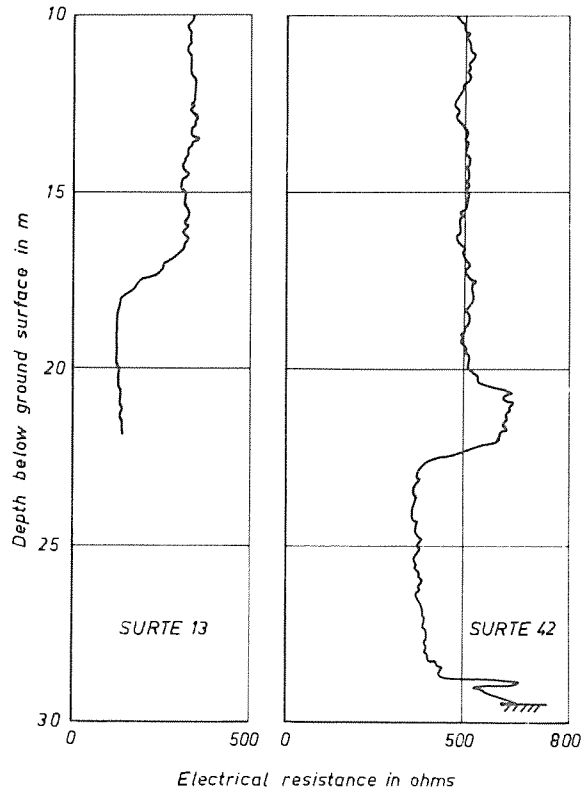


Fig. 57 Resistance curves from the Surte slide, Hole 16 and 42 (after Järnefors, 1958)

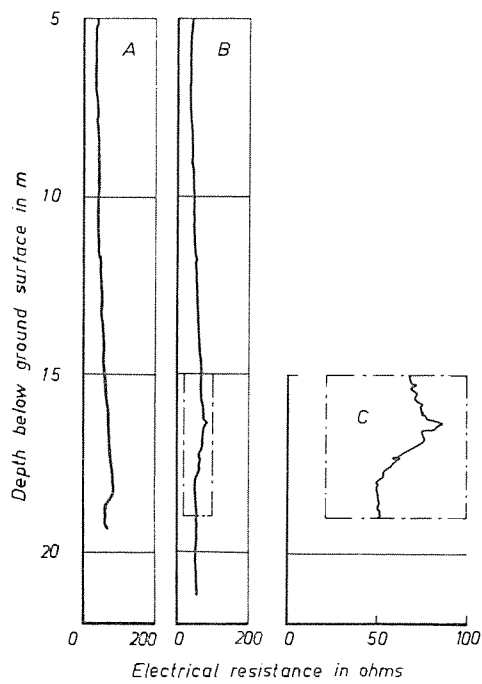


Fig. 58 Resistance curves from Göta slide, Section C, Hole 313. Curve A was obtained in 1968, Curve B in 1957 about 14 days after the slide. Curve C is a magnified part of Curve A, indicating the slip zone

No other essential changes have taken place in the profile during these years.

Corresponding measurements at Hole 352, Section I, are shown in Fig. 60. The measurements in 1957 were not made by the present author. The point was localized from a map. For this reason its position may differ a few metres from the original point. Curve A was obtained about 3 months after the slide and Curve B after 11 years. The diffusion zone in Curve A is about 0.4 m thick and in Curve B about 0.9 m.

Also in this case the jump seems to have moved upwards just as in Hole 313 (Fig. 61). Also in Hole 352 it was possible to localize the failure surface by salt soundings 11 years after the slide. The changes were, however smaller than at Hole 313. The distance between the two holes is about 500 m.

At Surte investigations were made at Hole 13 and at Hole 42. The original measurements were made by Järnefors (1958) and the present author had to localize the points from a map in his work. Jumps in the resistance curves were observed also here (Fig. 62). They

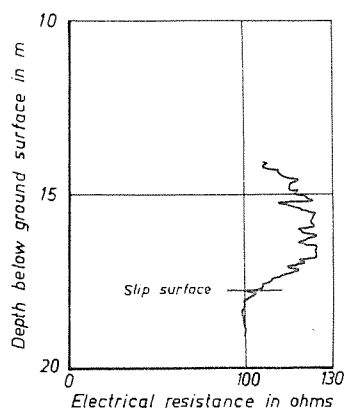


Fig. 59 Resistance curve determined on an extracted clay core from Göta slide, Hole 313, in 1968

had become somewhat more affected by diffusion than they were at the time of Järnefors' study, Fig. 57. It was not possible to localize, as at Göta, exactly the failure surface in the extracted cores. The typical transition zone between two clays of different colour (Fig. 52) was not visible at Surte. Hole 13 seems to be situated at a disturbed zone with several slip surfaces which explains the abnormally large extent of the diffusion zone. At Hole 42 there was sulfide-banded dark clay both below and above the resistance jump. It was not possible to distinguish between the sulfide bands and the slip surface. Here the clay was not so unaffected as at Göta.

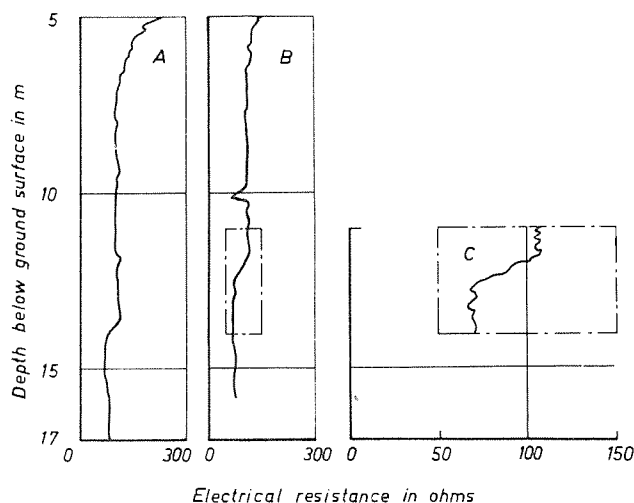


Fig. 60 Resistance curves in situ from Göta slide, Section I, Hole 352. Curve A was obtained in 1968, Curve B in 1957 about 3 months after the slide. Curve C is a magnified part of Curve A indicating the resistance jump

### 6.3 Discussion of Test Results

Slip surfaces may be located by salt soundings when the conductivity conditions are suitable. Few systematic examinations of salt distribution in slopes have been published. In a paper concerning the Cauca Valley in Colombia, Borrero (1956) reported salt distributions which were similar to those in the Göta River Valley. Thus the proposed method can probably be used in the Cauca Valley.

The method has also been used in Norway (Hutchinson, 1961). Hutchinson in some cases also found large differences in salt content above and below the slip surface, but in some cases no difference could be detected. In these cases he attributes the observed difference in resistivity to differences in grain size distribution. Recent investigations (not yet published) show that in the Göta River Valley the electrical resistance jumps are mainly due to different salt contents above and below the slip surfaces.

It has not yet been possible to apply the method in other areas in Sweden. The method has only been tried on minor slides which occasionally occur in the Göta River Valley. These measurements have not been successful because the displacements have been small and the conductivity in the clay close to the river varies only little.

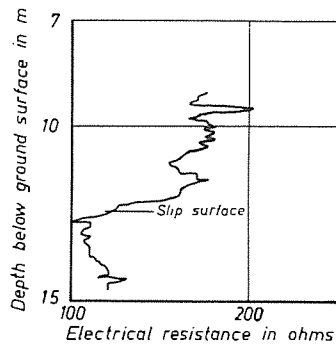


Fig. 61 Resistance curve determined on an extracted clay core from Göta slide, Hole 352, in 1968

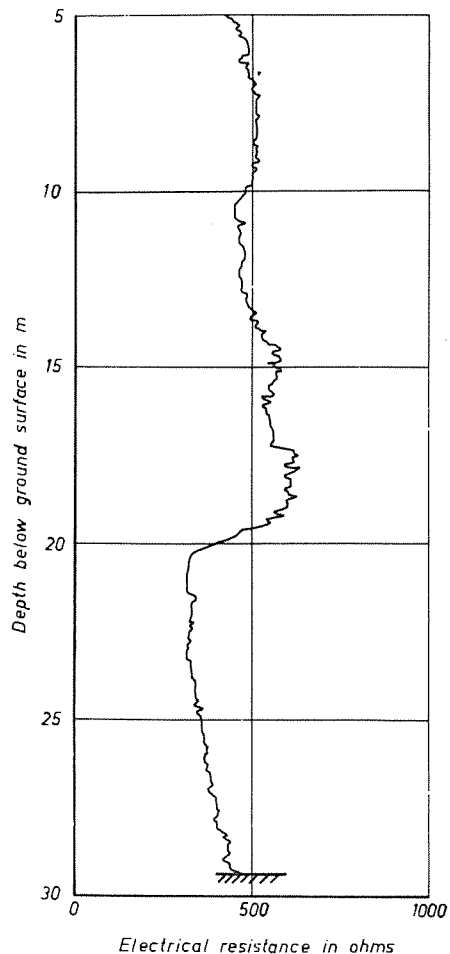


Fig. 62 Resistance curve in situ from Surte, Hole 42, measured in 1968

## 7. DIFFUSION OF SALT IN NATURAL CLAY PROFILES

### 7.1 General

In this work diffusion has often been mentioned as a very important factor which influences geotechnical processes. The process of diffusion will be discussed here in some detail.

If a clay is affected in some way the colloid chemical reactions usually are relatively rapid. It is e.g. possible to change the geotechnical properties of an undisturbed sample in a few days in the laboratory. If different substances are mechanically mixed into remoulded clay the properties will change instantly. In situ, however, the geotechnical properties change slowly and as a rule no changes measurable with existing methods are observed within moderate lengths of time. This indicates that diffusion or transportation of reac-

tion products in clay profiles in other ways governs the rate of the total process and not the chemical processes proper.

Usually one considers diffusion in clay profiles to be so slow a process that changes in the geotechnical properties require geological lengths of time. The studies of the slides at Surte and Intagan (Chapter 6) indicate, however, that measurable processes can occur relatively rapidly, as do observations by Jerbo (1964, 1969).

