STATENS GEOTEKNISKA INSTITUT
SWEDISH GEOTECHNICAL INSTITUTE

Quick clay in Sweden

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Report 65

LINKÖPING 2004

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Rapport
Report **No 65**

Quick clay in Sweden

- Processes leading to formation of quick clay
- Geological and hydrogeological conditions for formation of quick clay in nature
- Mapping of quick clay formations by geotechnical and geophysical methods.

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LINKÖPING 2004

Rapport/Report	Swedish Geotechnical Institute SE–581 93 Linköping
Order	SGI Information service Tel: +46 13 20 18 04 Fax: +46 13 20 19 09 E-mail: info@swedgeo.se Internet: http://www.swedgeo.se
ISSN ISRN	0348-0755 SGI-R--04/65--SE
Project number SGI Dnr SGI	12216 1-0303-0129

Preface

This report presents a study of quick clays in Sweden. Quick clays involve considerable risks, for example in connection with stability problems, where small initial slips may evolve into large landslides involving the entire quick clay formation. The sliding masses become consistencies of heavy liquids, which can flow over large distances and cause extensive damage to anything in their path. The formation of quick clay may also cause part of the structure to break down. Thereby the associated resistance to compression and the shear strength are reduced. This will increase the risk of both settlements and stability problems.

The report deals with geological prerequisites and chemical and mineralogical compositions and processes leading to the formation of quick clays. It also deals with the geotechnical and geophysical methods that can be used to find and map the extension of existing quick clay formations. The literature survey on the chemical and mineralogical compositions and processes leading to the formation of quick clays has previously been presented in Swedish in SGI Varia No. 526 (Rankka, 2003). A detailed data report concerning the geophysical resistivity measurements included in the present report has also been presented by the Department of Engineering Geology at Lund University (Leroux and Dahlin, 2003).

The report is intended for geotechnical engineers and all agencies, authorities and offices involved in the planning of land use and of preservation of existing land and structures.

The project has been financed jointly by the Swedish Rescue Services Agency, the Swedish Geotechnical Institute and the Department of Engineering Geology at Lund University. The geophysical investigations have been performed by the Department of Engineering Geology at Lund University and the geotechnical field investigations by FMGeo AB under supervision by the Swedish Geotechnical Institute. The project has also made use of data from previous SGI investigations and data from Skepplanda that has kindly been put at our disposal by GF Konsult AB.

The authors wish to express their gratitude to those who have worked on the project, those who have contributed data and other help, and the communities and landowners who have provided access to the test areas.

Linköping, Göteborg and Lund, October 2004

The authors

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Summary

The designation “quick clay” refers to a clay whose structure collapses completely at remoulding and whose shear strength is thereby reduced almost to zero. Quick clay is defined as a clay with a sensitivity of 50 or more and a fully remoulded shear strength of less than 0.4 kPa. The latter value corresponds to a penetration of 20 mm by the 60g cone with 60^o tip angle in the fall-cone test. The sensitivity is the relation between the undisturbed and the fully remoulded undrained shear strength.

The classification of less sensitive clays is made according to Table S1.

Table S1. Classification of clay with respect to sensitivity.

Designation	Sensitivity
Low sensitivity	< 8
Medium sensitivity	8 – 30
High sensitivity	> 30

Quick clay is formed through slow geological processes. Most quick clays have been formed in sediments that were deposited in sea water at the last deglaciation. The land then heaved as the inland ice retreated, leaving the clay deposits located above sea level. The clay deposits have then been subjected to leaching, whereby the ion concentration in the pore water has changed. The leaching has been caused by infiltration of rain water, artesian water pressures in underlying permeable soil or rock, and by diffusion. These processes are very slow and entail that quick clay is found more often in clay deposits with moderate thickness and less frequently in thick deposits, where it only occurs close to permeable layers and the ground surface. However, there are also quick clays that have been deposited in brackish and sweet water. Through contact with organic substances in peat and other humus-rich soils, for example, the ion concentration in the pore water may change and the clay become quick.

A clay consists of solid particles forming a skeleton and gas and/or liquid in the voids between the particles (or aggregates of particles). The particles contain mainly clay minerals, but also other minerals are present. The clay minerals have been formed through chemical weathering of mica, feldspar and amphibolite, among other rock minerals. Examples of clay minerals are illite, montmorillonite and chlorite. A common feature of the clay minerals is that they are built up from plane networks of aluminium hydroxide or magnesium hydroxide and silica oxide. A certain number of the positive ions in the clay minerals are replaced by positive ions of a lower valency when the mineral comes into contact with a fluid. The surface of the clay mineral then becomes negatively charged. To compensate for this, the clay mineral attracts positive ions from the fluid, for example K^+, Na^+ and Ca^{2+}. The concentration of the positive ions in the fluid determines the size of the "sphere" outside the clay particle that is required to compensate for the surface charge; the higher the ion concentration in the fluid, the smaller the sphere. This sphere is called the diffuse double layer.

The structure of the clay sediments depends on the ion concentration in the water in which they are deposited. If the particles are deposited in sea water with a high ion concentration, the sphere will be small and the particles will move closer to each other in the suspension. The attractive forces between the particles will then dominate and may cause the particles to flocculate, whereby large aggregates of particles will sediment without any preferred orientation and thereby create a clay with a high void ratio. On the other hand, if the particles are deposited in fresh water, the repulsive forces between the particles will dominate and prevent them from coming close together while suspended. This will result in the formation of a clay with a larger number of oriented particles and a lower void ratio compared to a clay deposited in sea water.

Research on why certain clays become quick started as far back as the 40's. Rosenqvist (1946) presented the theory that leaching of salts in marine clays resulted in the clays becoming quick. Further research has shown that a low salt content is a prerequisite for high sensitivity, but that this is not always sufficient to make the clay quick. Thus, there are many marine clays with a low salt content which are not quick or particularly sensitive. One reason for this is that the composition of the ions in the pore water has a major influence on the formation of quick clay. The ion composition depends, apart from leaching, on a possible weathering of the clay minerals, whereby ions may be released from the particles to the pore water. The larger the content of univalent ions in relation to the total content of ions in the pore water, the more favorable conditions for high sensitivity. The concentration of multivalent ions will thereby be lower and each clay particle has to have a large diffuse double layer in order to obtain a neutral charge. A re-flocculation after remoulding of the soil is thereby not possible, but a material may be created with clay particles suspended in the pore water. If the void ratio in the undisturbed clay is high, the water content may then be significantly higher than the liquid limit, which means that the remoulded clay behaves like a liquid.

The sensitivity may increase when organic and a number of inorganic substances affect the clay sediments. These substances act as dispersing agents, which remove positive ions from the surfaces of the minerals and absorb them. This causes an increasing negative charge of the surface of the clay particle and an increase in the extent of the diffuse double layer.

Brenner et al. (in Brand & Brenner, 1981) constructed a chart for the principles of quick clay formation. The chart is shown in Fig. S.1.

Quick clays are dominated by non-swelling clay minerals with low activity. Smectites, such as montmorillonite and saponite, are among the swelling clay minerals. The activity, a_c, is defined as

$$a_c = \frac{I_p}{l_c}$$

where $I_p = w_L - w_p$ (w_L = liquid limit, w_p = plastic limit)
l_c = clay content, per cent in weight of the total mass of fines

The clay is considered as low-active when the activity is less than 0.75.

Quick clays have liquid limits that are lower than their natural water contents. Compilations made by the Göta Älv Committee (Statens offentliga utredningar, 1962) and Larsson & Åhnberg (2003) show that the ratio between the water content and the liquid limit is normally higher than 1.1 in quick clays.

The preconditions for the formation of quick clay imply that such clays occur only in areas where the local geology and geohydrology create these preconditions. A flowchart for use in a screening process to distinguish such areas has been proposed, Fig. S2.

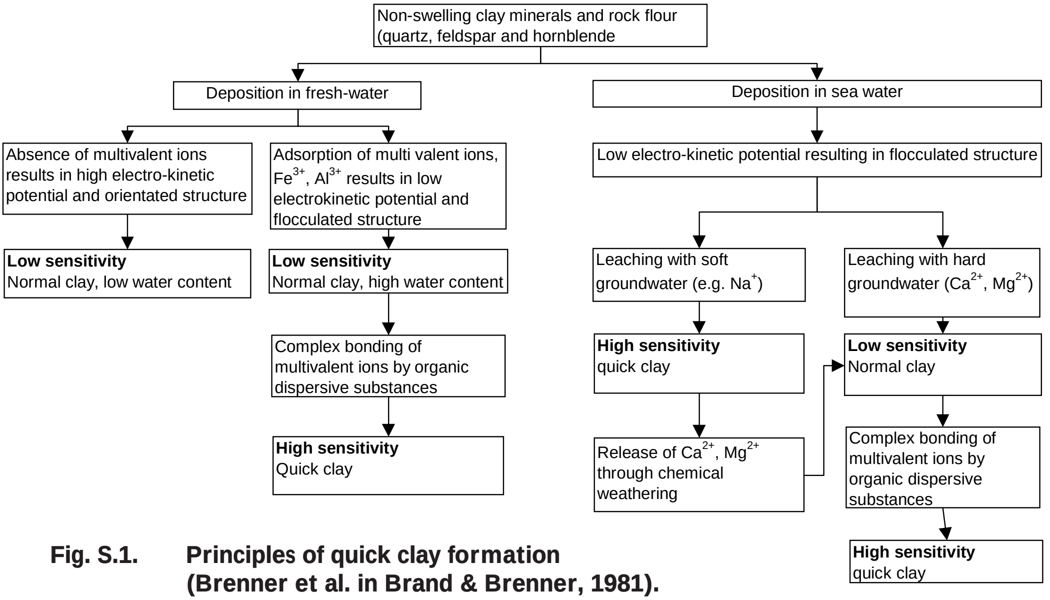

Fig. S.1. **Principles of quick clay formation (Brenner et al. in Brand & Brenner, 1981).**

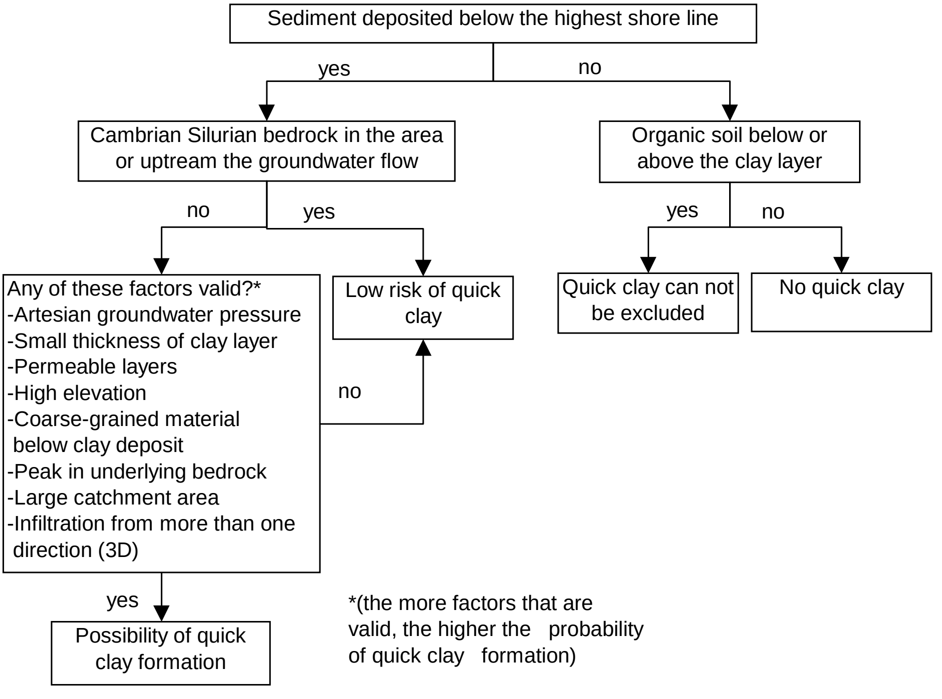

Fig. S2. **Flowchart for location of areas with prerequisites for quick clay formation.**

Fulfilment of the preconditions indicates only the possibility of a quick clay formation. The actual presence of quick clay has to be established by geotechnical site investigations and the extent of a quick clay formation can only be found by conducting investigations of the whole area.

Mapping of quick clay formations can be performed with a combination of laboratory tests, soundings and surface resistivity measurements. There is no field test for measuring the remoulded shear strength with sufficient accuracy and resolution for a detailed classification of the sensitivity in highly sensitive and quick clays according to the Swedish classification. This property therefore has to be measured in the laboratory. The undrained shear strength can be measured in the field by field vane tests or CPT tests, or by laboratory tests on undisturbed samples.

Good indications of the relative sensitivity in different parts of an area can be obtained with any sounding method that provides accurate measurement of the total penetration force. The most reliable of these methods, in which also a rough check of the estimated sensitivity can be obtained by the measurement of sleeve friction, is the CPT test combined with measurement of the total penetration force. However, also less elaborate methods yield fairly good information. The relative values from the soundings have to be checked and calibrated by actual measurements of the sensitivity at selected points.

Surface resistivity measurements can be a useful aid in areas where the quick clay formation has originated from leaching of salts. The method provides information on how far the leaching process has proceeded in different parts of the investigated sections, and by combining several measuring sections, a 3-dimensional picture of the soil mass can be obtained. The method can only be used in combination with the other test methods, but provides a continuous picture of the soil mass in contrast to the point information obtained by the others.

Introduction

Background

Almost all landslides involving clays in Sweden, Norway and Canada where there have been major consequences can be designated as quick clay slides. The final extent of a slide in clay is governed largely by the sensitivity of the clay to disturbance and particularly the presence of quick clay. Quick clay is therefore a significant factor for the risks involved with slopes of low stability. In assessments of risk areas, it is thus necessary to determine whether quick clay is present, and if so, to what extent. This is the case both in general mapping of slide risks and in specific slope stability investigations.

The only reliable method for the detection of quick clay used so far in Sweden is to take undisturbed samples and to perform fall-cone tests on the clay in its undisturbed and remoulded states. This is also the method that has been used in practice. Mapping of quick clay formations in this way requires extensive sampling. For economic reasons, the method is therefore not practically applicable to a detailed mapping of the extent of a quick clay formation, but only at a few points in selected investigated sections.

Quick clays are common in those parts of the world that have geological and climatic conditions similar to those in Sweden, for example Norway and Canada. Considerable effort has therefore been put into studying the basic conditions for the formation of quick clay and its properties. Much of this research was carried out during the 50's and 60's.

The project "Mapping of quick clay"

In 2002, a project entitled "Mapping of quick clay" was started at the Swedish Geotechnical Institute. This was an interdisciplinary project aiming at gathering knowledge among specialists in soil mechanics, geology, hydrogeology, geophysics and soil chemistry, and presenting this in a uniform way. The aim was also to develop a methodology for rational use of this knowledge in order to find quick clay formations and map their extent. The project was divided into the following parts:

1. Gathering of present knowledge concerning quick clay.
2. Geological and hydrogeological conditions for quick clay formation.
3. Control of estimated preconditions for quick clay formation in leached marine clay deposits by a geophysical method.
4. Geotechnical investigation of the presence of quick clay, its stratification and other properties by sampling and investigation of the possibility of mapping quick clay formations using common sounding methods.

This report deals with the results of this project.

Chapter 1.

Processes leading to formation of quick clay – a literature survey

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The author wishes to acknowledge the comments and views on this section which have been received from:
Tor Løken, Norwegian Geotechnical Institute
Roland Pusch, Geodevelopment AB
Karsten Håkansson, Claes Alén and Bo Lind, Swedish Geotechnical Institute

1.1 COMPOSITION AND STRUCTURE OF CLAY

In order to understand how and under what conditions a clay can be transformed into a quick clay, it is necessary to study the composition and structure of clay. Clay is composed of solid, liquid and gaseous substances. The solid particles form a skeleton and the voids between the particles are filled with gas or liquid, or a mixture of both.

1.1.1 Clay minerals

Minerals are small components of the earth's crust, occurring as chemically and physically homogeneous solid bodies. They consist of a basic element, an alloy or, which is most common, a chemical compound (Loberg, 1980). Silicates, i.e. compounds of silicon and oxygen, make up more than 90% of the Earth's continental crust. The most common clay minerals are kaolinite, illite (hydrated mica), smectite (montmorillonite, saponite etc.) and chlorite, see Table 1.1. Illite is the dominating clay mineral in Sweden. Clay minerals are so called secondary minerals that have been formed by weathering of other silicates such as mica, amphibolites and feldspar. Chemical weathering is a process whereby a mineral or rock is broken down by the action of water; alone or in combination with substances from the air or the soil layers. This process often occurs at elevated temperatures. A chemical weathering of potassium feldspar, $K[AlSi_3O_8]$, can thus result in the formation of the clay mineral kaolinite. The chemical weathering process can be written schematically as

$$4K[AlSi_3O_8] + 22H_2O \rightarrow 4K^+ + 4OH^- + Al_4[Si_4O_{10}](OH)_8 + 8H_4SiO_4$$

Table 1.1 Compilation of data for different materials. (After Mitchell, 1976.)

Clay mineral	Chemical designation	Bonds between layers	Ion exchange	Capacity of cation exchange (meq/100g)*
Kaolinite	$Al_4\ Si_4O_{10}(OH)_8$	O-OH, strong	Small	3 – 15
Illite	$(K,H_2O)_2Si_8(Al,Mg,Fe)_{4,6}O_{20}(OH)_4$	K-ions, strong	Some Si always exchanged with Al. K provides balance between the layers	10 – 40
Montmorillonite (smectite group)	$Si_8(Al_{3.34}Mg_{0.66})O_{20}(OH)_4$	O-O, very weak, swellable	Mg exchanged with Al	80 – 150
Chlorite	$(SiAl)_8(Mg,Fe)_6O_{20}(OH)_4$ (2:1 layer)	$(MgAl)_6(OH)_{12}$	Al against Si in 2:1 layer Al against Mg in intermediary layer	10 – 40

* meq = milliequivalents, i.e. the amount of the substance that in the chemical process corresponds to 1 mol of the other substance.

The type and amount of clay mineral in a weathered sediment depends mainly on the climate but also on the parent material, the drainage conditions and the local vegetation (Brenner et al. (in Brand & Brenner, 1981).

All clay minerals are built up from layers of plane networks. The networks consist of aluminium hydroxide or magnesium hydroxide (Al/Mg(O/OH) octahedrons and silica (SiO_4 tetrahedrons), Fig. 1.1. A tetrahedral coordination means that a cathodic ion is surrounded by four oxygen ions, whereas an octahedral coordination means that a central cathodic ion is surrounded by six oxygen ions (Appelo & Postma, 1994). A tetrahedral coordination has smaller cathodic ions, such as Si or Al, and octahedral coordinations have larger ions, such as Mg, Fe, Mn, C, Na and K. The stability of the structure depends on how well the cathodic ion fits in between the oxygen ions (Troedsson & Nyqvist, 1980). The radius of an oxygen ion is 1.32 nm (10^{-9} m) and a cathodic ion with a radius of 0.30 nm would theoretically have the best fit in a tetrahedral coordination. Silicon has an ion radius of 0.39 nm and is the element that fits best in between the oxygen ions, creating the most stable structure (Troedsson & Nykvist, 1980). To give further examples, a magnesium ion (Mg^{2+}) has a radius of 0.78 nm, an aluminium ion (Al^{3+}) 0.57 nm and an Fe^{3+} ion 0.67 nm.

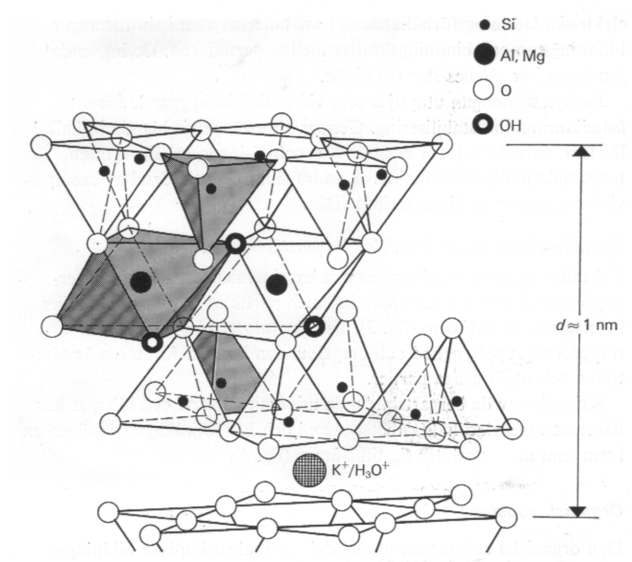

Fig. 1.1. Cluster of crystals of the clay mineral illite. (After Hansbo, 1975)

The following text is a summary of the descriptions given in “Geochemistry” by Appelo & Postma (1994) and “Fundamentals of soil behavior” by Mitchell (1976).

> The type of clay mineral formed is determined by the way in which the plane networks are stacked on top of each other. In kaolinite, octahedral layers (o) and tetrahedral layers (┤) are stacked in the pattern o ┤ o ┤ o ┤. The stacking of one tetrahedral layer with a thickness of 3 nm and one octahedral layer with a thickness of 4 nm gives a repetition of the structure every 7 nm. In smectite, the layers are stacked in a pattern of ├ o ┤ ├ o ┤ ├ o ┤ with a minimum thickness of the structure of 9.6 nm. In another group of clay minerals, of which chlorite is an example, each octahedral layer is surrounded by two tetrahedral layers and there is another octahedral interlayer between these three-layer structures in a pattern of ├ o ┤ o ├ o ┤ o ├ o ┤. A stacking of ├ o ┤ is also denoted 2:1.
>
> The mineral layers in illite and muscovite consist of networks of aluminium or magnesium hydroxide surrounded by two networks of silica oxide. A mineral layer of illite is bonded to another mineral layer by positive potassium or hydronium ions in a pattern of ├ o ┤ K^+ ├ o ┤ K^+ ├ o ┤. The bonding between the different mineral layers in illite is very strong and the counter ions are normally not exchangeable. In montmorillonite on the other hand, the ions are exchangeable and the distance between the layers can thereby increase and the material swell (denoted a swelling clay mineral).

The structural composition of montmorillonite, kaolinite, illite and chlorite is shown in Fig. 1.2.

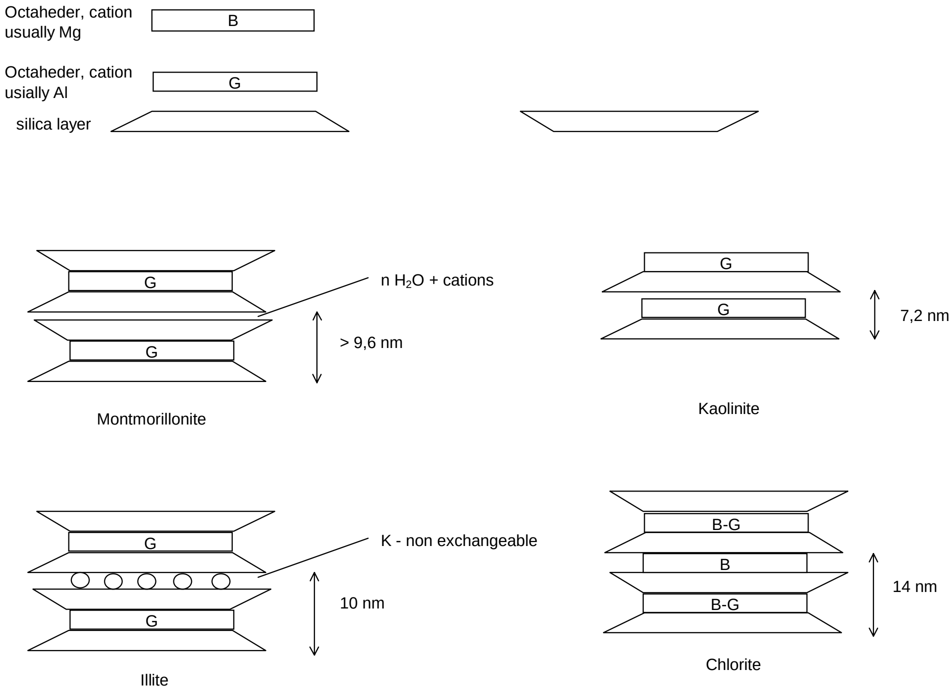

Fig. 1.2. Structural composition of montmorillonite, kaolinite, illite and chlorite, (efter Mitchell, 1976).

1.1.2 The clay particle

The solid parts of a clay are made up of small crystalline particles. The grain size of a clay particle clay is 0.002 mm or less. A soil classified as a clay contains at least 40% clay size particles by weight of the total mass of the fines, but particles of rock minerals in the silt and sand fractions are normally also present. Among the rock minerals are quartz, feldspar, carbonates and mica, for example muscovite and biotite. A clay mineral particle is made up solely of clay mineral and its grain size is normally not larger than 0.002 mm, (2,000 nm), although particles of kaolinite and illite may have sizes up to about 10,000 nm (Mitchell, 1976). Pusch (1970) studied the maximum diameter, *a*, (see Fig. 1.3) of particles with grain sizes less than 0.002 mm. The studies were performed on three illitic clays with the aid of a transmission electron microscope. The maximum diameter was found to vary between 4 and 2,000 nm.

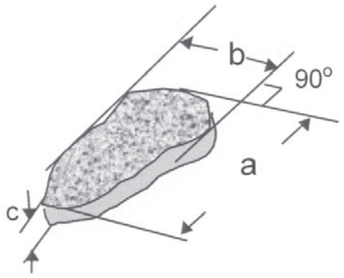

Fig. 1.3. Layout of a clay particle. (After Pusch, 1970).

The most common clay particles are flat, see Fig. 1.4. Mitchell (1976) states that a particle of the clay mineral illite is somewhat thinner at the edges and has a terraced surface.

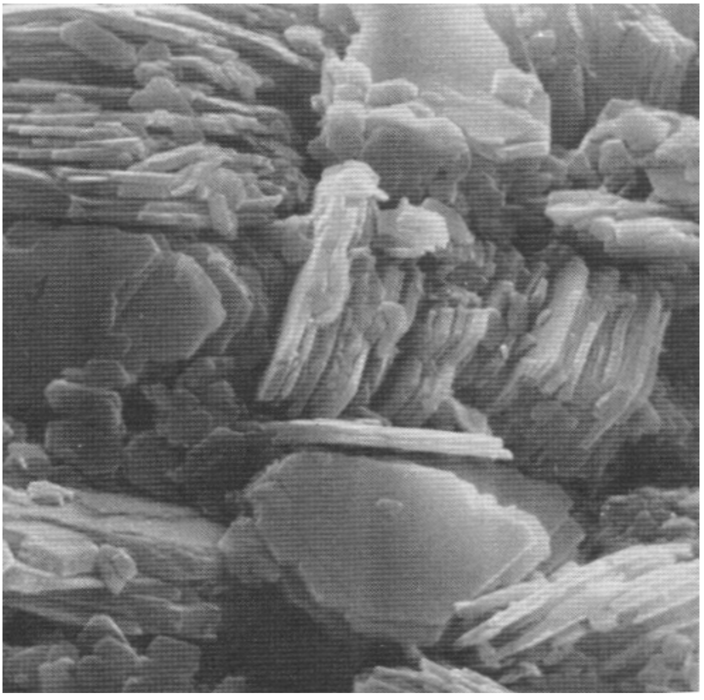

Fig. 1.4. Well crystallised kaolinite from Cornwall, England, photographed through a scanning electron microscope (after Tovey, 1971).

1.1.3 The system of clay particles and water

In a system containing both clay particles and water, there is a continuous reaction between the two phases. Clay minerals have considerable ion exchange capacities, which implies that ions from surrounding water, for example, can replace ions that are bonded weakly to the clay particle.

According to Mitchell (1976), the most common cations in pore water in clay are calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}) and potassium (K^{+}). The most common anions in soils are sulphate (SO_4^{2-}), chloride (Cl^{-}), phosphate (PO_4^{3-}) and nitrate (NO_3^{-}). Calcium is the dominating cation in fresh water, while in sea water there is a high concentration of magnesium (Talme, 1968). Sodium (Na^{+}) is though the most common ion in salt water. The possibility for one ion to be replaced by another depends mainly on the valency of the ions, access to different types of ions, the bonding strength of the ions and the size of the ions in a hydrated condition, i.e. in pore water. Smaller cations normally replace larger ones, but the opposite may also take place. For example, Ca^{2+} may be replaced by Na^{+}, Na^{+} by Ca^{2+}, Fe^{3+} by Mg^{2+}, and so on. The following series shows in decreasing order the relative bonding strength of the most common ions in the ground: Al^{3+}, Fe^{3+}, Ca^{2+}, Mg^{2+}, K^{+}, NH_4^{+}, Na^{+} (Troedsson and Nykvist, 1980). Løken (1970) found the same relation in chemical analyses on clays.