In order to understand the processes which govern the salt distribution in situ and the conductivity curves discussed in Chapter 4, diffusion and other processes resulting in a change of the salt content must be studied. The diffusion affects the formation of quick clays and the reduction of shear strength. Also in the search for

possible methods of chemical strengthening of clays the diffusion must be considered.

## 7.2 The Laws of Diffusion

In a solution having constant temperature and pressure in all its parts, but varying composition, the latter tends to equalize, although this is not a very rapid process. We consider pure diffusion, when there is no convection in the solution. The simplest case is a solution with varying concentration in a vessel,  $c_1$  at the top and  $c_2$  at the bottom. The amount of dissolved substance that will migrate per sec. through a horizontal  $1 \text{ cm}^2$  area is called the flow  $J$ . This flow is approximately proportional to the change in concentration  $dc/dx$ , where  $x$  is the coordinate of length in the direction of the flow. The proportionality factor is called the diffusion constant  $D$ . The flow is in the direction of decreasing concentration, so the formula for the one-dimensional case will be

$$J = -D \, dc/dx \quad (1)$$

The unity of the diffusion constant is  $\text{cm}^2/\text{sec.}$  if CGS units are used.

This law is called Fick's first law (1855). For the three dimensional case the formula will be slightly more complicated. It is valid if the material is isotropic so that the diffusion is the same in all directions. This is the case for all gases and liquids. In crystals, however, this is not always the case and one may then have different diffusion coefficients in the three axis directions. It should be noted that undisturbed clays also are anisotropic and in the exact treatment of the diffusion in clay slopes one should probably reckon with two different diffusion constants, one vertical and one horizontal (as well as a cross coefficient, in accordance with the Onsager relations). But this case has hardly been studied. In this work mainly the vertical diffusion will be pursued.

If more than one substance is dissolved they will influence each other's diffusion, so that the flow  $J_i$  of the substance  $i$  will be

$$J_i = \sum_{k=1}^n D_{ik} \, dc_k/dx \quad (2)$$

Few measurements have been made on the cross coefficients  $D_{ik}$  ( $i \neq k$ ).

In calculations on changes of concentration due to diffusion it is best to use Fick's second law, which for the one dimensional case has the appearance

$$dc/dt = d/dx(D \, dc/dx) \quad (3)$$

If  $D$  is constant for all values of  $c$  this is simplified to

$$dc/dt = D \, d^2c/dx^2 \quad (4)$$

Corresponding expressions can be deduced for the two- or three-dimensional cases.

The integrals of these differential equations will depend on the boundary conditions and will usually lead to non-elementary functions.

An important case ensues when a solution of concentration  $c_1$  is put in contact with another of concentration  $c_2$ . The integral to Fick's law will then contain the normal distribution function  $P(x)$  so that the concentration  $c$  at the distance  $x$  from the original contact surface ( $x$  counted positive in the direction against  $c_1$ ) at the time  $t$  after the first contact will be

$$c = c_2 + (c_1 - c_2) P(x/\sqrt{2Dt}) \quad (5)$$

The numerical values of the function  $P(x)$  are found in mathematical or statistical tables. The course of the curve is shown in Fig. 63.

Sometimes the Gaussian error function is used, which should not be confused with  $P(x)$ . The relation is

$$\text{erf } x = 2P(x/\sqrt{2}) - 1 \quad (6)$$

Hence we can also write

$$c = \frac{1}{2}(c_1 + c_2) + \frac{1}{2}(c_1 - c_2) \text{erf}(x/2\sqrt{Dt}) \quad (7)$$

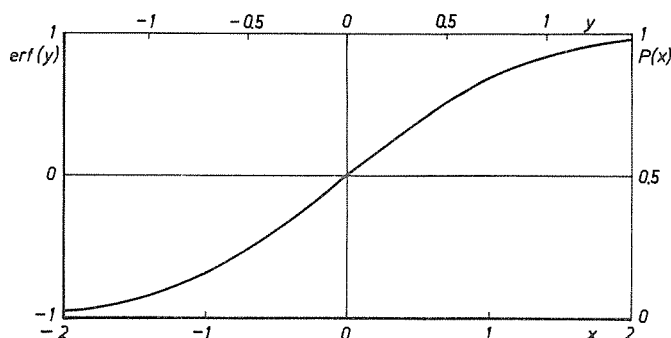


Fig. 63 Error function and normal probability function

## 7.3 Approximate Calculation of the Diffusion in some Clay Profiles

As already mentioned, the conductivity measurements indicate that diffusion has taken place in some clay profiles.

The present measurements are not accurate enough for a detailed study of the diffusion. The clays are far from

homogeneous and it is not possible to carry out accurate conductivity measurements in field work. The imperfect proportionality between conductivity and salt concentration in a solution will in fact only be a minor source of error.

If the materials were homogeneous and if diffusion is the main cause of the salt transport, accurate measurements would yield curves of concentration vs. depth similar to that in Fig. 63. If such measurements are plotted on a so called "normal distribution paper" where the highest and lowest ordinate values are extended compared with Fig. 63 the curve is transformed into a straight line. From the slope of this line the diffusion constant can be calculated.

For the present crude measurements it will be sufficient to find out at which heights in a profile the smoothing out of the concentration jump has been e.g. half completed, i. e. where the salt concentrations are  $(3c_1 + c_2)/4$  and  $(c_1 + 3c_2)/4$ . (At the original contact surface the concentration will always be  $(c_1 + c_2)/2$ .) From a normal distribution function table it will be seen that this occurs when

$$x/\sqrt{2Dt} = \pm 0.6745 \quad (8)$$

i. e. at the distance  $x = 0.95\sqrt{Dt}$  above and below the original contact surface. The distance between the two levels will then be

$$2x = 1.9\sqrt{Dt} \quad (9)$$

Before discussing the diffusion in clay it is suitable to consider the diffusion of sodium chloride in water at  $7^\circ\text{C}$  (temperature in the soil in the Göta River Valley). The value of the diffusion constant is  $D = 1.10 \text{ cm}^2/\text{day}$ . The smoothing out of the concentration gradient will proceed as seen in Table 14.

Because the diffusion proceeds proportionally to the square root of time, the initially rather rapid process

Table 14 Diffusion of NaCl in water at  $7^\circ\text{C}$

t	2x cm
8 hours 46 minutes	1.2
3 days 16 hours	3.8
36.5 days	12
1 year	38
10 years	120
100	380
1000	1200
10000	3800

later on will become very slow, if convection or other disturbances can really be excluded.

If a clay sample is dialysed against water (cf. Fig. 64)

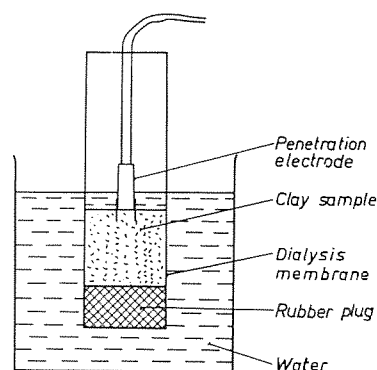


Fig. 64 Dialysis apparatus

which is being changed during the process the surface of the clay will correspond to  $x = 0$  in Fig. 63. It is seen from Fig. 65 that the salt content in a sample with a diameter of 50 mm will be small after a few days.

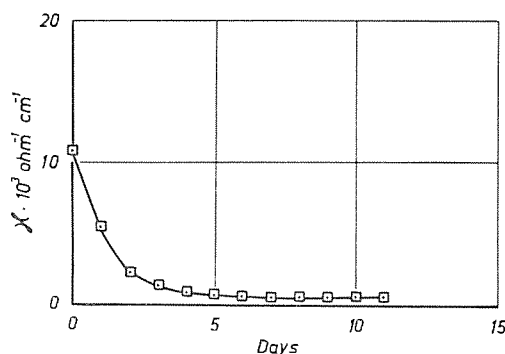


Fig. 65 Course of dialysis process in an artificially salted, mechanically undisturbed quick clay from Utby, Hole 658, 11 m

In a clay the mineral particles usually will delay the diffusion process, the more the less the water content is. Of the total volume only the water phase and the double layer on the surface of the clay particles are accessible for the diffusion. The diffusion length  $x$  is therefore curved around the mineral particles. This has been discussed by several authors, e.g. Porter et al. (1960). The ratio of the apparent diffusion constant  $D_p$  of a substance in a porous medium, e.g. a clay and the diffusion constant  $D_o$  in a water solution, is called the diffusion transmission factor (cf. Gast & East, 1964, on conductivity transmission factor). According to Porter et al. the transmission factor is composed of several factors

$$D_p/D_o = \alpha\gamma (L/L_e)^2 \phi \quad (10)$$

where  $\alpha$  is a factor which depends on the water viscosity, which is believed to change in the adsorption layer,  $\gamma$  is a factor for negative adsorption,  $(L/L_e)^2$  is the so-called tortuosity factor depending on the geometry of the clay gel, and  $\phi$  is the volumetric moisture content.

Rosenqvist (1955) studied the diffusion of heavy water in clay pastes and found diffusion coefficients of 0.034 to 0.054 cm<sup>2</sup>/day at 20°C. These values are very small. Wang (1951) found the diffusion coefficient for heavy water in ordinary water to be about 1.7 cm<sup>2</sup>/day. The diffusion coefficients found by Rosenqvist in clays thus correspond to a transmission factor of 0.02-0.03.

Zatenatskaya (1965) has found by a study of the salt composition that the diffusion of Cl<sup>-</sup> ions in muds and clays obeys Fick's law of diffusion. She found that the coefficient of diffusion in such systems varied between 0.13 and 0.51 cm<sup>2</sup>/day.

For diluted bentonite solutions Gast (1966) tried to verify the Einstein-Nernst relation  $D = 1000 \lambda RT / czF^2$  and compared curves for D-values obtained by experiments with values calculated by the formula above. He found a rather good agreement for sodium ions but not so good for strontium ions.

Gast & East (1964) have studied the correspondence between the conductivity and diffusion transmission factors and found that in principle the same factors which delay the conductivity also delay the diffusion. In their paper a table is given comparing diffusion and conductivity transmission factors for different salt-treated bentonite solutions. The factors are not equal, but it seems possible to estimate the order of magnitude of the diffusion from the conductivity transmission factor.

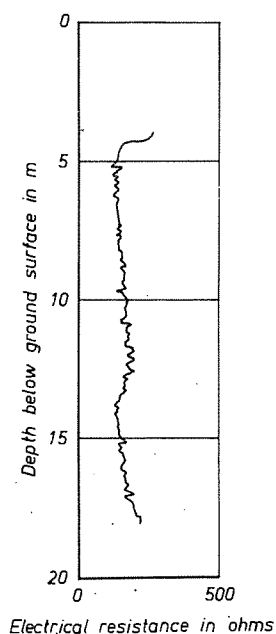


Fig. 66 Salt sounding curve from Göta in 1967 showing the equalizing of the former sharp gradient in salt content by diffusion (cf. Fig. 51)

In the Göta slide in 1957, a sharp conductivity gradient was formed in the slip surface due to the displacement of the clay masses. The appearance of the resistance curve about 14 days after the slide is seen in Fig. 51. The corresponding curve from an adjacent profile in 1967 (the slip surface is somewhat deeper here) is shown in Fig. 66. It is seen from these figures that the sudden jump was partially equalized. In this case  $2x$  is approximately 50 cm. According to Eq. (9) this distance corresponds to a diffusion constant  $D = 0.23$  cm<sup>2</sup>/day. This value is less than the diffusion coefficient for NaCl in water, the transmission factor being 0.21 if pure diffusion has taken place. This value is quite reasonable and in accordance with the values obtained by Zatenatskaya (1965) and Briling (1965).

Fig. 58 shows results from Hole 313 in Section C at Göta, 11 years after the slide. Here  $2x$  is approximately 40 cm which corresponds to  $D \approx 0.11$  cm<sup>2</sup>/day. Corresponding measurements at Hole 352 Section I are seen in Fig. 60. In this case  $2x$  is about 35 cm after 11 years and  $D \approx 0.09$  cm<sup>2</sup>/day.

Fig. 57 gives two profiles measured in 1957 within the 1950 Surte slide area. In this case the slip surface appears as a partly smoothed out jump in the resistance curves. In Hole 13 (Fig. 57)  $2x$  is about 75 cm and in Hole 42 about 30 cm. If a pure diffusion is assumed to have taken place we find  $D = 0.53$  cm<sup>2</sup>/day and 0.14 cm<sup>2</sup>/day, respectively.

A new investigation was made at Surte in 1968, 18 years after the slide. The results for the two points mentioned above are shown in Fig. 62. The distance  $2x$  is now about 200 cm in Hole 13 and about 50 cm in Hole 42. In Hole 42,  $D$  is 0.11 cm<sup>2</sup>/day and in reasonable accordance with the value 0.14 cm<sup>2</sup>/day determined 7 years after the slide. It was impossible to detect slip surfaces in extracted cores from this point at the depth of the resistance jump (Fig. 62) nor was it possible to detect any disturbed zones. No sharp colour differences were present as was the case at Göta. At Hole 13 the value  $D \approx 1.8$  cm<sup>2</sup>/day was obtained. But at this point disturbances seem to have occurred. In an extracted clay core one could detect a relatively large disturbed zone at the resistance jump and therefore a reliable value of the diffusion constant could not be calculated in this point.

#### 7.4 Studies of Natural Leaching

In Chapter 4 it was mentioned that leaching is important for the understanding of the salt conditions in marine clay profiles. The appearance of the resulting conduc-



tivity curves are caused by leaching both from the top and from the bottom of the clay profile (cf. Fig. 14). Both the upper and lower parts of such a curve follow pretty well a normal distribution curve and this supports the theory that a diffusion has taken place.

Assuming that the Lödöse profile (Fig. 16) emerged from the sea about 6,000 years ago with a pore water containing 3.5% salt and has been leached since then, the present conditions at 57 m from the river correspond to a value of  $D = 0.13 \text{ cm}^2/\text{day}$  in the upper part. The bottom gravel layers may have carried fresh water even earlier, maybe already during the first clay sedimentation period, but if the same diffusion time is used one obtains  $D = 0.70 \text{ cm}^2/\text{day}$  in the bottom part of the profile, possibly too high a value. The diffusion transmission factor will then be 0.12 and 0.6, respectively, which should be compared with the conductivity transmission factors in Table 12, viz. 0.3 - 0.4 at the top and 0.5-0.4 at 20-25 m depth.

In Chapter 5.3 it was, however, pointed out that the ionic composition in the pore water was not the same throughout the whole Lödöse profile. Towards the surface,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  were the dominating cations, in the middle sodium, and near the bottom  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  began to dominate again. It has been found in Chapter 5 that  $\text{Ca}^{2+}$  in quick clays is complexly bound, presumably to organic material. Therefore not only pure diffusion but also more complex processes govern the natural salt conditions.

As mentioned in Chapter 3.3 Rosenqvist (1955) has found that leached clays contain relatively more  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ -ions than salt clays. This he calls partial leaching.

#### 7.41 Dialysis Studies on Different Clay Samples

When studying the leaching process it is necessary to arrange the experiments so that only salts can leave the system. For this purpose a dialysis technique was used. The apparatus is sketched in Fig. 64. The clay sample was enclosed in a membrane of cellophane (Union Carbide Co) with 24 Å pores, permitting only low molecular substances to pass. The leaching water was changed every day during a period of 10-14 days. The change of the salt content in the sample during the process was followed with the aid of a penetration electrode. The equipment can of course also be used to introduce salts into a leached clay.

Before starting the leaching experiment the conductivity of the sample was determined and the ionic composition

of the pore water estimated by means of paper chromatography. The ionic composition of the leaching waters was also studied.

Several quick clay samples from Utby, Hole 658, 9 through 16 m, were dialysed against a 3.5 % NaCl solution. The results were practically identical and therefore only the results from a depth of 11 m are reported here. Thereafter the salt was removed by dialysis against distilled water. The change of  $\kappa$  in the sample is shown in Fig. 65. The result is shown in Table 15. It is seen that the quick clay increased its  $H_3$ -value by the salt treatment and its sensitivity decreased. After the leaching of the salt the sample became quick again.

A chromatogram of the ionic composition in the pore water of the dialysed quick clay sample from Utby is shown in Fig. 67. If this chromatogram is compared with a similar one for untreated quick clay from the same hole (Fig. 37) it is seen that the ionic composition of the water is almost unchanged by the dialysis treatment.

The experiment was repeated with 2%  $\text{CaCl}_2$  instead of NaCl. The change of  $\kappa$  was determined and the ionic composition was studied both in pore water from the treated sample and in the  $\text{CaCl}_2$ -solution after the experiment. Thereafter the salt was removed by dialysis against distilled water. The result is shown in Table 15 and Fig. 68. In this case the clay did not become quick again. The treatment with  $\text{CaCl}_2$  has thus caused changes in the colloid system which were not eliminated by the leaching. Fig. 68 indicates that the pore water after the treatment with  $\text{CaCl}_2$  still contains  $\text{Na}^+$ -ions but also considerable amounts of  $\text{Ca}^{2+}$  (and  $\text{Mg}^{2+}$ ). Thus the pore water has obtained a composition similar to that of many natural non-quick clays. Fig. 69 shows that most of the water-leached cations are  $\text{Na}^+$ -ions. This indicates that besides diffusion a Donnan effect is fundamental. In the adsorbed ion layer  $\text{Ca}^{2+}$  is exchanged for  $\text{Na}^+$ , and  $\text{Ca}^{2+}$  cannot be removed by water leaching alone.

Two quick clay samples from Hole 658 13 m were dialysed against the simplified synthetic sea water described in Chapter 2. The change in the geotechnical properties was almost the same as found for NaCl above. Thereupon the samples were leached against distilled water. The results are shown in Table 15 and in Fig. 70. In this case the quick properties of the samples reappeared after leaching. Also the ionic composition of the pore water after leaching was similar to that of a quick clay as shown in Fig. 70. Thus the small amounts of  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  in sea water do

Table 15 Test Results from leaching experiments in different clays

Site Hole Depth	Treatment	H <sub>3</sub>	H <sub>1</sub>	H <sub>3</sub> /H <sub>1</sub> (S <sub>t</sub> )	w %	Liquid limit, w <sub>L</sub>		R ohm	κ · 10 <sup>3</sup> ohm <sup>-1</sup> cm <sup>-1</sup>	pH	Ionic composition						Remarks
						Natural %	Predried %				Na <sup>+</sup>	K <sup>+</sup>	Ca <sup>2+</sup>	Mg <sup>2+</sup>	Cl <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	
<u>Utby 658</u>	Untreated	183	0.98	186	65	53	-	360	1.11	-	++	-	-	-	-	+	
15 m	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
<u>Utby 658</u>	Untreated	153	0.82	187	70	56	51	360	1.11	-	++	-	-	-	-	+	test
15 m	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	-	++	-	-	-	+	+	
<u>Utby 658</u>	Untreated	163	0.384	425	66.5	44	41.8	330	1.26	7.6	++	-	-	-	-	+	
15 m	After dialysis against 3.5% CaCl <sub>2</sub> solution							31.5	12.7								
	After leaching of added salt	163	13.8	11.8	67.2	66.5	53.7	433		7.3	+	-	+	+	+	+	
<u>Utby 658</u>	Untreated	163	0.384	425	66.5	44	41.8	330	1.26		++	-	-	-	-	+	
15 m	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	++	-	-	-	+	+	
<u>Utby 99</u>	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	-	++	-	-	-	+	+	
<u>Älvängen</u>	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	-	+		+	+	+	+	
<u>Strand- backen</u>	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	-	+	-	+	+	+	+	
<u>Strand- backen</u>	Natural salt clay with about 2.3% salt	281	26.8	10.5	70	78	61	52	7.7	7.4	+	-	+	+	+	+ <sup>1)</sup>	Fresh sample
20 m	After leaching of salt	66.2	0.60	110	84	63	50	430	0.93	7.8	++	-	-	-	-	+ <sup>1)</sup>	
<u>Älvängen</u>	Natural salt clay with about 2% salt	120	10.4	11.5	86	90	54	31	12.9	7.5	++	-	+	+	+	+ <sup>1)</sup>	Fresh sample
14 m	After leaching of salt	68.0	0.60	113	91.5	63		460	0.87	8.4	++	-	-	-	-	+ <sup>1)</sup>	
<u>Älvängen</u>	Natural salt clay with about 2% salt	69.8	9.09	7.68	85	90	56	27	14.7	7.2	++	-	+	+	+	+ <sup>1)</sup>	Fresh sample
15 m	After leaching of salt	69.8	0.44	157	92	65	57	435	0.92	8.2	++	-	-	-	-	+ <sup>1)</sup>	