In the mineral cluster of all clay minerals, except for kaolinite, a certain number of positive ions are always replaced by ions of lower valency. This provides a negatively charged surface on the long sides of the mineral. In illite, for example, a certain number of Si^{4+} ions are always replaced by Al^{3+} ions. In order to obtain a neutral charge, the surface attracts and bonds positive ions such as K^{+}, Na^{+} and Ca^{2+}. These cations are bonded strongly in a clay with low water content. The cations that are not required to neutralise the negative charge are then instead precipitated as salt on the surface of the clay particle (Mitchell, 1976). At a high degree of water saturation, the positive ions may be dissolved while they are still retained by the negatively charged particle surface. These compensating ions in the fluid surrounding the charged particles are denoted counter ions. The counter ions do not form a well defined layer around the particle, but a more widely spread zone in which the ion concentration decreases with distance to the particle surface. This layer of positive ions is called the diffuse electrical double layer, see Fig. 1.5. The extent of the double layer is small at a high ion concentration in the pore water, while a much larger double layer is required to obtain charge neutrality at a low ion concentration. The extent of the double layer is a measure of the electrokinetic potential of the system, see Fig. 1.5. The cations are thermally mobile and an

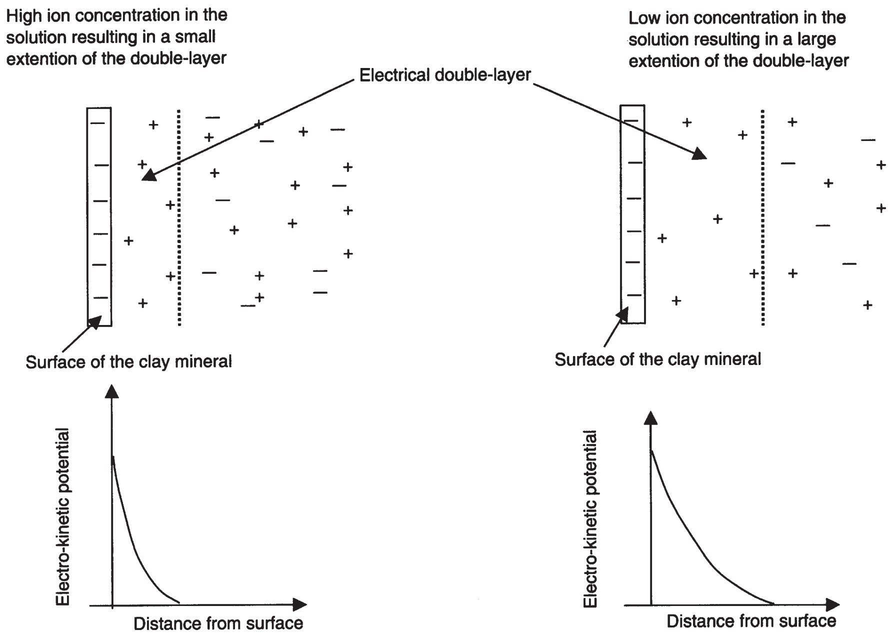

Fig. 1.5. The extent of the electrical double layer depending on the ion concentration in the pore water.

exchange of ions proceeds between the double layer and the pore water outside. An equal number of cations move in and out of the double layer per unit of time (Troedson & Nykvist, 1980).

Clay particles in a suspension influence each other with both repelling and attracting forces. The repelling forces occur when both particles have the same charge. The size of the repelling force depends on the extent of the diffuse electrical double layers around the clay particles. At high ion concentrations, the double layer is thin and the clay particles move closer to each other. The attracting forces consist of van der Waal bonding forces (forces that create fluctuating dipolar bonds), hydrogen bonds, and Coulomb attraction due to the fact that the edges of the particles may be positively charged while the base planes are negatively charged. The repelling forces are largest when the particles are suspended in fresh water. When salt is added, the repelling forces cease to dominate and the particles flocculate. The flocculation is proof of the existence of attracting forces between the particles (van Olphen, 1977). Other theories have been proposed to explain the distribution of ions around charged particles in colloids. No description of the different theories is given here, but the reader is directed to authors such as Mitchell (1976).

The following text is a summary of more detailed descriptions of the clay particle/ pore water system by Mitchell (1976) and Appello & Postma (1994):

> The edges of a clay mineral have a crystal structure that differs from that in the base planes and the diffuse electrical double layers are thereby also different. The charge at the edges depends on the value of pH in the solution. The value of pH at which the particles have minimum mobility in an electric field is called the point of zero net proton charge, pH_{PZNPC}. The clay minerals have an ability to exchange anions when the pH in the water is lower than pH_{PZNPC} and to exchange cations when the pH is above this value. Positive surface charges therefore occur in acid conditions and negative surface charges in basic conditions.

Appelo & Postma (1994) give values of pH_{PZNPC} = 4.6 for kaolinite and pH_{PZNPC} lower than 2.6 for montmorillonite. The pH is thus very low when the clay mineral is capable of exchanging anions. The influence of pH is described further in Chapter 1.2.2.

Particles in a suspension abundant with positive ions will be connected, i.e. flocculated and aggregated, which may lead to many different types of particle arrangements. The flocculation leads to sedimentation and the deposited material becomes an open structure with large voids between the aggregates. According to van Olphen (1977), the flocculation can take place in the following manner, see Fig. 1.6:

1. *Plane to plane*
   This results in large, thick sheets.
2. *Edge to plane*
   This results in a three-dimensional "house of cards" structure.
3. *Edge to edge*
   This results in a three-dimensional "house of cards" structure.

A combination of the connections mentioned above may also occur, according to van Olphen (1977). For example, plane to plane and edge to plane connections may occur at the same time, see Fig. 1.6.

There are also proposals for other types of particle connection, see for example Rosenqvist (1955) and Tan (1957). An important factor that affects the particle bonding is the variation in particle size. The smallest particles are most mobile and surface active, and are primarily connected. If the concentration of positive ions in

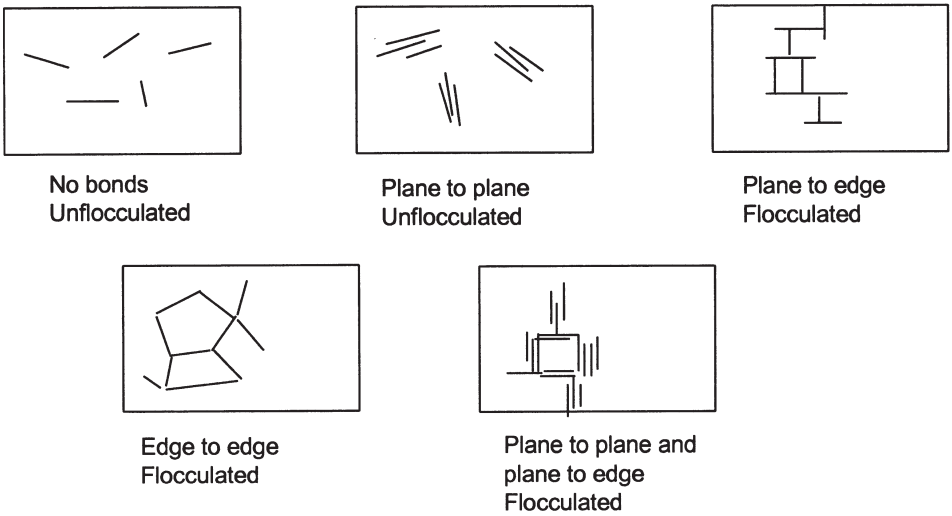

Fig. 1.6. **Different types of particle connection in clay suspensions (after van Olphen, 1977).**

the pore water is low, only a few particles will be connected, while a larger number of particles will be connected when the ion concentration is high. Brenner et al. (in Brand & Brenner, 1981) state that the flocculation is also affected by type of clay mineral, organic content, particle collisions and temperature. The number of particle collisions is in turn affected by the turbulence of the medium, temperature, and the concentration of particles. Concerning the type of clay minerals, Whitehouse et al. (1969) have shown experimentally that kaolinite and illite can flocculate at lower chloride contents than montmorillonite.

The clay particles were deposited after the latest glaciation at places where the water flow was low, i.e. initially at great distances from the ice front and then mainly in sea and lake bays as post-glacial sediments. Depending on the concentration of particles and the salt content in the water, among other factors, sediments were formed with different structures. These sediments were later affected by further overlying deposition and other subsequent processes. A common characteristic of the clays in Sweden that were formed in this way is that they are built up from aggregates connected by links consisting of smaller particles. Pusch (1970) showed that the aggregates in clay deposited in sea water are larger and denser than in clay deposited in fresh water, see Fig. 1.7. As explained above, this may be related to the electrical double layer being thinner in a suspension with a high concentration of cations than in one with a low concentration, and the fact that the clay particles can thereby move closer to each other and form large aggregates. When these large

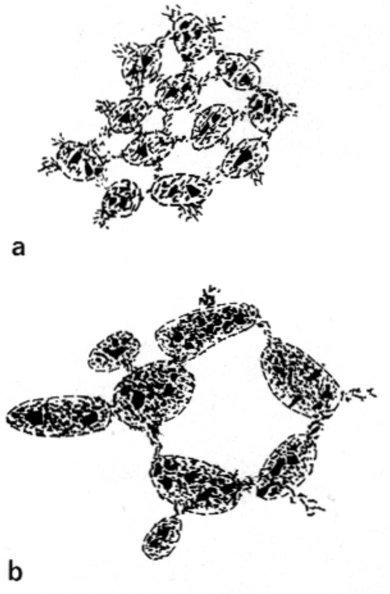

Fig. 1.7. **Schematic pictures of aggregates of particles and structure in clay deposited in a) sea water and b) fresh water. (After Pusch, 1970).**

aggregates sediment, they will be arranged without any preferred orientation, resulting in a structure with a high void ratio. In a suspension with a low cation content, each aggregate will consist of only a few particles and these can thereby sediment into a denser and more uniform structure.

Brenner et al. (in Brand & Brenner, 1981) are of the opinion that the successive increase in load that is created by the subsequent deposition of overlying sediments has to be slow if the open structure created during sedimentation in sea water is to be retained.

Pusch (1970) investigated the structure of different clays. He measured a structural parameter for the clays, which was defined as the ratio between total pore area, P, and total investigated area, T, in transmission micrographs of ultra-thin, i.e. 2-dimensional, slices. It was then found that the highest values of P/T corresponded to the clays with the highest sensitivities, which indicates that a high porosity is required for the clay to be quick.

1.2 FORMATION OF QUICK CLAYS

1.2.1 General

Research into the formation, properties and occurrence of quick clay has been carried out since the 1940's, mainly in Sweden, Norway and Canada. Rosenqvist (1946) presented a theory that the properties of quick clays are due to leaching of the salt content in marine clays.

The following is a summary of a description by Brenner et al. (in Brand & Brenner, 1981):

> Quick clays are found in areas which were once glaciated during the Pleistocene epoch (1.65 million to 10,000 years ago). They have mainly been identified in northern Russia, Norway, Finland, Sweden, Canada and Alaska. These areas are characterised by isostatic uplift which took place after the retreat of the ice. The development of very high sensitivity is usually the result of processes that have taken place after the deposition of the clay layers. All sediments with quick properties are young in a geological sense. Most of them are deposited in sea water but in some cases also in brackish or fresh water.

1.2.2 Factors affecting sensitivity

Leaching of salt

Clays that have been deposited in sea water contain a certain amount of salt. In everyday language, salt is usually taken to mean sodium chloride (NaCl), while salt in the context of chemistry refers to chemical compounds consisting of cations and anions, such as potassium hydrogen phosphate (KH_2PO_4). The compounds occur as free ions in a solution, for example Ca^{2+}, Mg^{2+}, Cl^-, Na^+, CO_3^{2-}, K^+, but form salts on drying. It is important to note what the term “salt” really stands for when studying the literature. In soil chemistry, it is necessary to distinguish the chemical composition of the pore water measured in analyses of water squeezed out of the soil from the amount (number) and type of adsorbed ions determined by ion exchange analyses.

The original salt content in the pore water in a deposit may decrease due to leaching. Leaching is a process that removes substances such as dissolved salt ions from part of the soil profile. It is a natural process in all temperate regions with marine clays that through the isostatic uplift of the land have been raised above sea level (Torrance, 1978). In principle, there are three different types of leaching process; rain (and snow) water percolating through the deposit, water seeping upwards through the deposit due to artesian pressure, and diffusion of salts towards zones with lower ion concentrations. Combinations of these processes may also occur.

Leaching affects the forces between the particles, but normally not the flocculated structure as such, (Brenner et al. in Brand & Brenner, 1981). On the other hand, leaching strongly affects the ability of the particles to re-flocculate after remoulding. As described in Chapter 1.1.3, a clay deposited in sea water is built up from large aggregates joined by a system of links. If the salt in such a clay is leached and the clay is remoulded, the clay particles cannot be connected into large aggregates again. The water holding capacity of the clay, which is reflected in the liquid limit, is thereby reduced. If the void ratio and thus the water content is high as a result of the original conditions at the deposition of the clay, remoulding will result in a clay gruel with small and separated particles and a liquid, low viscous consistency. This also implies a reduction in remoulded shear strength and an increase in the sensitivity of the clay. Changes in sensitivity, shear strength and consistency limits during leaching were studied by Bjerrum (1954 b) and Rosenkvist (1955), see Fig. 1.8.

The rate of the leaching process depends mainly on the hydraulic gradient and the hydraulic conductivity (Torrance, 1978). The presence of permeable layers, such as sand and silt layers, that are connected to surface water or other water conducting layers greatly enhances the possibility of leaching. It may be possible to locate so called discharge areas (areas with an upward hydraulic gradient) by studying the type of vegetation that occurs in the area.

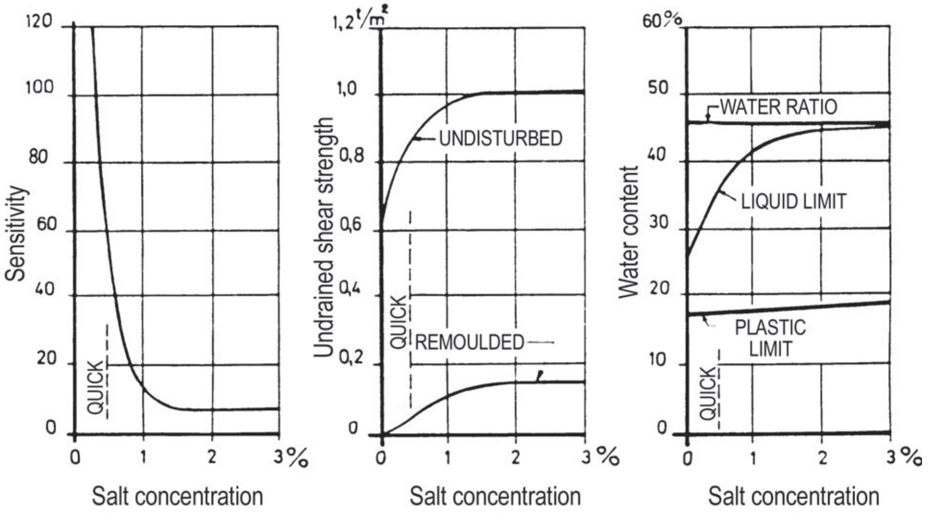

Fig. 1.8. **Changes in sensitivity, shear strength and consistency limits as functions of the salt concentration in pore water during leaching. (After Bjerrum, 1954 b).**

It was earlier considered that a low salt content as a result of leaching was the primary factor for the formation of quick clay. The original quick clay model proposed by Rosenkvist (1946), which is based on experience from Norwegian clays deposited in sea water, showed a connection between low salt content and high sensitivity. Later research by Talme (1968), Söderblom (1969) and Penner (1965), among others, has shown that a low salt content is a precondition for high sensitivity, but that this condition alone is not always sufficient. Thus, there are a large number of clays deposited in sea water which today have low salt contents but are not quick or even highly sensitive. The explanation for this can be found in the following Section, "Ion composition in the pore water".