1) Contains phosphates

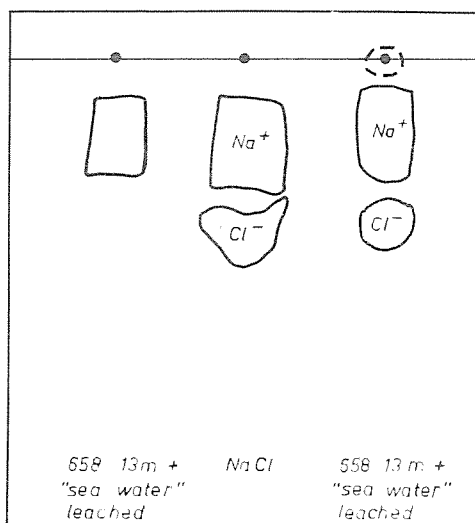


Fig. 67 Small-paper chromatogram of pore water salts in a salt-treated and dialysed quick clay sample, Utby Hole 658, 9 m

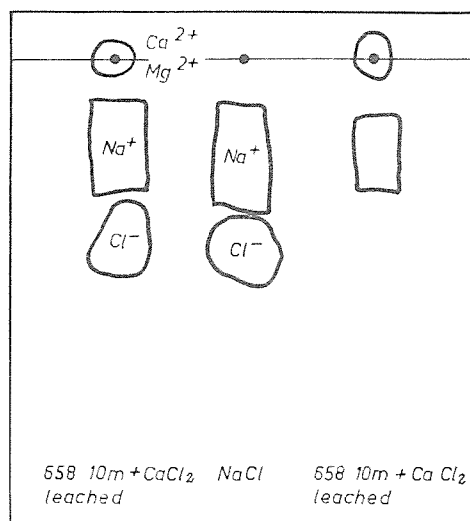


Fig. 68 Small-paper chromatogram of pore water salts in a  $\text{CaCl}_2$ -treated and dialysed quick clay sample, Utby Hole 658, 10 m

not accumulate in the sample. As a result the sensitivity of the clay will be relatively high.

Leached clay samples with low salt content and low sensitivity, containing  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$  and  $\text{SO}_4^{2-}$  in the pore water, from Hole 99, 9 m, were dialysed against 3.5%  $\text{NaCl}$ -solution. They were thereafter dialysed against distilled water. The results are shown in Table 15. It is seen that the salt treatment decreased the  $H_3$ -value of the clay. After dialysis against water the ion composition of the pore water corresponds to that of a quick clay. The sample has in this case been transformed into a quick clay.

Natural salt clay samples, two from Älvängen and two from Strandbacken (1/2 - 1 years old) were simultaneously leached against distilled water. The ionic composition of the pore water of the samples from Älvängen was similar to that of sea water. In the case of Strandbacken (Fig. 72)  $\text{MgCl}_2$  was present in the pore water salt in great quantities forming a tail in the chromatogram. The result is shown in Table 15 and in Figs. 73 and 74. None of the samples were transformed into quick clay.

The ion composition of the pore water after the leaching of the samples is shown in Figs. 73 and 74. In every case  $\text{Mg}^{2+}$ -ions had remained in the sample to a higher degree than the  $\text{Na}^+$ -ions. After the leaching the salt contents in the pore waters of these samples were so low, that it was necessary to concentrate them by evaporation before the chromatography test. In all cases it seems that the sulfate ions are decreasing in the system slower than the chloride ions. Also these experiments indicate that quick clays cannot be formed

by leaching alone.

In order to study the leaching effect additional samples were extracted at Älvängen and Strandbacken. The samples were transported the same day to the laboratory in Stockholm by bus and express train. The following morning the samples were dialysed against distilled water as described above. The results are shown in Table 15. In all these cases quick clays with a sensitivity somewhat larger than 100 were obtained.

The chromatograms of pore water from the fresh clay samples squeezed before and after the dialysis showed that calcium and magnesium had disappeared during this treatment and that monovalent ions now dominated. Thus the dialysis process was different from that in the stored samples. The addition of salt as discussed in Chapter 5.3 indicated that  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  were not leached during the dialysis. They seemed to be complexly bound. By evaporating the water covering the clay in the dialysis membrane (Fig. 64) a brown-yellow mass was obtained which had strong clay dispersing properties. This indicates the importance of dispersing agents in the quick clay forming process.

When the pore water was treated in an anion exchanger as described in Chapter 3.26 and chromatographed according to Seiler et al. the positive ions were mainly  $\text{K}^+$  and  $\text{Na}^+$ , but also some  $\text{Mg}^{2+}$  was found. The last-named ion is not so distinctly visible in the small chromatograms and might partly have appeared after disintegration in the ion exchanger of organic bound  $\text{Mg}$ .

The anions which became accumulated in the ion exchanger were evaluated by means of 1 N  $\text{HCl}$  and chroma-

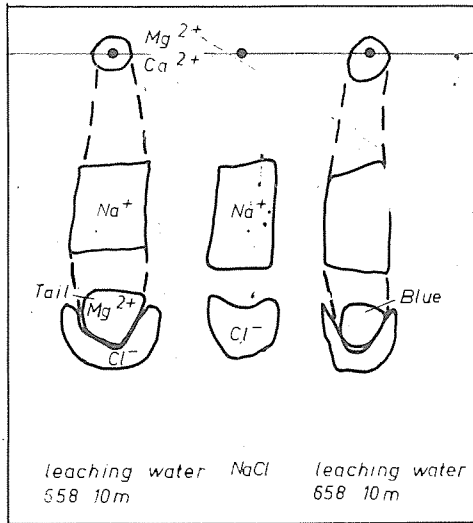


Fig. 69 Small-paper chromatogram of leaching water from a dialysing of a  $\text{CaCl}_2$ -treated quick clay sample, Utby Hole 658, 10 m against distilled water

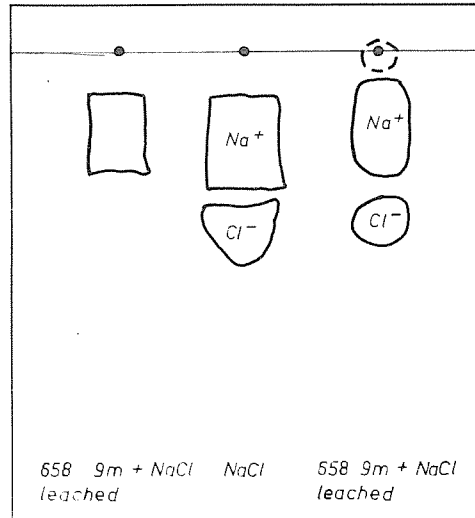


Fig. 70 Small-paper chromatogram of pore water of a quick clay, Utby Hole 658, 13 m treated with a simplified synthetic sea water and then dialysed against distilled water

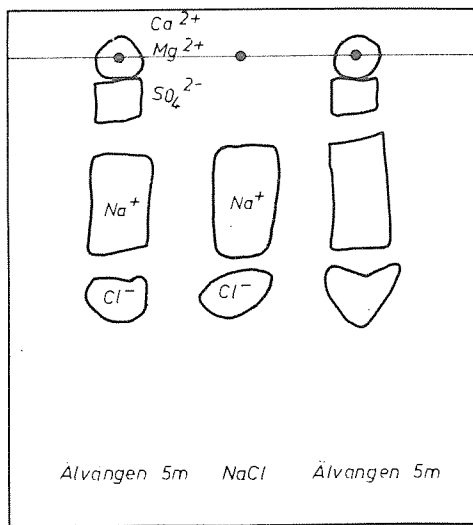


Fig. 71 Small-paper chromatogram of pore water of a clay sample from Älvängen 5 m

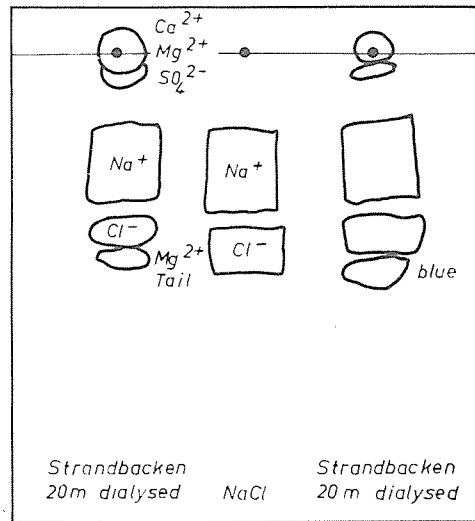


Fig. 72 Small-paper chromatogram of pore water of a clay sample from Strandbacken 20 m

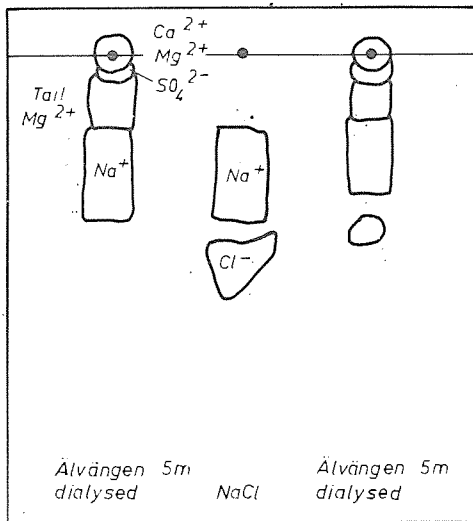


Fig. 73 Small-paper chromatogram of pore water of a clay sample from Älvängen 5 m dialysed against distilled water

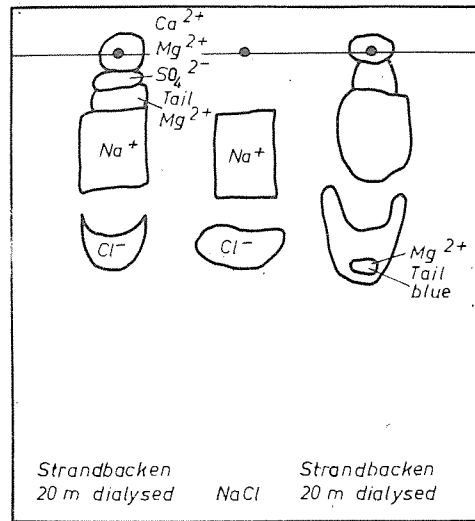


Fig. 74 Small-paper chromatogram of pore water of a clay sample from Strandbacken 20 m dialysed against distilled water

tographed in the solvent system butanol - formic acid - water (4:1:5) according to Linskens (1959). About seven distinct anions could be detected. It should be observed, that almost all chloride ions had left the system during the dialysis. From Table 15 it is also seen that the leaching of the fresh clay samples increased the pH-value.