Leaching may also cause a reduction in the undisturbed, undrained shear strength. Investigations by Bjerrum & Rosenkvist (1965) showed that both the undisturbed and the remoulded shear strength may be reduced by leaching, see Fig. A9. Brenner et al. (in Brand & Brenner,1981) report that leaching causes not only a reduction in shear strength but also an increase in the compressibility of the clay, i.e. the compression modulus at consolidation decreases. Bjerrum (1967) simulated leaching of a clay under load in the laboratory. A sea water deposited clay specimen was mounted in an oedometer and loaded to a vertical stress of 55 kPa. It was then leached by fresh water and loaded further with increasing load steps. The stress strain curve is compared to that for unleached clay in Fig. 1.9. The results show that a compression was obtained during leaching under constant load and that further loading showed a stress-strain relation with a lower compression modulus than that for the unleached clay. The increase in compressibility is attributed to the large reduction in water holding capacity (liquid limit) that occurs at leaching and the resulting decrease in water content if the clay is subjected to a stress close to its

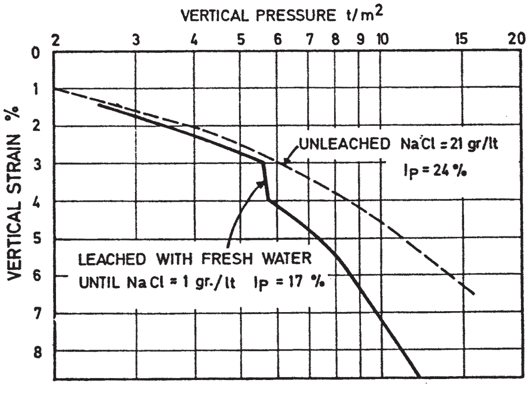

Fig. 1.9. Results from leaching tests in the laboratory on clay specimens from Drammen, Norway. (After Bjerrum, 1967)

original preconsolidation pressure and stresses above that. Torrance (1974) also conducted leaching tests on sea water deposited clay in the oedometer. A significant compression was obtained when the salt content decreased below 1.3 g /l, see Fig. 1.10.

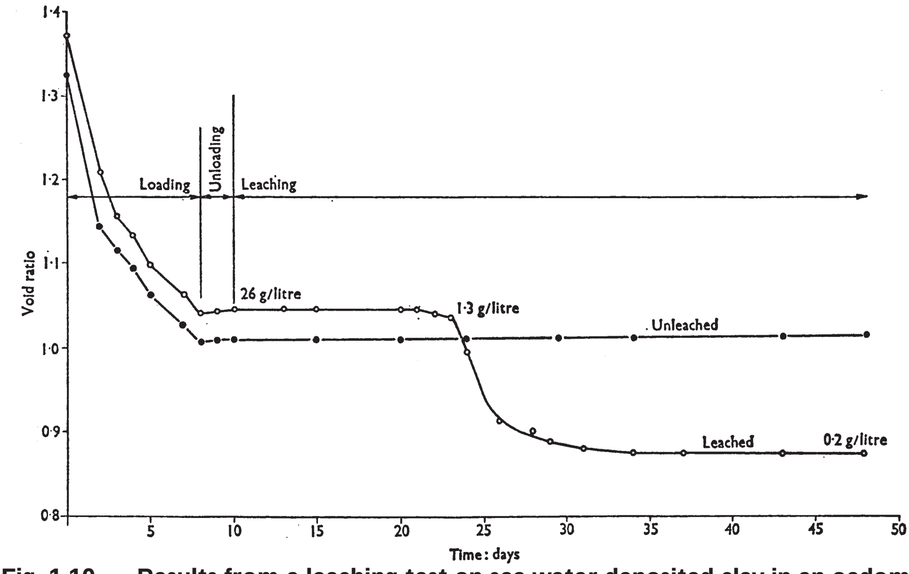

Fig. 1.10. **Results from a leaching test on sea water deposited clay in an oedometer. (After Torrance, 1974).**

The Göta Älv Committee (Statens offentliga utredningar, 1962) reported that certain general rules for the course of the leaching process can be given as follows:

- The location of the clay in relation to the recipient determines the depth of the leaching.
- The rate of the leaching process is higher the more coarse-grained sediments there are. Presence of sand and till layers is beneficial for the leaching process.
- The leaching process is often complete at the valley sides and in thin clay layers.
- Leaching occurs through diffusion combined with ground water flow.
- The leaching of clays from the top of the profiles takes place with rain water containing carbon dioxide. Cl^- ions are then exchanged by bicarbonate (HCO_3^-), among other ions. (The carbon dioxide in the rain water reacts with water and forms carbonic acid H_2CO_3, which is dissolved into HCO_3^- and hydrogen ions).

The Göta Älv Committee (Statens offentliga utredningar, 1962) was of the opinion that leaching occurs as a combination of diffusion and ground water flow. Talme (1968) showed the connection between permeable layers and quick clay, but did not mention that there should also be a combination of diffusion and water seeping through the clay.

Values of the diffusion constant, D, have been proposed, for example, for ions in water. Atkins (1982) reported that the diffusion constant in a free water phase is $1.33 \cdot 10^{-9}$ for Na^+ and $2.03\ 10^{-9}$ m^2/s for Cl^-. The distance an ion moves during a certain time at redistribution through diffusion in two directions can be calculated as:

$$\bar{x} = \sqrt{2 \cdot D \cdot t}$$

where	D = diffusion constant	*[m^2/s]*
	t = time	*[s]*

The distance travelled by Na^+ through diffusion in a free water phase will then reach 20 m after 5,000 years. Söderblom (1969) studied diffusion of salts in natural clay deposits. Diffusion constants with values of between 0.11 and 0.14 cm^2/day ($1.27 \cdot 10^{-10}$ and $1.62 \cdot 10^{-10}$ m^2/s) were measured at Surte in the Göta älv valley. This corresponds to a diffusion of 6–7 metres over a period of 5,000 years.

The Göta Älv Committee (Statens offentliga utredningar, 1962) reported that all clay deposits in the Göta älv valley located north of Lilla Edet community are almost completely leached. Investigations performed south of Lödöse, about 10 km south of Lilla Edet, have shown several clay deposits in which the original salt content (i.e. that of sea water) is preserved. About 500 years ago, Lödöse was the main port on the Swedish west coast and large areas further south in the Göta älv valley have been located above sea level for less than 100 years.

Ion composition in the pore water

The ion composition in the pore water has shown to be of great importance for the formation of quick clay. In principle, the amount of Na^+ and K^+ ions in the clay affects the sensitivity in such a way that the larger share of Na^+ and K^+ ions of the total amount of cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) in the pore water, the more favorable the conditions for high sensitivity. A large proportion of monovalent ions leads to large diffuse double layers around the clay particles. A larger extent of the double layer is required to achieve charge neutrality when the pore water contains monovalent ions compared to when it contains bivalent ions (provided that the same number of ions are present). Larger diffuse double layers imply larger repulsive forces between the particles. After remoulding, these forces will prevent flocculation of the clay particles. This reduces the remoulded shear strength and increases the sensitivity of the clay.

Fällman et al. (2001) studied the flocculation of colloids in suspensions at different ion concentrations. They established that a decrease in the ion concentration reduced the flocculation considerably and that contents of Ca^{2+} and Mg^{2+} ions in the pore water resulted in a better flocculation than corresponding contents of the monovalent ions.

There are two main types of ground water in Sweden; so called hard and soft water. Hard water contains Ca^{2+} and Mg^{2+} as dominating ions. When clay is leached by hard water, pore water containing mainly bivalent ions will be created and, regardless of the ion composition before the leaching process, the clay will then normally not become quick (see Söderblom, 1974, for example). On the other hand, leaching with soft water, which contains Na^{+} as the dominating cation, will provide a pore water in which monovalent ions dominate. This is a beneficial condition for the formation of quick clay. Hard water occurs in areas where the bedrock in the surroundings consists of limestone. Lundqvist (1958) has produced a map showing the occurrence of Cambrian-Silurian material in deposits and the bedrock in Sweden, see Fig. 1.11. Söderblom (1969) states that it is not necessary to remove by for instance leaching the Ca^{2+} and/or Mg^{2+} ions from the clay by for instance leaching and/or from the clay in order to terminate their influence. Instead, they can be bonded in conglomerates with mainly organic matter. They will then no longer remain as free cations in the pore water or in the electrical double layers.

Talme (1968) reports that normally quick clay occurs in post-glacial clay deposits, that it is found directly above glacial clay layers, and that there is often a permeable layer above, below or embedded in the layer of quick clay. Glacial clay normally contains a larger share of calcium carbonate than post-glacial clay, which according to Talme (1968) may explain why glacial clay is more seldom quick. The original content of calcium carbonate in a clay depends on the amount of limestone in the bedrock in the surroundings and the location in this area where the clay has been deposited.

Weathering of minerals can change the ion composition in the pore water. Positive ions that have been bonded to the clay particles can be released in weathering and thereby increase the concentration of such ions in the pore water (see Chapter 1.4). Troedsson & Nykvist (1980) describe how the balance that exists between different

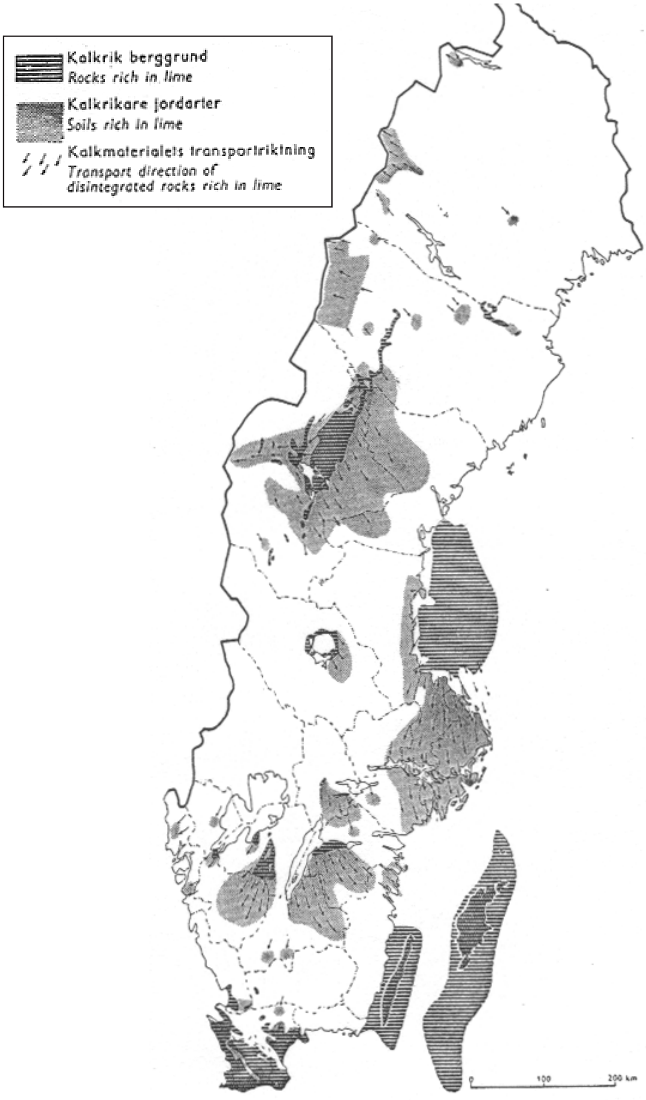

Fig. 1.11. **Distribution of Cambrian-Silurian material originating from limestone bedrock in Sweden. (After Lundqvist, 1958).**

layers in the minerals is changed because of the action of roots, whereby hydrogen ions are released. The clay mineral illite becomes more easily eroded when, for example, Al^{3+} replaces Si^{4+} in the mineral since the new ion has a poorer fit in the cluster. Hydrogen ions can then enter the mineral and force out other ions. If the latter are dispersed by the ground water and new hydrogen ions are added, the process leads to a weathered clay.

The remoulded shear strength in a quick clay increases when salt is added. This was shown by Talme et al. (1966), among others, in tests on clays from Ugglum outside Göteborg. 0.5 meq of six different salts, (NaCl, KCl, $CaCl_2$, $MgSO_4$, $Al_2(SO_4)_3$, $FeCl_3$), was added to 100 g clay specimens. All the salts gave increased values of the remoulded shear strength, but the largest effects were obtained when adding the bivalent and trivalent ions. Løken (1970) and Moum et al. (1971) also performed tests aiming at increasing the remoulded shear strength in quick clay by adding different salt ions (Na^+, K^+, Ca^{2+}, Mg^{2+}, Al^{3+}, Fe^{2+}, Fe^{3+}). In the presentation of the results, the amount of added ions was normalised by expressing it as the molar concentration of the ions in the pore water (mol/litre) divided by the valency of the ions. The results are shown in Fig. 1.12. They showed that Al^{3+} and K^+ were most efficient in increasing the remoulded shear strength at equal values of the ratio between molar concentration and valency.

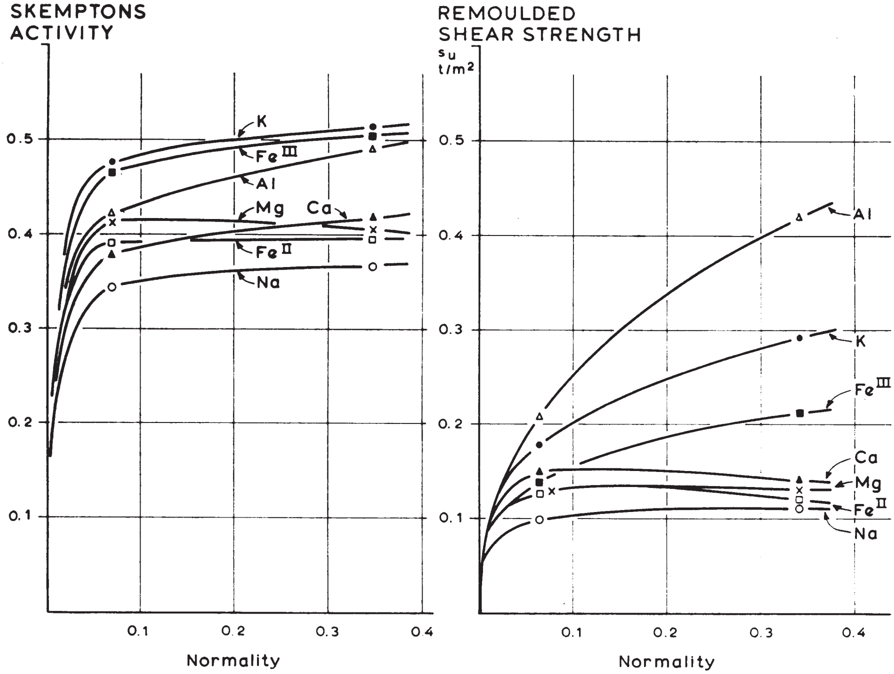

Fig. 1.12. Ability of different ions to increase the remoulded shear strength of a quick clay (After Løken, 1970).

pH level

The pH in the pore water affects the properties of clay. The pH is most important during deposition of the sediment, but also later changes in the chemical composition of the clay are affected by the pH of the pore water.

Fällman et al. (2001) performed laboratory tests on laboratory prepared clay originating from Holma mosse, Östergötland. The clay was remoulded into a suspension, sedimented and consolidated, and the influence of three different parameters in the pore water on the undisturbed and the remoulded shear strengths was studied. The clay was remoulded and the clay particles were suspended in solutions of water with different chemical compositions. The variables in the pore water were the pH, the ionic strength and the relative amounts of different ions. The clay particles were sedimented by using a centrifuge and specimens of the clay were then consolidated and tested regarding shear strength properties. Fig. 1.13 shows the measured sensitivity at different ionic strengths (25 and 50 mM respectively), pH ranges (6–8 and 9.5–10.5 respectively) and amount of sodium ions in relation to the total amount of calcium, magnesium and potassium ions. The results showed that with a normal relation between sodium ions and total amount of calcium, magnesium and potassium ions (Na/(Ca, Mg, K) ≈5,5) there was a drastic increase in sensitivity with pH. There was no increase in sensitivity with pH at a low proportion of sodium ions (Na/(Ca, Mg, K) ≈1,5), while the sensitivity increased with the proportion of sodium ions at high pH.

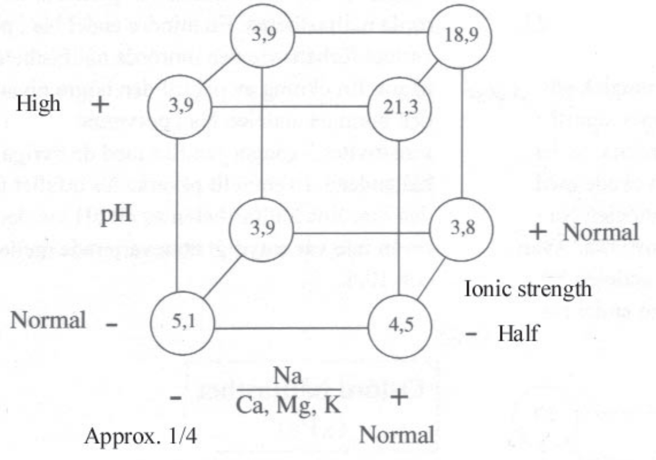

Fig. 1.13. Measured sensitivity related to proportion of sodium ions in the pore water, pH, and ion concentration. (After Fällman et al., 2001).

It should be pointed out that the artificial method used to produce the clay does not yield the open structure dominated by aggregates that is a precondition for a clay with very high sensitivity (Pusch, 2002).

Talme (1968) investigated the influence of the pH level on the remoulded shear strength of clay. An acid solution (hydrogen chloride) and a basic solution (sodium hydroxide) were added to both normal and quick clays. The remoulded shear strength in both normal and quick clay increased when adding the acid solution and decreased when adding the basic solution.

Bjerrum (1967) assumes the following processes to take place when rain water percolates through a clay deposit:

> The rain water contains dissolved O_2 and CO_2. CO_2 reduces the pH in the pore water. If this reduction continues for a sufficiently long time, the pH will finally reach a level that is so low that a decomposition of feldspar, mica and chlorite starts. The decomposition results in a release of multivalent ions bonded to the mineral surface.

As described above, an increased amount of multivalent ions in the pore water leads to a decrease in the extent of the double layers and thereby a decrease in the repelling forces between the particles and a lower sensitivity.

Mitchell (1976) reports that if, on the other hand, the pH level in the pore water is high, there is a tendency for hydrogen ions to be dissolved ($SiOH \rightarrow SiO^- + H^+$), resulting in a higher negative charge at the particle surface. This leads to an expansion of the double layer and thus a higher sensitivity.

The Göta Älv Committee (Statens offentliga utredningar, 1962) considered that the pH level should be within certain limits if the clay is to be highly sensitive. However, no values for these limits were given.

Dispersing agents

Dispersing substances break up bonds and separate particles similar to the effects of detergents and washing-up liquids. They consist mainly of natural organic substances but there are also a number of inorganic dispersing agents. When organic substances act dispersively, they can bond bivalent ions (Ca^{2+}, Mg^{2+}) and change the ion composition in the pore water, which in turn can lead to an expansion of the diffuse double layer (Brenner et al. in Brand & Brenner, 1981). According to Söderblom (1974), the dispersing agents act in such way that they bond cations from a clay particle and thereby increase the negative charge of the particle surface. The double layers around the particles thereby expand. Among the inorganic dispersing agents are silicates, phosphates, sulphides and bicarbonates.

Penner (1965) studied the effect of chemical dispersing agents on the remoulded shear strength of clay. Addition of sodium metaphosphate ($Na(HPO_3)_x$) had shown to result in increased sensitivity. Measurements of the electrokinetic potential showed that also this parameter increased upon the addition of sodium metaphosphate. Penner (1965) proposed the explanation that particles which were held together by strong van der Waal forces were separated by remoulding. When adding sodium metaphosphate, the phosphate is absorbed on the mineral surfaces and thereby increase the repulsive forces between the clay particles. The repulsive forces are too high to allow the clay particles to be reconnected and the remoulded shear strength is thereby reduced.

Also clays deposited in fresh water, and which have flocculated structures and low activity, may become quick due to the action of dispersing agents. This was shown indirectly by Söderblom (1974), who treated fresh water deposited clays with different dispersing substances and found very low remoulded shear strengths. The tests were performed in such a way that an artificial kaolin clay was remoulded and the remoulded shear strength measured. The dispersive agents was then added and remoulding and shear strength measurement of the specimen repeated. Söderblom (1974) also showed an example of a natural, quick, fresh water deposited clay beneath peat.

According to Söderblom (1974), organic agents affect clays in several ways from a chemical point of view. Certain organic agents can, apart from their ability to act dispersively, also act in a cementing way. They thereby provide a stable gel structure, which in certain cases can result in a heterogeneous macrostructure with fine fissures and increased permeability.

Particle shape

Pusch (1962) considers that also the shape of the clay particles is important for the tendency of the soil to become quick. Flat particles with a large value of a/c, see Fig. 1.3, become more highly separated at remoulding than particles with more uniform dimensions. This is mainly the case for normally consolidated clays of low density, i.e. with high water contents.

1.2.3 Principles of quick clay formation

Rosenqvist, (1978) proposed the following general theory for quick clay formation:

1. Clay size particles of non-swelling clay minerals sediment in a flocculated condition since the electrokinetic potential is low (small electrical double layers), either because the water is salt or because of adsorption of strongly bonded counter ions such as Fe^{3+}, Al^{3+}, Ca^{2+} and Mg^{2+}.

2. After deposition and moderate consolidation of the clay, the electrokinetic potential is increased, (i.e. the electrical double layer expands), due to leaching, reduction of trivalent iron to bivalent iron (Fe^{3+} to Fe^{2+}), or bonding of multivalent ions to organic compounds, for example.

3. A subsequent mechanical remoulding of the clay causes a unidirection of the particles. A reflocculation thereafter is not possible because of the strong repulsive forces between the particles and it is only possible to bring the particles into contact again after a considerable reduction in the water content, i.e. consolidation.

Fig. 1.14 shows a flowchart for quick clay formation presented by Brenner et al. (in Brand and Brenner, 1981).

Illite and chlorite are examples of non-swelling clay minerals. Smectite is a swelling clay mineral.

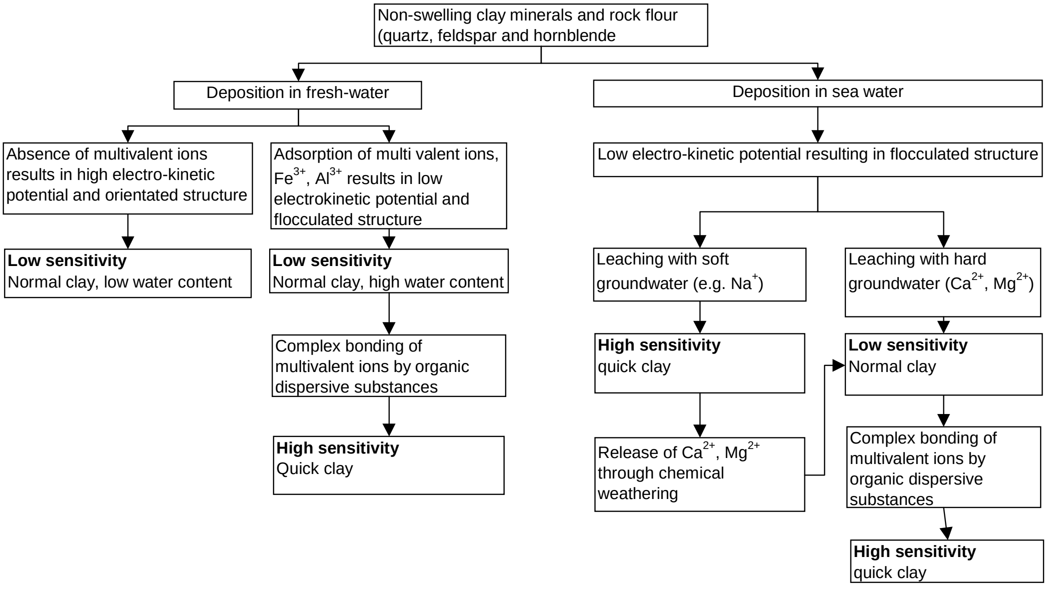

Fig. 1.14. Flowchart for formation of quick clay. (After Brenner et al. in Brand and Brenner, 1981).

1.3 GEOTECHNICAL PROPERTIES OF QUICK CLAY

This chapter deals with typical geotechnical properties of quick clays. Quick clays differ from non-quick clays mainly concerning the relation between water content, consistency limits and activity. Talme et al. (1966), for example, showed that quick clay and clay with normal sensitivity can have the same type of mineralogy and that the difference in sensitivity was not related to the particle size distribution. The differences in sensitivity are instead related to microstructural and physical/ chemical conditions in the pore water in the clay, as shown in Chapters 4.1 and 4.2.

1.3.1 Activity and clay mineral

A precondition for the formation of quick clay is that the sediment is dominated by a non-swelling mineral with low activity.

The concept of activity of clay minerals was introduced by Skempton (1953). He studied the relation between plasticity index and clay content in clay. This relation was designated the activity of the clay, a_c, and is defined as:

$$a_c = I_P/l_c$$

where I_P = plasticity index = w_L–w_P, %
w_L = liquid limit, %
w_P = plastic limit, %
l_c = clay content, percent of the total mass of fines, %

Skempton (1953) found the activity to be different for different clay minerals but fairly independent of the particle size distribution. He thus obtained straight lines when plotting plasticity index versus clay content for each type of clay mineral. Values of activity for some types of clay minerals are listed in Table 1.3. Activity depends mainly on the ion exchange capacity and the specific surface of the clay minerals, as well as on the content of organic colloids (Hansbo, 1975). According to Bjerrum (1954a), a designation of clay with respect to activity can be made according to Table 1.4.

Bjerrum (1955) compiled values of clay content and plasticity index for several natural Norwegian clays, see Fig. 1.15. He found that the activity of all these clays fell in the range $0.15 < a_c \leq 0.65$ and the clays were thus designated as low-active clays. The activity of quick clay is normally less than 0.5 (Mitchell, 1976).

Table 1.3. Activity, ac,, of various clay minerals. Values from Skempton (1953) and Mitchell (1976).

Mineral	Activity, a_c
Muscovite	0.23
Kaolinite	0.4 – 0.5
Smectite *	1 – 7
Illite	0.5 – 1

* The activity of montmorillonite depends on the type of adsorbed cation. Na montmorillonite has an activity of about 6, while Ca montmorillonite has a considerably lower activity, (about 1.5 according to Skempton (1955)).

Table 1.4. Designation of clay with regard to activity according to Bjerrum (1954a).

Activity	Designation
$0 < a_c \leq 0.75$	low-active
$0.75 < a_c \leq 1.4$	normal
$1.4 < a_c \leq \infty$	active

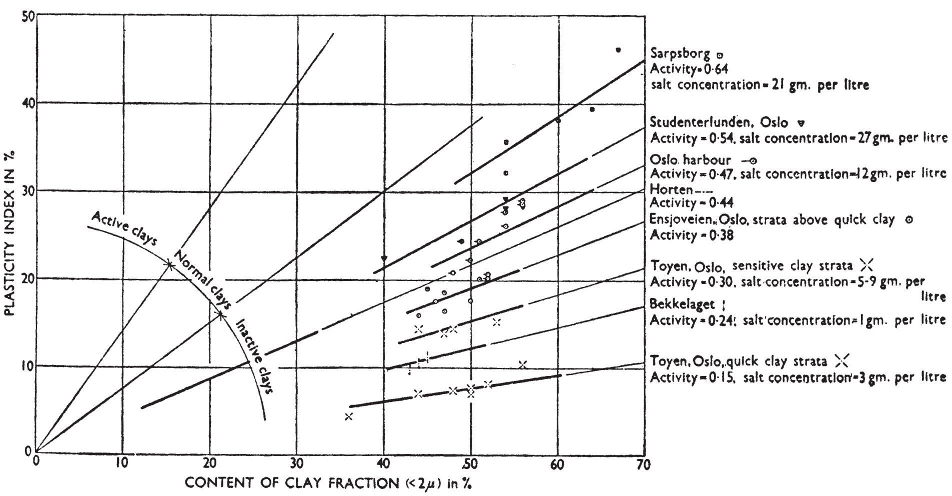

Fig. 1.15. Activity of various Norwegian clays. (After Bjerrum, 1955).