These studies on fresh clays are continued and will be reported in detail in a subsequent paper.

## 7.5 Discussion of Test Results

Irregularities in the conductivity curves in natural clays tend to be smoothed out with time as expected from the normal diffusion laws. The results from e.g. Surte support this, cf. Hole 42 with a diffusion constant  $D$  of 0.11 to 0.14  $\text{cm}^2/\text{day}$ .

As said before the salt distribution in the clays in the Göta River Valley can be explained as follows. These clays were originally sedimented in sea water. After the rise of the clay sediments above sea level the clay was leached from the top and also from the bottom. Such processes should give a conductivity curve as that shown in Fig. 14. Close to the present river, where the clay sediment is very deep, the diffusion process has still not removed the salt from the middle of the profile. The salt has here about the same ionic composition as that in sea water. Up the slopes where the depth of the sediments is smaller the clay now has a low salt content, the leaching having been more complete.

At many locations the whole clay profile is leached. This is the case especially where there is an artesian water pressure in the ground. This condition is common in the Göta River Valley. If points with the same conductivity are connected, a section of the type shown in Fig. 16 is obtained, illustrating the conductivity near Lödöse. The clay with high conductivity occurs as a lens within the deeper parts of the profile. The larger height of the bottom diffusion zone in comparison with the upper zone can be explained, either by a flow from the bottom layer due to artesian pressure, or to different diffusion transmission factors.

It is seen from Figs. 59 and 61 from Göta that the diffusion in natural clays is not symmetrical around the slip surface. The conductivity jump seems to be moving slowly upwards. This movement may be caused by convection of the pore water in the clay, but can also be due to more complicated causes. Although Gast & East (1964) have found that the diffusion and conductivi-

ty transmission factors are not equal it should be possible to estimate the order of magnitude of diffusion transmission factors from the conductivity transmission factors. As seen in Table 12 the conductivity transmission factor varies considerably within the Lödöse section. It is then reasonable to expect that also the diffusion constant varies. As a consequence the diffusion constant may be different above and below a slip surface. The diffusion will then be asymmetrical.

At Hole 5 at Lödöse the value of the conductivity transmission factor was larger than 1, i.e. the diffusion constant is larger than in water. This is not unreasonable as shown by van Schaik, Kemper & Olsen (1966) who found that the total flow of ions through a clay could be much larger than in water due to a strong surface diffusion. A similar effect has also been found with respect to conductivity (Cremers & Laudelout, 1965).

The diffusion transmission factor is of great importance for chemical stabilization of clay. The slip surface studies at Surte and Göta indicate that this factor can vary from about 0.08 to 0.70. These values should be compared with the Lödöse conductivity transmission factors (Table 12). It is evident that it would be easy to stabilize a soil chemically if the diffusion coefficient (and the transmission factor) is high. Therefore the study of diffusion and conductivity transmission factors is of importance. A rough calculation shows that at places where the transmission factor is low, it is hardly possible to stabilize soils with lime or other chemicals in a reasonable time, say 1 - 2 years.

The discussion of diffusion is valid only if the total salt content is considered. As shown in Chapter 5.3 the ionic composition varies considerably in clay profiles, cf. Utby Hole 680. This cannot be disclosed from the measured conductivity curve. At a moderate depth below the ground surface the cations are mainly calcium and magnesium. In the typical "salt clays" the ionic composition is similar to that in sea water, but in the quick clays a composition prevails with sodium as almost sole pore water cation, and calcium and magnesium being complex-bound in the clay system.

Ageing effects in the extracted clay samples are playing an important role. Fresh clay samples are giving other results than samples which have been stored for some months. Chemical changes have taken place in the stored samples. A fresh extracted salt clay sample had a yellow pore water containing organic substances, but the pore water of a sample which had been stored some months was uncoloured. The salt content and the ionic composition of the waters were approximately the same. This suggests the importance of changes in the

organic part of the clay both for the ageing process and for the quick clay formation. On the other hand, the appearance of  $K^+$ -ions (and in some cases  $Li^+$ ) and the rise of the pH-value during the dialysis of fresh samples indicate mineral weathering. Such relatively rapid processes, which have been described by e.g. Hammer (1949) disturb the results of the salt determination by the leaching method (cf. Chapter 3).

A chromatogram of the anions of the pore water from the original fresh salt clay shows besides chloride and sulfate also at least 7 different organic anions. One of these anions is some sort of phosphate ion of unknown composition. Especially chloride and some sulfate leave the system during the dialysis, but other ions, e.g. the phosphate, remain. The anionic residue could bind  $Ca^{2+}$  and  $Mg^{2+}$  complexly. The pore water of the resulting dialysed clay thus contains mainly monovalent ions but the ionic composition can easily be changed, e.g. by salt treatment of the clay.

The results from a dialysis of a clay can differ. If for instance, a salt clay with a clear, non-organic pore water is dialysed,  $Ca^{2+}$  and  $Mg^{2+}$  and sulfate ions remain in the sample as reported by Rosenqvist (1955). This is also in agreement with results obtained by Mattson (1926) who found that during electrodialysis mainly the monovalent ions are the first to leave a clay system, thereafter follow divalent ions and at last aluminium ions in accordance with the binding energy of the ions in a clay system. The leaching gives a pore water composition with mainly  $Ca^{2+}$  and  $Mg^{2+}$  as cations and  $SO_4^{2-}$  as anions. This composition was found e.g. at Utby Hole 680 at a depth of 4 m (Chapter 5.3) and at Hole 99 at a depth of 4 to 5 m (Chapter 5.3).

Treatment of quick clays with NaCl and a subsequent

leaching of the introduced salt restore quick clays in accordance with results obtained by Bjerrum & Rosenqvist (1956). However, if the introduced salt is  $CaCl_2$ , the clays do not become quick after leaching.

The present author did not find any systematic experiments reported in the literature treating the leaching of natural salt-clay samples and the transformation of the leached non-quick clays into quick clays. It seems difficult to simulate in the laboratory the processes going on in nature. In the present investigation the dialysis experiments were carried out under aerobic conditions, instead of the anaerobic conditions prevailing in nature, thus giving rise to different processes. Natural quick clays usually contain only very small amounts of  $K^+$ , but in the laboratory leaching experiments this ion sometimes can be found (and also  $Li^+$ ) indicating that other chemical processes are occurring in the laboratory than in situ. The pH-value increases during leaching in the laboratory experiments.

Allison (1947) found deflocculation effects for soil crumbs under non-sterile conditions. These effects could not be observed when the sample was sterilized by ethylene oxide and the water used for the percolation contained small amounts of  $HgCl_2$ .

The increase of the sensitivity of salt clays during leaching seems to be a rapid process. A clay sample in the laboratory changes its sensitivity in a few days. A change of the ground water conditions also seems to change the sensitivity of a clay in situ in a relative short time. A clay layer in the vicinity of a water pumping station at Lödöse, built in 1956, is a good example. The clay was salt and its sensitivity normal in 1955, whereas the clay was desalted and quick in 1968.

## 8. CONCLUSIONS

In the present investigation it was found that the commonly used methods of leaching dried clay material can cause gross errors both in the absolute values of the salt content of a clay and in the course of the curve of the salt content vs. depth in a clay profile. The most reliable method found for studying the pore water of a Swedish clay is to squeeze it out from samples and to examine it by suitable analysis methods. By measuring the electric conductivity of the clay it is only possible to obtain a very rough estimate of the total salt content in its pore water. The present author has used two types of electrodes, the penetration electrode and the

salt sounding tool, which have been found to be suitable for many geotechnical purposes.

Systematic measurements in situ with the salt sounding tool have shown that the conductivity curves in undisturbed Swedish clay profiles investigated usually have no pronounced irregularities except where e.g. sand layers occur. It seems that possible irregularities at the time of sedimentation or later have been smoothed out by diffusion.

It has not been possible to find a correlation between

sensitivity and the total salt content in the pore water. The conductivity and the sensitivity curves as a rule are of quite different appearances.

There seems, however, to be a correlation between the ionic composition of the pore water of a clay and its sensitivity. The ionic composition of pore waters was determined by means of standard paper chromatography methods. Three main types of ionic composition of the pore waters in Swedish clays were found. Salt clays contained sodium chloride but also distinct amounts of calcium, magnesium and sulfate ions. Naturally leached "normal" clays contained mainly  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$  and  $\text{SO}_4^{2-}$  -ions in their pore water. Quick clays contained mainly  $\text{Na}^+$  and  $\text{SO}_4^{2-}$  -ions. It is, however, very important that calcium and magnesium have not been removed from the quick clay system, but these ions are complexly bound and can be set free by different means. Similar ionic pore water composition as in quick clays was obtained by treating a "normal" clay of low salt content with a dispersing agent. This suggests that the complex binding of  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  can be caused by naturally occurring dispersing agents, primarily of organic type.