Certain clay minerals, such as montmorillonite, have a swelling capacity (see Chapter 1.1.1). Only very small amounts of these minerals are found in those clay sediments that have shown to have the potential to become quick. Rosenqvist (1978) stated that no quick clay has been found in sediments containing more than a few percent of swelling minerals of the smectite type.

1.3.2 Void ratio and water contents

A clay that sediments into a flocculated structure develops a higher void ratio and water content compared to sediments with orientated structures. The extent of the electrical double layer may decrease if a flocculated clay is subjected to leaching, and a re-flocculation after remoulding may thereby not be possible. This would lead to a significant reduction in the liquid limit, whereas the natural water content normally remains constant. A characteristic of quick clay is that the water content is higher than the liquid limit. The liquid limit determined by fall-cone tests is defined as the water content at which the penetration of the 60 g–60^o cone into the remoulded soil is 10 mm. The corresponding remoulded shear strength is about 1.5 kPa. The percussion liquid limit is approximately the same as the cone liquid limit and investigations concerning the remoulded shear strength at the percussion liquid limit have yielded approximately the same remoulded shear strength. According to the Swedish definition of quick clay, the remoulded shear strength must be equal to or less than 0.4 kPa if the clay is to be designated as quick. The water content therefore has to be higher than the liquid limit in a quick clay.

The plastic limit decreases only slightly at leaching, see Fig. 1.8. A larger decrease in liquid limit than in plastic limit implies that the plasticity index ($I_p = w_L – w_p$) decreases. Brenner et al. (in Brand and Brenner, 1981) also report that quick clays often have low values of the plasticity index ($I_p \approx 10 – 15$), which may be explained by a high content of low-active minerals. However, the quick clays found in Sweden often have considerably higher plasticity indices. The main changes in liquid limit, plasticity limit, remoulded shear strength and sensitivity occur when the salt content is reduced below about 2 g/litre (Torrance, 1974).

The sensitivity increases with increasing liquidity index, $I_L = (w_n – w_p)/(w_L – w_p)$, see Fig. 1.16. For the same type of clay, there is a fairly linear relation between the liquidity index and the logarithm of the sensitivity. An increase in liquidity index is caused by leaching, ion exchange or the action of a dispersing substance. A decrease in liquidity index is normally caused by drying, weathering or consolidation.

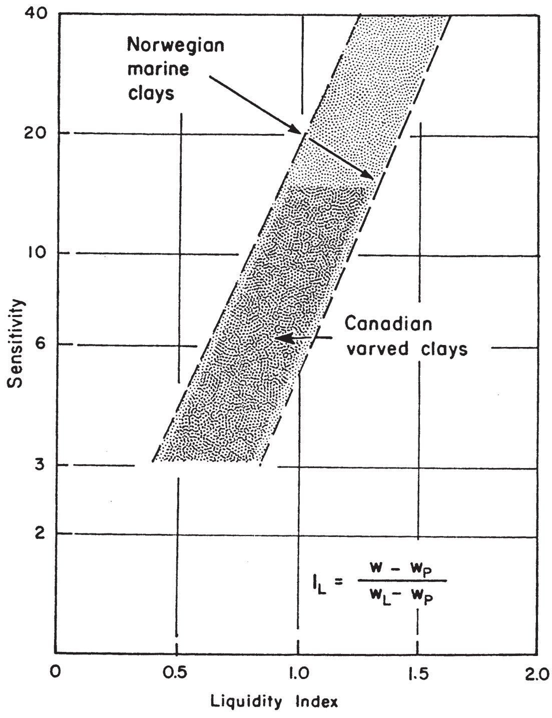

Fig. 1.16. Relation between sensitivity and liquidity index in Norwegian and Canadian marine clays (Kenney, 1976).

A schematic diagram for an approximate relation between liquidity index, effective vertical stress and sensitivity in normally consolidated clay is shown in Fig. 1.17. The diagram, which has been presented by Mitchell (1976), was intended for rough estimations of sensitivity when undisturbed samples were not available. It is based on average values from several normally consolidated clays in Norway, the UK, the USA and Canada. However, it cannot be used for clays in Sweden.

Results from 1450 clay samples taken along the Göta älv valley were compiled in the Göta älv investigation (Statens offentliga utredningar, 1962). The relation between the sensitivity of the clays and the quotient between water content and liquid limit is shown in Fig. 1.18. The results show that the quotient should exceed 1.1 if the clay is to be quick. Corresponding results have been obtained for clay from Munkedal (Larsson & Åhnberg, 2003).

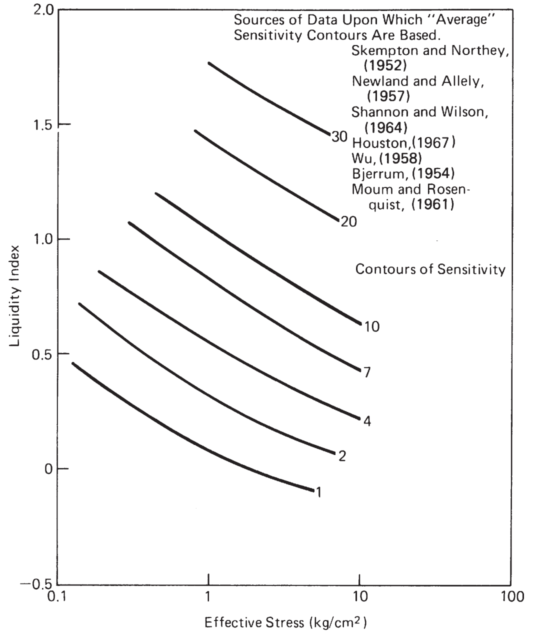

Fig. 1.17. Approximate relation between sensitivity, liquidity index and effective vertical stress in normally consolidated clay. (After Mitchell, 1976).

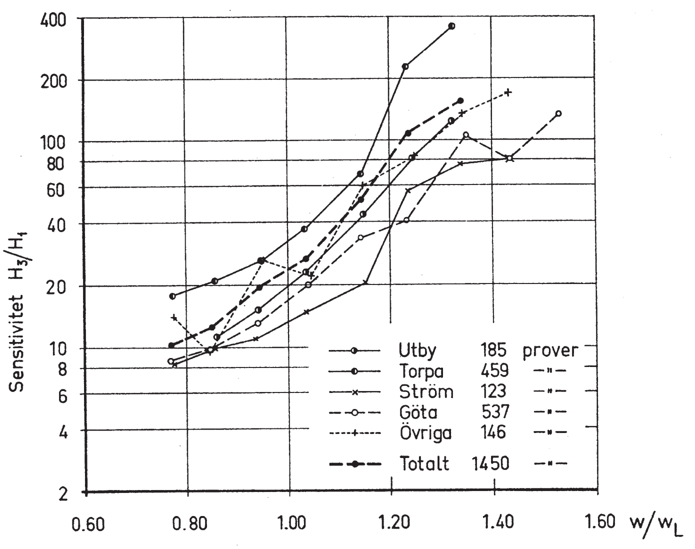

Fig. 1.18. Relation between sensitivity and quotient between water content and liquid limit for clays from the Göta älv valley (Statens offentliga utredningar, 1962).

1.4 EXAMPLES OF QUICK CLAY OCCURRENCE AT SOME TEST SITES

1.4.1 Courthouse in Drammen, Norway

An example of the way in which the ion composition and the sensitivity can vary with depth in a marine clay was presented by Moum et al. (1971; 1972). They investigated and analysed clay samples from a site at the courthouse in Drammen, Norway. The soil at the site consists of up to 25 metres of soft clay with an undrained shear strength of 15–20 kPa, increasing slightly with depth. The minerals in the soil are quartz, feldspar, illite and chlorite. The present salt content in the pore water is less than 0.35%. Chemical analyses of the concentration of different ions (K^+, Na^+, Mg^{2+}, Ca^{2+}) showed an inverse relation between the concentration of Mg^{2+} and Ca^{2+} ions in the pore water and sensitivity. Results from the geotechnical investigations and the chemical analyses are shown in Figs. 1.19 and 1.20.

Leaching has occurred both from below because of artesian ground water pressure and by a horizontal water flow and percolating rain water in the upper layers. However, the leaching process has not resulted in quick clay throughout the clay profile, see Fig. 1.20, which may be explained by the varying concentration of different salt ions, see Fig. 1.20. Moum et al. (1971;1972) explained the differences between borings nos. I and II by an assumption that the sensitivity in the lower clay layers had once been high but then decreased due to an increase in the concentration of K^+, Ca^{2+} and Mg^{2+}. They further assumed that this increase is a result of weathering, in which Mg^{2+} has been released from the clay mineral chlorite, Ca^{2+} from calcium carbonate and K^+ from illite.

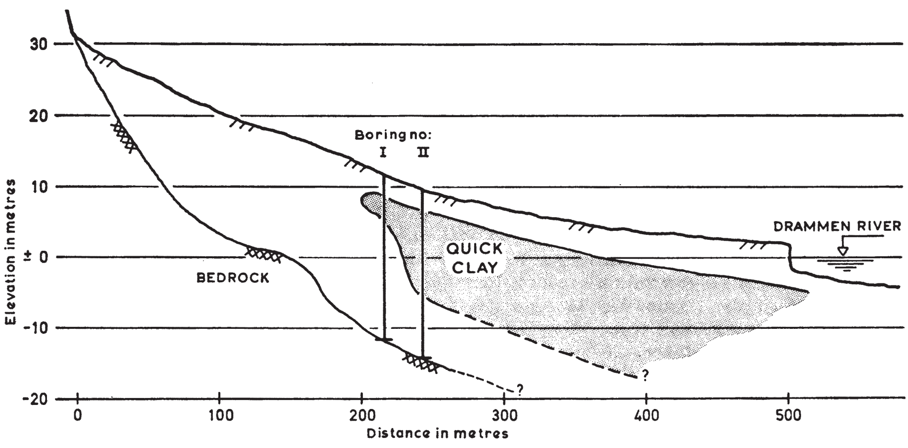

Fig. 1.19. Section of the test site at the courthouse in Drammen, Norway, showing the thickness of the clay sediments and the occurrence of quick clay. (After Moum et al., 1971).

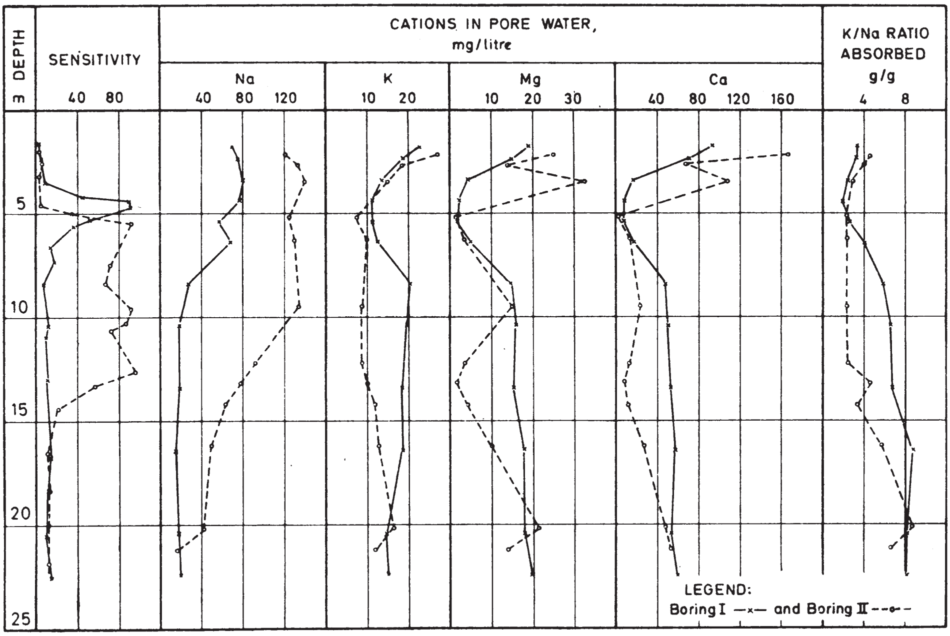

Fig. 1.20. **Sensitivity and pore water chemistry of the clay at the test site at the courthouse in Drammen, Norway. (After Moum et al., 1971).**

1.4.2 Jönåker and Ugglum

Talme et al.(1966) investigated clay from Jönåker near Nyköping in eastern Sweden and Ugglum near Göteborg in western Sweden, among other places. The purpose of the investigation was to study differences between quick clay and clay with normal sensitivity. The clay at Jönåker was deposited at a time when the Baltic Sea was a fresh water lake, the so called Ancylis Lake, with a salt content of less than 0.2%, while the clay at Ugglum was deposited in a sea bay with a salt content of over 3%. Today, Ugglum is located about 15 km from the sea.

No differences regarding particle size distribution or clay minerals could be observed between the quick and non-quick clays in the investigation. The clay contents, i.e. the percentage of particles smaller than 2 mm , was 50 – 60%. The main clay minerals were illite and chlorite. The differences were found to be related mainly to the chemical composition of the clays. The concentration of ions (meq/l) in normal and quick clay at Jönåker and Ugglum is shown in Table 1.5 and Fig. 1.21. The quick clay at Jönåker was found to have a considerably lower total amount of ions compared to the clay with normal sensitivity, whereas that at Ugglum had a total ion content that was only slightly lower compared to the normal clay here. A characteristic of both sites is that the content of the bivalent ions Mg^{2+} and Ca^{2+} is considerably lower in the quick clay compared to the normal clay.

Table 1.5. Concentration of ions in the pore water of clay from Jönåker and Ugglum (after Talme et al., 1966).

Test site	Type of clay	Positive ions (meq/l)	Negative ions	Totalion concentration (meq/l)
Jönåker	Normal Quick	33.66 13.82	35.54 13.52	69.20 27.34
Ugglum	Normal Quick	33.87 29.28	33.96 29.27	67.83 58.55

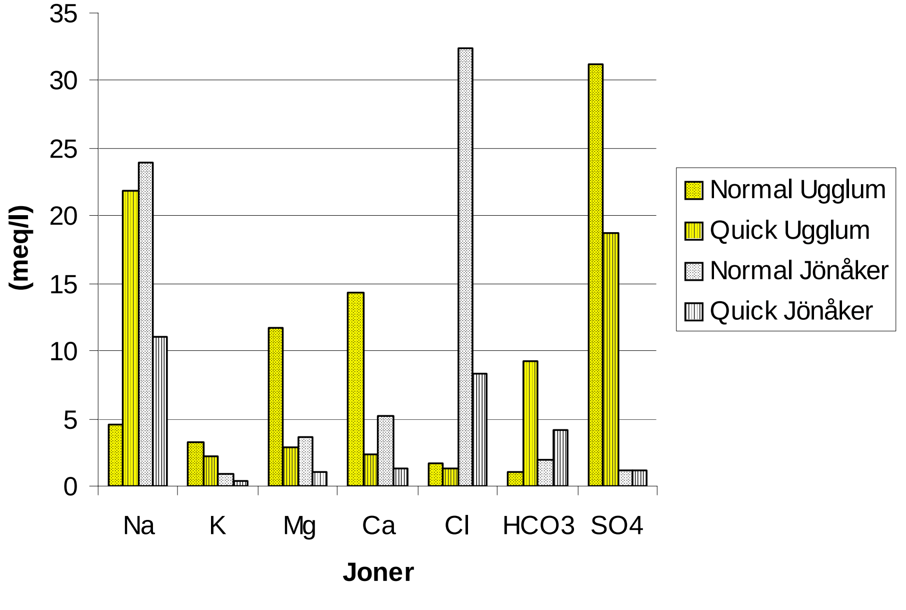

Fig. 1.21. Concentration of different ions in the pore water (meq/l) in clay from Jönåker and Ugglum. (After Talme et al., 1966).

1.4.3 Åtorp, Munkedal

An investigation of a slope towards the river Örekilsälven in the southern part of Munkedal community in the early 1980's showed that the stability of the slope was unsatisfactory. An excavation was therefore carried out at the crest of the slope in 1985 in order to increase the stability. New investigations regarding the long-term effect of the stabilising measures were started at the end of the 1990's. These investigations involved geophysical methods, among them surface resistivity measurements. The results of the investigations were reported by Larsson and Åhnberg (2003) and Dahlin et al. (2001). No investigation has been performed regarding the pore water chemistry in the area.

The soil deposits in the area consist of glacial and post-glacial marine clay with delta and lateral fluvial sediments on top. The thickness of the soil layers varies. Quick clay was found in the laboratory tests on samples from some parts of the area. The natural water content is generally equal to or slightly less than the liquid limit in the non-quick clay, whereas it is higher than the liquid limit in the quick clay, see Fig. 1.22. The resistivity measurements in the area showed that quick clay could be found in those parts of the investigated section where the resistivity was less than about 7 Wm, see Fig. 1.23. A corresponding limit for the resistivity, which in turn is related to the salt content, was proposed by Söderblom (1969). The lateral extent of the quick clay formation was not investigated in that project.

The results showed that the quick clay occurred at a certain distance from the river towards the valley side.

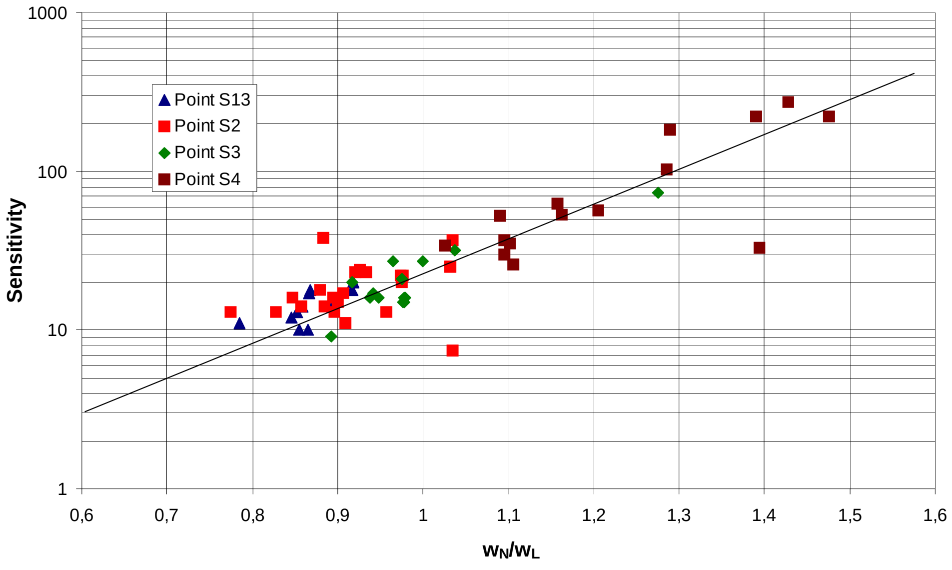

Fig. 1.22. **Relation between sensitivity and quotient between water content and liquid limit in clay samples from Åtorp (Larsson & Åhnberg, 2003).**

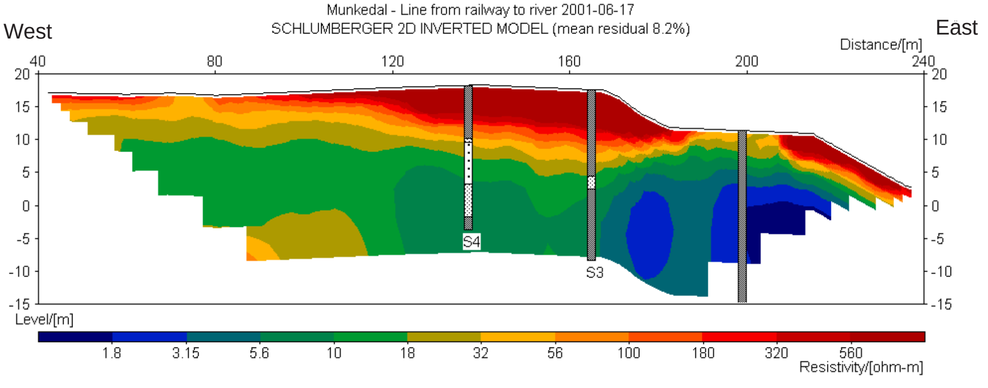

Fig. 1.23. **Sensitivity and evaluated resistivity in Section A at Åtorp. Superficial layers with high resistivity consist of lateral fluvial sediments of sand and silt and/or dry crust (after Dahlin et al., 2001). The dark grey zones in the boreholes indicate sensitivities lower than 50, light grey zones correspond to sensitivities between 50 and 100, and light zones with single dots to sensitivities over 100.**

Chapter 2.

Geological and geohydrological prerequisites for formation of quick clay in nature

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The processes leading to the formation of quick clay were presented in the literature survey in the previous section.

In this section, guidelines are presented on how to distinguish areas with prerequisites for quick clay formation based on geological, topographical and hydrological maps and site inspections. Examples of the geological and hydrogeological conditions in three areas with quick clay in western Sweden are also given.

However, the fact that areas have prerequisites for quick clay formation does not necessarily imply that quick clay is present.

2.1. GUIDELINES FOR DISTINGUISHING AREAS WITH PREREQUISITES FOR QUICK CLAY

In an early stage in the planning process or in a survey mapping of the risk of landslides, certain conditions leading to the possibility of quick clay occurrence can be found with the aid of geological, topographical and hydrogeological maps and descriptions.

The conditions that should therefore be studied are given in Chapters 2.1.1 – 2.1.11. Fig. 2.6 shows a simple flowchart for use in the screening process when distinguishing areas with prerequisites for quick clay.

2.1.1 Ice sea sediments

Most quick clays have been formed in deposits which were deposited in sea water after the latest glaciation, c.f. Fig. 2.1. Quick clays may be found also in other areas

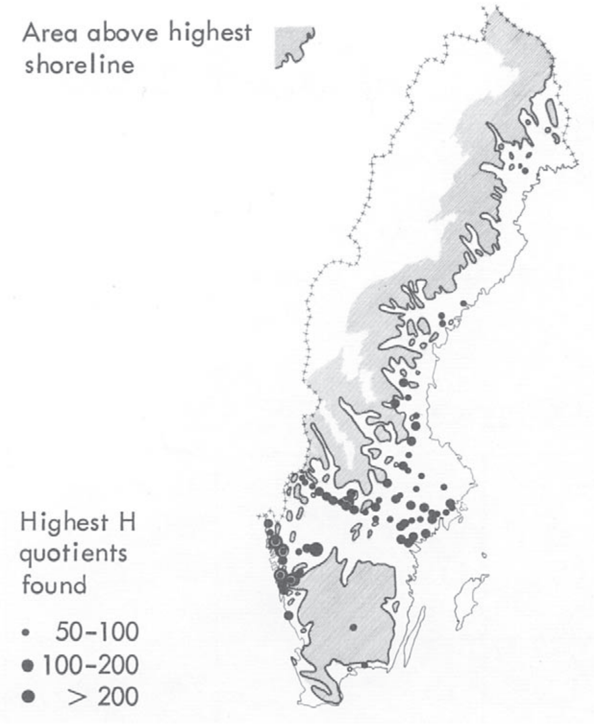


Fig. 2.1. **Occurrence of quick clay in Sweden. (After Jerbo & Hall, 1961).**

if the clay is in contact with organic substances, see Chapter 1.2.2. Clays deposited in sea water can be found by examining the highest sea level for the area. In Sweden, the highest sea level can be found on the "Map of ice regression and the highest shoreline in Sweden – Karta över landisens avsmältning och högsta kustlinjen i Sverige" (1961) .

Very little clay is found in the area adjacent to the highest shoreline. The largest deposits are found at elevations below approximately 80% of the level of the highest shoreline.

2.1.2 Thickness of clay sediments

The leaching process in a low-permeable soil is a very slow process. The thicker the sediment layer, the longer it will take for the leaching process to reduce the salt content to a sufficiently low level. Quick clays are thus more common in thin deposits and close to permeable water-conducting layers. The clay thickness may be estimated from geological maps or from earlier investigations.

2.1.3 Cambrian-Silurian bedrock

During the Cambrian, Ordovician and Silurian geological periods, bedrock of limestone was formed in seven main areas in Sweden, see Fig. 1.11. These rocks contain the two-valency cation Ca^{2+}, which as a result of weathering can be found in the surrounding ground water. Leaching with hard ground water (containing, for example, Ca^{2+} and Mg^{2+}) gives a pore water with a high concentration of polyvalent ions and thus limited possibilities of quick clay formation. This implies that clays in areas adjacent to Cambrian-Silurian bedrock, which have been leached by water that has percolated the bedrock, are seldom quick. However, it should be noted that quick clays have been found fairly close to limestone areas in Sweden. Such deposits have been found along the stream Slumpån about 15 km south of Hunneberg and in Sköttorp along the stream Lidan about 20 km south-west of Kinnekulle, among other places. Both Hunneberg and Kinnekulle are hills built up partly of Cambrian-Silurian bedrock. The direction of the ground water flow from the bedrock has to be studied in order to evaluate the likelihood of leaching with hard ground water.

Bedrock maps over Sweden are available from the Swedish Geological Survey, SGU.

2.1.4 Underlying coarse-grained material

Due to its high permeability, coarse-grained soil beneath the clay may transmit large quantities of ground water. The quantity of water depends, apart from the permeability, on the thickness of the coarse-grained layer and whether it is in direct contact with infiltrating rain water or water-conducting fractures in the rock, see Fig. 2.2.

There is often a thin layer of till between the clay deposits and the top of the bedrock. Whether this layer can be considered as water-conducting can only be determined by some type of *in situ* test.

The occurrence of larger (thicker) deposits of till underlying the clay can be inferred by looking at the location of extensive ice-marginal deposits. During the recession of the ice after the glaciation, the movement of the ice-front slowed down or stopped during colder periods. Large deposits of ice-marginal till and other coarse-grained soils were then deposited at the ice front. Large formations of ice-marginal tills are common in a wide band across Sweden from the provinces of Halland and Bohuslän in the west, across Västergötland, Värmland, Närke and Östergötland in the centre, to the provinces around Lake Mälaren and the province of Uppland in the east. Most of the quick clay formations in Sweden are found in the same area, see Fig. 2.3.

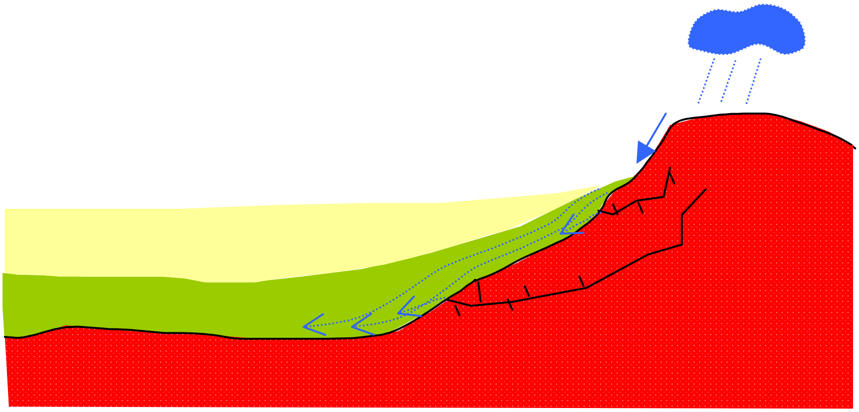
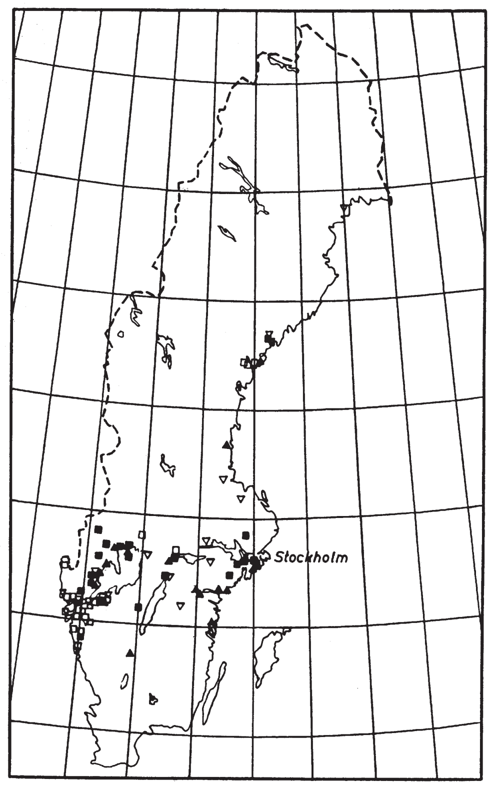


Fig. 2.2. **Ground water infiltrating a coarse-grained soil layer beneath a clay deposit.**



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. 2.3. **Occurrence of quick clay in Sweden. After Wenner (in Talme et al., 1966).**

The fracture zones in the bedrock can be studied from tectonic maps and bedrock maps. The possibility of water infiltration into the clay sediments increases in areas with frequent fracture zones.

Hydrological maps show main fracture zones and areas where laterally continuous, thick, fine-grained sediments occur, and in which water-bearing sand and gravel layers may be found beneath the clay.