Swedish quick clays as a rule show large ageing effects after sampling. The undisturbed shear strength then decreases after sampling as well as does the sensitivity (although there occur exceptions). The remoulded shear strength usually increases. The chemically caused part of these effects is not yet fully understood. There is an increase of  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  -ions in the pore water with time, indicating alterations of the colloid chemical system. Organic dispersing agents which are masking  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  seem to be of great importance.

It was unexpected that the observed ageing of the clay samples could be so rapid. But this effect is important for the understanding of the geotechnical properties. The effect is in accordance with the behaviour of gels

in general, for gels usually show ageing phenomena. It is rather more surprising that clays in nature can be so stable with time as they are. This colloid chemical process of ageing should be investigated further.

It is possible to localize slip surfaces in large slides by conductivity soundings. This technique has proved to be one of the best methods for this purpose.

The diffusion in natural clay slopes has been studied. At Surte the diffusion seems to follow Fick's law and it was possible to calculate the diffusion constant over 18 years. It was 0.11 to 0.14  $\text{cm}^2/\text{day}$ .

The leaching process was also studied. Two different behaviours were found when leaching natural salt clay samples. In many cases there was an increase in the ratio divalent/monovalent cations in the pore water and the leaching gave a non-quick clay system. But in the leaching of quite fresh clay samples having a brown-yellow organic pore water the  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  -ions disappeared from the pore water and must have been complexly bound to the polyanions which were left in the clay during the leaching process and the samples became quick. However, it has not been possible during these laboratory experiments to obtain a dialysed quick clay system with exactly the same pore water composition as the natural system. Uncontrolled weathering processes which gave  $\text{K}^+$  -ions were occurring during the laboratory experiments.

Chromatography is a suitable method to study processes of this kind. By means of chromatography it has been possible to follow the formation and disappearance of a large number of substances in clays which are of importance for an understanding of the quick clay formation processes. The method seems also to be useful for the study of corrosion in the soil.

#### ACKNOWLEDGEMENTS

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Rolf Söderblom





Cone type	Penetration mm	0	1	2	3	4	5	6	7	8	9	
100 g 30°	2,	1 140	1 050	970	895	825	760	700	650	605	563	
	3,	526	493	463	435	411	389	369	349	330	313	
	4,	296	281	267	253	241	230	220	208	204	196	
	5,	189	183	178	173	168	163	158	153	149	145	
	6,	141	136	132	128	124	120	117	113	110	107	
	7,	104	101	98,0	95,5	93,0	90,6	88,3	86,0	83,7	81,5	
	8,	79,4	77,4	75,4	73,5	71,6	69,8	68,0	66,2	64,5	63,0	
	9,	61,5	60,0	58,5	57,1	55,8	54,6	53,4	52,2	51,1	50,0	
	10,	49,0	47,9	46,9	45,9	45,0	44,1	43,2	42,4	41,6	40,8	
	11,	40,0	39,2	38,4	37,6	36,9	36,2	35,5	34,8	34,2	33,6	
	12,	33,0	32,4	31,8	31,2	30,6	30,0	29,4	28,8	28,2	27,6	
	13,	27,1	26,6	26,2	25,8	25,4	25,0	24,6	24,2	23,8	23,5	
	14,	23,2	22,9	22,6	22,3	22,0	21,7	21,4	21,1	20,7	20,4	
	15,	20,0	19,7	19,4	19,1	18,8	18,5	18,2	17,9	17,6	17,3	
	16,	17,0	16,8	16,6	16,4	16,2	16,0	15,8	15,6	15,4	15,2	
	17,	15,0	14,8	14,6	14,4	14,2	14,0	13,8	13,6	13,4	13,2	
	18,	13,0	12,8	12,6	12,4	12,2	12,0	11,8	11,6	11,4	11,2	
	19,	11,1	11,0	10,9	10,8	10,7	10,6	10,5	10,4	10,3	10,2	
	60 g 60°	4,	57,9	55,0	52,6	50,3	48,1	46,0	44,0	41,9	40,0	38,4
5,		37,0	35,6	34,3	33,3	32,3	31,3	30,4	29,5	28,6	27,7	
6,		26,8	25,9	25,0	24,2	23,5	22,8	22,1	21,4	20,7	20,2	
7,		19,7	19,2	18,7	18,2	17,8	17,4	17,0	16,6	16,2	15,8	
8,		15,4	15,0	14,7	14,4	14,1	13,8	13,5	13,2	12,9	12,6	
9,		12,3	12,0	11,7	11,4	11,2	11,0	10,8	10,6	10,4	10,2	
10,		10,0	9,80	9,60	9,43	9,26	9,09	8,92	8,75	8,58	8,41	
11,		8,25	8,10	7,96	7,82	7,69	7,56	7,43	7,30	7,17	7,05	
12,		6,93	6,81	6,69	6,59	6,49	6,39	6,29	6,19	6,09	5,99	
13,		5,89	5,79	5,69	5,59	5,49	5,39	5,29	5,20	5,11	5,02	
14,		4,93	4,84	4,75	4,66	4,57	4,48	4,39	4,30	4,22	4,15	
15,		4,09	4,03	3,97	3,92	3,87	3,82	3,77	3,72	3,67	3,62	
16,		3,57	3,52	3,47	3,42	3,37	3,32	3,28	3,24	3,20	3,16	
17,		3,12	3,08	3,04	3,00	2,96	2,92	2,88	2,84	2,80	2,76	
18,		2,72	2,68	2,64	2,60	2,56	2,52	2,49	2,46	2,43	2,40	
19,		2,37	2,34	2,31	2,28	2,25	2,22	2,19	2,16	2,13	2,10	
10 g 60°		5,	6,40	6,10	5,83	5,63	5,43	5,24	5,06	4,89	4,73	4,58
		6,	4,44	4,30	4,17	4,05	3,94	3,83	3,72	3,61	3,50	3,41
		7,	3,32	3,23	3,14	3,05	2,97	2,90	2,83	2,76	2,70	2,64
	8,	2,58	2,52	2,46	2,40	2,35	2,29	2,23	2,18	2,13	2,09	
	9,	2,05	2,00	1,96	1,92	1,88	1,84	1,80	1,76	1,72	1,69	
	10,	1,66	1,63	1,60	1,57	1,54	1,51	1,48	1,45	1,42	1,39	
	11,	1,37	1,35	1,33	1,30	1,28	1,26	1,23	1,21	1,19	1,17	
	12,	1,15	1,13	1,11	1,09	1,07	1,05	1,04	1,03	1,02	1,00	
	13,	0,983	0,966	0,949	0,932	0,915	0,898	0,881	0,864	0,847	0,830	
	14,	0,816	0,802	0,788	0,774	0,760	0,746	0,733	0,721	0,710	0,699	
	15,	0,688	0,677	0,667	0,658	0,650	0,642	0,634	0,626	0,618	0,610	
	16,	0,602	0,594	0,586	0,578	0,570	0,562	0,554	0,546	0,538	0,530	
	17,	0,522	0,514	0,506	0,498	0,490	0,482	0,474	0,466	0,459	0,452	
	18,	0,445	0,438	0,432	0,426	0,420	0,414	0,408	0,402	0,396	0,390	
	19,	0,384	0,378	0,372	0,366	0,360	0,354	0,348	0,342	0,336	0,330	

Appendix 1 Relation between penetration and H-values (Swedish Committee on Piston Sampling, Supplement in Kallstenius & Hallén 1963)

Cone type	Penetration mm	0	1	2	3	4	5	6	7	8	9	
100 30 <sup>g</sup>	2,	9,56	9,20	8,86	8,54	8,24	7,98	7,72	7,48	7,24	7,02	
	3,	6,80	6,58	6,36	6,14	5,92	5,70	5,48	5,28	5,10	4,94	
	4,	4,78	4,62	4,46	4,32	4,19	4,06	3,94	3,84	3,74	3,64	
	5,	3,55	3,46	3,38	3,30	3,22	3,14	3,07	3,00	2,93	2,86	
	6,	2,79	2,73	2,67	2,61	2,55	2,49	2,43	2,37	2,31	2,25	
	7,	2,19	2,13	2,07	2,02	1,97	1,92	1,87	1,83	1,79	1,75	
	8,	1,71	1,67	1,63	1,59	1,55	1,52	1,49	1,46	1,43	1,40	
	9,	1,37	1,34	1,31	1,28	1,25	1,22	1,19	1,16	1,13	1,10	
	10,	1,08	1,06	1,04	1,02	1,00	0,980	0,960	0,940	0,920	0,900	
	11,	0,880	0,862	0,848	0,835	0,822	0,809	0,796	0,783	0,770	0,757	
	12,	0,744	0,731	0,718	0,706	0,694	0,682	0,670	0,660	0,650	0,640	
	13,	0,630	0,620	0,610	0,600	0,590	0,580	0,570	0,560	0,550	0,540	
	14,	0,530	0,520	0,510	0,505	0,500	0,495	0,490	0,485	0,480	0,475	
	15,	0,470	0,465	0,460	0,455	0,450	0,445	0,440	0,435	0,430	0,425	
	16,	0,420	0,415	0,410	0,405	0,400	0,395	0,390	0,385	0,380	0,375	
	17,	0,370	0,365	0,360	0,355	0,350	0,345	0,340	0,335	0,330	0,325	
	18,	0,320	0,315	0,310	0,305	0,300	0,296	0,292	0,288	0,285	0,282	
	19,	0,280	0,278	0,276	0,274	0,272	0,270	0,268	0,266	0,264	0,262	
	60 60 <sup>g</sup>	4,	0,890	0,840	0,795	0,765	0,735	0,710	0,685	0,660	0,637	0,616
5,		0,595	0,576	0,558	0,542	0,526	0,512	0,498	0,486	0,474	0,463	
6,		0,452	0,441	0,430	0,419	0,408	0,397	0,386	0,375	0,364	0,354	
7,		0,344	0,334	0,324	0,315	0,306	0,298	0,290	0,282	0,274	0,268	
8,		0,260	0,254	0,248	0,244	0,238	0,233	0,227	0,222	0,218	0,214	
9,		0,210	0,206	0,202	0,198	0,194	0,190	0,186	0,182	0,178	0,174	
10,		0,170	0,167	0,164	0,161	0,158	0,155	0,152	0,149	0,146	0,143	
11,		0,140	0,137	0,135	0,133	0,131	0,129	0,127	0,125	0,123	0,121	
12,		0,119	0,117	0,115	0,113	0,111	0,109	0,107	0,105	0,103	0,101	
13,		0,100	0,0985	0,0970	0,0955	0,0940	0,0925	0,0910	0,0895	0,0880	0,0865	
14,		0,0850	0,0835	0,0820	0,0805	0,0790	0,0775	0,0760	0,0745	0,0730	0,0715	
15,		0,0700	0,0690	0,0680	0,0670	0,0660	0,0650	0,0640	0,0630	0,0620	0,0610	
16,		0,0600	0,0590	0,0580	0,0570	0,0560	0,0550	0,0540	0,0530	0,0520	0,0510	
17,		0,0500	0,0495	0,0490	0,0485	0,0480	0,0475	0,0470	0,0465	0,0460	0,0455	
18,		0,0450	0,0445	0,0440	0,0435	0,0430	0,0425	0,0420	0,0415	0,0410	0,0405	
19,		0,0400	0,0397	0,0394	0,0391	0,0388	0,0385	0,0382	0,0379	0,0376	0,0373	
10 60 <sup>g</sup>		5,	0,110	0,106	0,102	0,0983	0,0948	0,0915	0,0884	0,0855	0,0830	0,0805
		6,	0,0780	0,0755	0,0730	0,0710	0,0690	0,0670	0,0650	0,0630	0,0613	0,0598
		7,	0,0583	0,0568	0,0553	0,0538	0,0523	0,0509	0,0495	0,0482	0,0470	0,0459
	8,	0,0449	0,0439	0,0429	0,0420	0,0411	0,0402	0,0393	0,0384	0,0376	0,0368	
	9,	0,0360	0,0352	0,0345	0,0338	0,0331	0,0324	0,0317	0,0310	0,0303	0,0296	
	10,	0,0290	0,0285	0,0280	0,0275	0,0270	0,0265	0,0260	0,0255	0,0250	0,0246	
	11,	0,0242	0,0238	0,0234	0,0230	0,0226	0,0222	0,0218	0,0214	0,0210	0,0206	
	12,	0,0203	0,0200	0,0197	0,0194	0,0191	0,0188	0,0185	0,0182	0,0179	0,0176	
	13,	0,0173	0,0170	0,0167	0,0164	0,0161	0,0158	0,0155	0,0152	0,0149	0,0146	
	14,	0,0143	0,0140	0,0137	0,0134	0,0132	0,0130	0,0128	0,0126	0,0124	0,0122	
	15,	0,0120	0,0118	0,0116	0,0114	0,0112	0,0110	0,0108	0,0107	0,0105	0,0104	
	16,	0,0102	0,0101	0,0099	0,0098	0,0096	0,0095	0,0093	0,0092	0,0090	0,0089	
	17,	0,0087	0,0086	0,0084	0,0083	0,0081	0,0080	0,0078	0,0077	0,0076	0,0075	
	18,	0,0074	0,0073	0,0072	0,0071	0,0070	0,0069	0,0068	0,0068	0,0067	0,0067	
	19,	0,0066	0,0066	0,0065	0,0065	0,0064	0,0064	0,0063	0,0063	0,0062	0,0062	

Appendix 2 Relation between penetration and shear strength (Swedish Committee on Piston Sampling, Supplement in Kallstenius & Hallén 1963)

Site Hole Depth m	Unit weight t/m <sup>3</sup>	Natural water content w %	Fineness number w <sub>F</sub> %	Shear strength (cone test)		Sensitivity (cone test)			H <sub>3</sub> /H <sub>1</sub> (S <sub>t</sub> )	Liquid limit		κ · 10 <sup>3</sup> ohm <sup>-1</sup> cm <sup>-1</sup>
				Un-remoulded t/m <sup>2</sup>	Re-moulded t/m <sup>2</sup>	S <sub>t</sub>	H <sub>3</sub>	H <sub>1</sub>		w <sub>L</sub> %	pH	
<u>Utby 99</u>												
3	1.70	52	54	2.79	0.260	11	141	15.4	9.1	55	5.2	0.320
5	1.67	54	52	2.79	0.140	20	141	8.25	18	51	5.4	0.533
6	1.70	41	39	2.73	0.127	22	136	7.43	19	49	5.6	0.548
7	1.68	54	50	2.73	0.117	24	136	6.81	20	52	6.2	0.533
8	1.68	54	50	2.73	0.099	28	136	5.79	24	48	6.4	0.588
9	1.70	52	48	2.61	0.099	27	123	5.79	22	46	6.3	0.727
10	1.70	52	48	2.67	0.097	28	132	5.69	23	52	6.3	0.910
11	1.72	50	49	2.86	0.140	21	145	8.25	18	51	6.1	1.00
12	1.70	52	43	2.86	0.042	68	145	2.40	61	53	6.8	1.05
13	1.70	52	52	2.86	0.170	17	145	10.0	15	49	6.9	1.11
14	1.72	51	40	3.00	0.044	68	153	2.52	61	41	7.0	1.05
15	1.76	49	39	3.55	0.037	97	189	2.09	90	36	7.2	0.975
16	1.72	49	41	3.55	0.038	92	189	2.18	87	42	7.0	1.33
17	1.72	55	42	3.55	0.046	78	189	2.64	72	42	6.9	1.43
18	1.72	55	44	3.55	0.037	97	189	2.09	91	41	7.1	1.60
19	1.72	55	47	3.55	0.045	79	189	2.58	73	50	7.1	1.82
20	1.72	53	41	3.64	0.045	81	196	2.58	76	43	7.0	1.91
<u>Utby 620</u>												
4	1.61	77	52	2.79	0.014	195	141	0.816	173	49	7.1	1.43
5	1.64	62	54	2.79	0.020	139	141	1.15	122	51	7.5	1.38
6	1.62	63	61	2.86	0.021	136	145	1.19	122	50	7.3	1.45
7	1.61	67	54	3.07	0.022	138	158	1.26	125	59	6.9	1.18
8	1.61	73	63	2.79	0.027	105	141	1.51	93	58	7.2	1.9
9	1.61	70	60	3.00	0.031	99	153	1.72	89	57	7.5	2.0
10	1.62	67	62	3.00	0.044	69	153	2.52	61	58	7.0	1.82
11	1.61	68	55	3.64	0.067	55	196	3.83	55	55	7.0	1.86
12	1.64	66	65	3.30	0.058	57	173	3.32	52	63	6.6	2.76
13	1.65	66	60	3.38	0.088	39	178	5.11	35	56	6.9	2.35
14	1.64	65	63	3.74	0.137	28	204	8.10	25	61	7.1	2.58
15	1.64	62	62	3.55	0.170	21	189	10.0	19	57	6.9	2.58
16	1.68	61	57	3.84	0.121	32	208	7.05	30	60	6.8	2.50
17	1.71	53	52	3.84	0.178	22	208	10.4	20	46	6.9	1.85
18	1.74	58	59	4.62	0.206	23	281	12.0	23	46	6.9	1.60
19	1.72	47	46	4.94	0.129	38	313	7.56	41	-	-	-

Appendix 3 Geotechnical data for Test Site at Utby, Hole 99 and 620  
(Continued on next page)

Site Hole Depth m	Unit weight t/m <sup>3</sup>	Natural water content w %	Fineness number w <sub>F</sub> %	Shear strength (cone test)		Sensitivity (cone test) S <sub>t</sub>	H <sub>3</sub>	H <sub>1</sub>	H <sub>3</sub> /H <sub>1</sub> (S <sub>t</sub> )	Liquid limit		κ · 10 <sup>3</sup> ohm <sup>-1</sup> cm <sup>-1</sup>
				Un-remoulded t/m <sup>2</sup>	Re-moulded t/m <sup>2</sup>					w <sub>L</sub> %	pH	
<u>Utby 658</u>												
5	1.57	71	55	2.61	0.024	108	128	1.37	94	60	6.1	0.364
7	1.57	67	38	2.61	0.019	117	128	1.07	101	53	6.3	0.564
8	1.53	73	61	2.55	0.014	178	124	0.816	152	51	6.4	0.645
9	1.59	73	61	2.79	0.013	214	141	0.746	189	50	6.5	0.770
10	1.59	69	53	3.07	0.012	256	158	0.688	229	51	6.7	0.890
11	1.61	70	54	3.46	0.011	303	183	0.650	282	47	6.7	0.975
12	1.61	70	50	3.30	0.011	312	173	0.626	276	48	6.7	1.11
13	1.56	70	56	2.93	0.010	287	149	0.602	248	45	7.2	1.03
14	1.62	65	54	2.93	0.011	279	149	0.618	241	48	6.9	1.03
15	1.62	63	54	3.14	0.013	249	163	0.721	226	50	6.7	1.11
16	1.57	67	53	3.00	0.015	206	153	0.830	184	51	6.6	1.11
17	1.67	59	49	3.00	0.016	189	153	0.898	170	47	6.6	1.05
18	1.67	57	50	3.14	0.021	147	163	1.21	134	45	7.0	0.678
19	1.62	61	50	2.86	0.025	116	145	1.39	104	43	6.6	0.952
<u>Utby 680</u>												
4	1.64	58	55	2.79	0.110	24	141	6.93	21	52	6.4	0.417
5	1.64	58	52	2.59	0.084	33	141	4.84	29	51	6.4	0.588
6	1.64	63	57	2.79	0.380	32	141	5.11	28	54	6.7	0.533
7	1.64	64	65	2.70	0.043	65	141	2.46	60	51	6.6	0.625
8	1.64	60	63	2.70	0.044	64	141	2.52	56	49	6.9	0.755
9	1.64	63	65	2.79	0.024	115	141	1.37	103	49	6.9	0.910
10	1.64	54	50	3.14	0.024	132	163	1.35	121	47	7.1	0.975
11	1.64	61	64	3.07	0.018	174	158	1.00	158	49	7.0	1.38
12	1.64	64	59	3.00	0.014	210	153	0.816	188	47	7.1	1.38
13	1.64	63	57	3.46	0.013	258	183	0.774	236	45	7.0	1.08
14	1.67	57	58	3.64	0.016	230	196	0.898	218	45	7.3	1.14
15	1.67	59	67	4.19	0.021	203	241	1.17	203	47	7.5	1.14
16	1.65	60	61	4.06	0.027	153	230	1.51	152	46	7.1	1.14
17	1.67	57	60	3.84	0.030	126	208	1.72	121	42	7.2	1.03
18	1.71	52	58	3.64	0.031	117	196	1.76	111	45	7.1	0.975
19	1.72	48	46	2.31	0.050	47	110	2.83	39	41	7.1	1.00
20	1.76	48	44	3.64	0.085	43	196	4.93	40	38	7.0	0.690

Appendix 3 Geotechnical data for Test Site at Utby, Hole 658 and 680

Site Depth m	Unit weight t/m <sup>3</sup>	Natural water content w %	Fineness number w F %	Shear strength (cone test)		Sensi- tivity (cone test) S <sub>t</sub>	H <sub>3</sub>	H <sub>1</sub>	H <sub>3</sub> /H <sub>1</sub> (S <sub>t</sub> )	κ · 10 <sup>3</sup> ohm <sup>-1</sup> cm <sup>-1</sup>
				Un- remoulded t/m <sup>2</sup>	Re- moulded t/m <sup>2</sup>					
<u>Ellesbo</u>										
1	1.47	93	94	1.34	0.178	7.5	60	10.4	5.8	1.70
2	1.44	104	83	1.34	0.102	14	60	5.8	10.4	1.51
3	1.38	103	92	1.31	0.088	15	58.5	5.11	11.4	1.86
4	1.48	100	80	1.25	0.055	23	55.8	3.1	18.0	1.45
5	1.48	90	73	1.02	0.025	41	45.9	1.42	32.4	1.25
6	1.41	91	72	0.88	0.023	39	40.0	1.3	30.8	1.20
7	1.51	87	66	1.08	0.023	47	49.0	1.3	37.6	1.12
8	1.51	84	66	1.10	0.017	66	50.0	0.95	52.5	0.87
9	1.53	80	55	1.28	< 0.006	> 210	57.1	< 0.33	> 173.0	1.01

Appendix 4 Geotechnical data for the Test Site at Ellesbo



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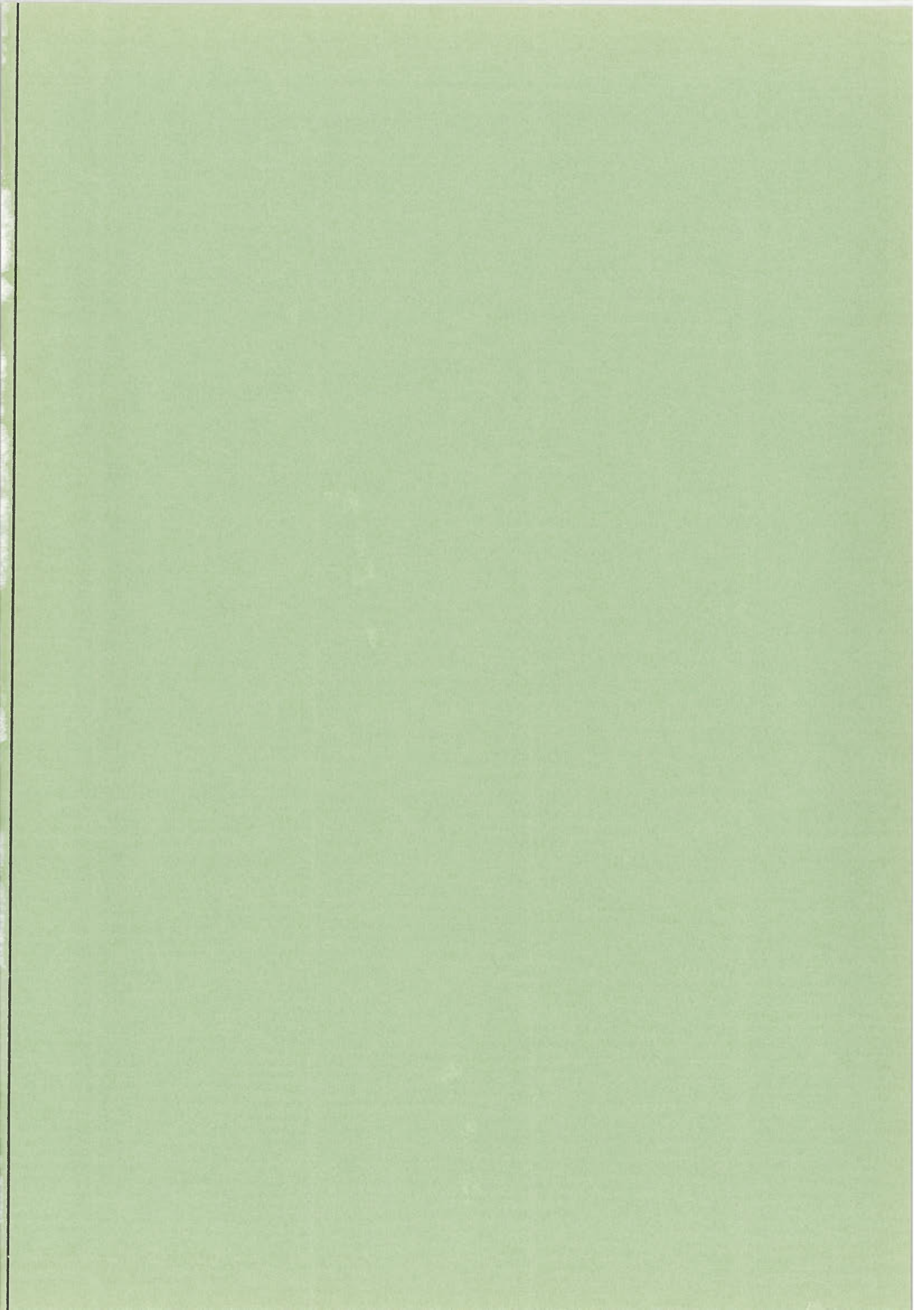
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LIST OF PROCEEDINGS  
OF THE SWEDISH GEOTECHNICAL  
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No.		Sw. Crs. Price
1.	Soil Sampler with Metal Foils. Device for Taking Undisturbed Samples of Very Great Length. <i>W. Kjellman, T. Kallstenius and O. Wager</i> .....	1950 4:—
2.	The Vane Borer. An Apparatus for Determining the Shear Strength of Clay Soils Directly in the Ground. <i>Lyman Cadling and Sten Odenstad</i> .....	1950 4:—
3.	Device and Procedure for Loading Tests on Piles. <i>W. Kjellman and Y. Liljedahl</i> .....	1951 Out of print
4.	The Landslide at Sköttorp on the Lidan River, February 2, 1946. <i>Sten Odenstad</i> .....	1951 4:—
5.	The Landslide at Surte on the Göta River, September 29, 1950. <i>Bernt Jakobson</i> .....	1952 8:—
6.	A New Geotechnical Classification System. <i>W. Kjellman, L. Cadling and N. Flodin</i> .....	1953 Out of print
7.	Some Side-Intake Soil Samplers for Sand and Gravel. <i>Torsten Kallstenius</i> .....	1953 4:—
8.	Influence of Sampler Type and Testing Method on Shear Strength of Clay Samples. <i>Bernt Jakobson</i> .....	1954 4:—
9.	Some Relations between Stress and Strain in Coarse-Grained Cohesionless Materials. <i>W. Kjellman and B. Jakobson</i> ....	1955 4:—
10.	Accurate Measurement of Settlements. <i>W. Kjellman, T. Kallstenius and Y. Liljedahl</i> .....	1955 4:—
11.	Influence of Organic Matter on Differential Thermal Analysis of Clays. <i>Lennart Silfverberg</i> .....	1955 4:—
12.	Investigations of Soil Pressure Measuring by Means of Cells. <i>Torsten Kallstenius and Werner Bergau</i> .....	1956 4:—
13.	Pore Water Pressure Measurement in Field Investigations. <i>Torsten Kallstenius and Alf Wallgren</i> .....	1956 4:—
14.	A New Approach to the Determination of the Shear Strength of Clay by the Fall-Cone Test. <i>Sven Hansbo</i> ....	1957 4:—
15.	Chemical Determination of Soil Organic Matter. A Critical Review of Existing Methods. <i>Lennart Silfverberg</i> .....	1957 4:—
16.	Mechanical Disturbances in Clay Samples Taken with Piston Samplers. <i>Torsten Kallstenius</i> .....	1958 6:—
17.	Measurements of the pressures of Filling Materials against Walls .....	1959 6:—
	Earth Pressure from Friction Soils. A Report on Half Scale Tests. <i>Arne Rinkert.</i>	
	Measurements in Grain Silos during Filling and Emptying. <i>Werner Bergau</i>	
18.	Consolidation of Clay, with Special Reference to Influence of Vertical Sand Drains. A Study Made in Connection with Full-Scale Investigations at Skå-Edeby. <i>Sven Hansbo</i> ....	1960 12:—
19.	Standard Piston Sampling. A Report by the Swedish Committee on Piston Sampling .....	1961 6:—
20.	A Theoretical Study of the Failure Conditions in Saturated Soils. <i>Justus Osterman</i> .....	1962 6:—
21.	Studies on Clay Samples Taken with Standard Piston Sampler. <i>Torsten Kallstenius</i> .....	1963 16:—
22.	Salt in Swedish Clays and its Importance for Quick Clay Formation. Results from some Field and Laboratory Studies. <i>Rolf Söderblom</i> .....	1969 25:—





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