2.1.5 Peaks in the bedrock surface

If there is a local peak in the surface of the bedrock underlying the soil, the outflow of ground water may be concentrated to this point. A concentration of the outflow of water results in more extensive leaching and thus a greater possibility of quick clay formation at this point, see Fig. 2.4. Such areas may be found by an inspection of the ground surface and the topography. If the ground surface has a small depression, which cannot be explained in any other way, this may be an indication of quick clay formation below.

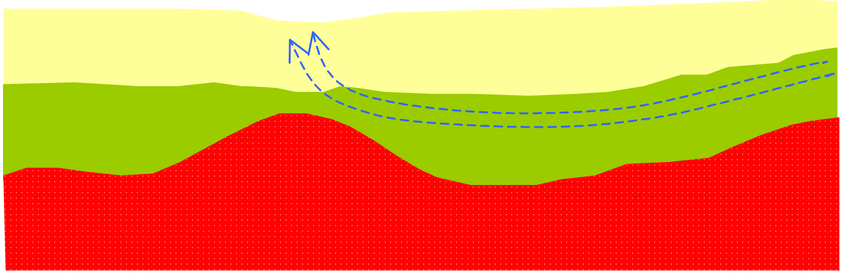


Fig. 2.4. Peak in bedrock surface causing a concentrated outflow of ground water through the clay and thus increased leaching.

2.1.6 Artesian ground water

There are mainly three different types of leaching process: rain water percolating through the deposit, an upward hydraulic gradient and diffusion (see Chapter 1.2.2 and section Leaching of salt). The rate of the leaching process is affected strongly by the hydraulic gradient. Areas with a high artesian ground water pressure therefore have better prerequisites for quick clay formation than areas with hydrostatic ground water conditions.

The risk of artesian ground water conditions is highest where thick water-conducting layers are found below the clay deposits, where the bedrock surface is sloping and rain water from higher ground is led into the layers beneath the clay deposits, and where the bedrock has many fracture zones.

Downward gradients in the pore water may have an effect similar to that of artesian water pressures if the surface run-off is insufficient or if the clay layers are overlaid by water-bearing formations.

Possible occurrence of underlying water-bearing layers of sand and gravel is given on hydrological maps.

2.1.7 Layers with high permeability within the clay deposit

The occurrence of permeable layers such as silt and sand layers, that are embedded in the clay deposit and are in contact with surface water or other water-conducting layers, increases the possibility of leaching. The occurrence of layers with high permeability depends on variations during sedimentation, i.e. in the distance to the ice front, the material carried and deposited by the streaming water, the flow velocity, the topography, the sea water level and on the situation after the ice regression (post-glacial sediments). Major geological events causing formations of distinctly different layers are temporary re-advancements of the ice front during colder periods, transgression periods with rising sea-level, the breaking through of ice-dammed lakes etc.

Geotechnical and geological investigations carried out in or close to the area of interest should be studied in order to estimate the possibility of such layering.

2.1.8 Height above present sea level

Sediments at higher elevations have been above the sea for a longer period compared with those at lower elevations. The time available for leaching has therefore been longer for the sediments at a higher level. For two areas with all other prerequisites being equal, the area with the highest elevation has the greatest possibility of quick clay formation. Exceptions are clays located above the elevation of the highest shoreline, which have not been deposited in sea water.

2.1.9 Organic soils

Through contact with organic materials, such as peat and other soils rich in humus, bark heaps etc., the ion composition in the pore water may change and thereby provide preconditions for quick clay formation.

Organic soil deposits are shown on geological maps. The occurrence of quick clay in connection with organic soil in eastern Sweden is shown in Fig. 2.5. (see also Fig.2.1 and 2.3)

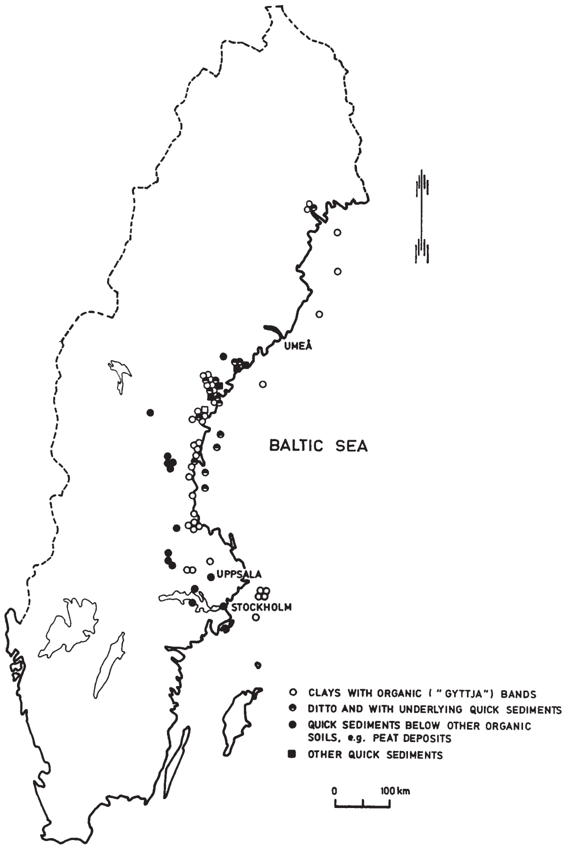


Figure 2.5. Occurrence of quick clay in eastern Sweden. (After Söderblom, 1974).

2.1.10 Catchment area

The possibilities of leaching increase with an increasing amount of water percolating through the deposit. The amount of water depends on the annual precipitation and on the size of the catchment area. The catchment area is the area from which all precipitation (except for evapotranspiration) is led to the clay deposit studied. The larger the catchment area is, the larger will be the potential for leaching.

The extent of the catchment area can be determined from topographical maps.

2.1.11 3D-effects

In areas surrounded by bare hills in more than one direction, the possibility of water infiltration and leaching is enhanced. The surrounding topography can be studied from topographical maps.

2.1.12 Flowchart for finding areas with prerequisites for quick clay

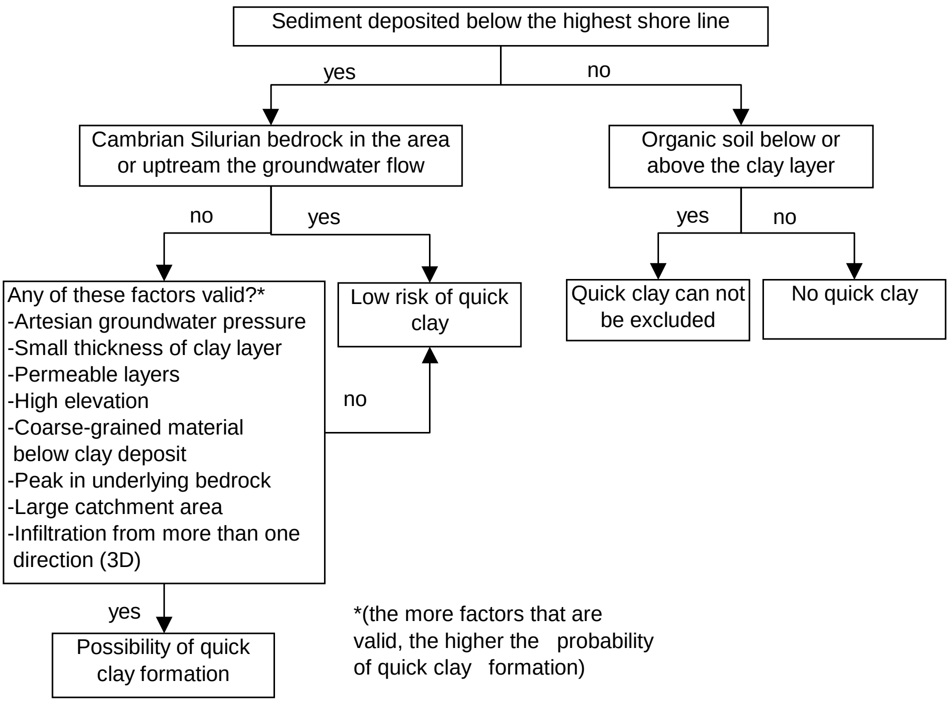


Fig. 2.6. Flow chart for distinguishing areas with prerequisites for quick clay formation.

2.2 EXAMPLES OF PREREQUISITES FOR QUICK CLAY FORMATION IN THREE AREAS IN SOUTH-WESTERN SWEDEN

This chapter provides a description of the prerequisites for quick clay in three areas in south-western Sweden. The prerequisites are discussed according to the guidelines given above. Quick clay has been found in all three areas. Two of the areas, Torp and Utby, have been used as test sites in this project, see Chapter 3.2.2 of the report.

2.2.1 Torp

Torp is located in the community of Munkedal on the west coast of Sweden, about 115 km north of Göteborg. Parts of the community border on the bay named *Saltkällefjorden*. Torp is situated on the west bank of the river *Örekilsälven*, see Fig. 2.7, along which the stability conditions are known to be unsatisfactory in many places. In the mid 1980's, the Torp area was stabilised by a large excavation along the slope crest. For a more detailed description of the Torp area, see Larsson and Åhnberg (2003) and Part 3 of this report.

Fig. 2.7 Photo of the Torp test site.

Information from the "Hydrological map of the county of Västra Götaland (western part)" (SGU, Serie Ah nr 12), the geological map (SGU, Serie Ac nr 3), the bedrock map of the county of Göteborg and Bohus (SGU, Serie Ah nr 12) and from Larsson and Åhnberg (2003) has been used in the following description.

Highest coastline
The sediments were deposited in salt water after the latest glaciation, which in this area ended about 12,400 years ago.

Thickness of clay sediment
The valley along the river *Örekilsälven* is surrounded by bare rock hills, which rise about 75 m above the present sea level. Fine-grained sediments were deposited in the valley after the retreating ice front had passed the area. Later on, the land rose from the sea and Örekilsälven was formed. The river transported new materials, which were deposited on top of the clay sediments. These new sediments became coarser as the river mouth approached the area and sand and silt layers now overlie the clay deposit. Since the period of deposition, the river has eroded its channel approximately 20 m through the sediments. Due to the topographical conditions and the eroded river course, the thicknesses of the soil layers vary within the area, with thinner layers close to the valley sides and below the river. In spite of the erosion process, the fine-grained soil layers are thick in the central part of the valley, and at least 40 m of low-permeable clay remains in this part.

Cambrian-Silurian bedrock
The bedrock at Torp consists of grey, usually veined gneiss. There is no limestone in the vicinity.

Underlying coarse-grained soil
From earlier geotechnical investigations, it can be inferred that a layer of till underlies the clay sediments. The till layer is estimated to vary and be from 1–2 metres and up to about 10 metres thick.

Peak in the bedrock surface
A study of the surrounding topography shows that it is most likely that the bedrock surface varies. No depressions in the ground surface could though be detected.

Artesian ground water
The pore pressure situation in the clay is probably affected by a high permeability in the overlying layers of sand and silt, the water level in the river and the underlying layer of till. Rain water may infiltrate the layer of till where it reaches the ground

surface at the valley sides. Since the bedrock and the ground surface slope towards the central parts of the valley, water from the catchment area on the hillsides will infiltrate the till layer at an elevation that is higher than the ground surface in the central parts of the valley and much higher than the water level in the river. Thus, there are prerequisites for artesian ground water in these parts. The underlying layer of till also provides preconditions for a downward pore pressure gradient in the ground higher up towards the valley sides.

On the tectonic map, no distinct fracture zones are shown within the area. On the hydrological map, the area is designated as an area with continuous, thick, fine-grained sediments. Water-conducting sand and gravel may occur in or beneath these sediments.

Artesian ground water has been measured below the river bank and river bed, and downward pore pressure gradients have been measured in higher ground.

Layers with high permeability within the clay deposit
No high-permeable layers have been found in the geotechnical investigations of the clay deposit.

Height above present sea level
The area is located below the highest shoreline and at an elevation between 5 and 20 meters above the present sea level.

Organic soils
No organic soils have been found in the area.

Catchment area
The catchment area around Torp on the west side of the valley extends to the ridge of the hill at a height of 70 m above the present sea level. The size of the catchment area is about 1.5 ha.

3D-effects
The valley at Torp is narrow and there is thus a possibility of water infiltration from two sides.

Results
According to the conditions listed above, quick clay could be expected below the sand and silt layers and along the valley sides. Geotechnical investigations have shown that quick clay is present in the area, as shown in Fig. 3.49. As can be seen,

a deduction that quick clay may be found towards the valley sides is correct. A deduction that quick clay may be found close to the upper sand and silt layers is also valid. Quick clay is not found where the clay layer is very thick.

2.2.2 Utby

The Utby area is located about 10 km north of the community of Lilla Edet along the west side of the river *Göta älv*. The river makes a sharp turn around a couple of small outcropping hillocks just upstream of the Utby area. This is a rural area with farmland all the way from the riverbank up to the nearest buildings and the public road about 1 km away. The area nearest the river is used solely as pastureland. Most of the area is flat or slopes only gently towards the river and then changes to steep slopes down to the river or in the ravines at its tributaries. Further to the west, the area is bordered by a range of bare hills extending to a level of around 150 metres above the present sea level. A number of small streams, which have eroded gullies in the clay deposit, carry water from the mountains through the area towards the river. The area is described in more detail in Chapter 3.2.2.2 of this report.

Information from the Hydrological map of the county of Älvsborg (SGU, Serie Ah nr 13), the geological map (SGU, Serie Ae nr 48) and from the bedrock map of the county of Älvsborg (SGU, Serie Ah nr 13) has been used in the following description.

Geological processes that have formed the sediments in the valley of the river Göta älv

During the regression of the latest inland ice, extensive sediments of clay began to be deposited in the valley of the river Göta älv. The deposition started about 12,000 years ago. At this time, the sea level was located 125 m above its present level and the sediments were thus deposited in salt water. The glacial clay formed by this process shows a higher content of silt towards the top of the profiles compared to the postglacial clay deposit above. In the central part of the valley, extensive post-glacial clays were deposited on top of the glacial clay. By the end of the period of deposition, when the area was still below sea level, a river had been formed which entered the valley at Lilla Edet. This river transported sand and silt particles, which were deposited on the post-glacial clay. The ice regression was not a continuous process, but was often subject to stops and re-advancements. During re-advancements of the ice front, coarser material was deposited on top of the existing clay layers and such embedded coarser layers have been found in many places along the Göta älv valley. Many landslides have occurred, both during and after the sedimentation period, which has led to a disturbed and irregular soil layer formation in many places.

The ice-marginal deposits constitute moraine ridges of some length stretching in a south-east – north-west direction. The largest ice-marginal deposits in the county of Västra Götaland (the provinces of Bohuslän and Västergötland) are the Göteborg till, the Berghem till and the Trollhätte till (Engdahl et al., 1999), see Fig. 2.8.

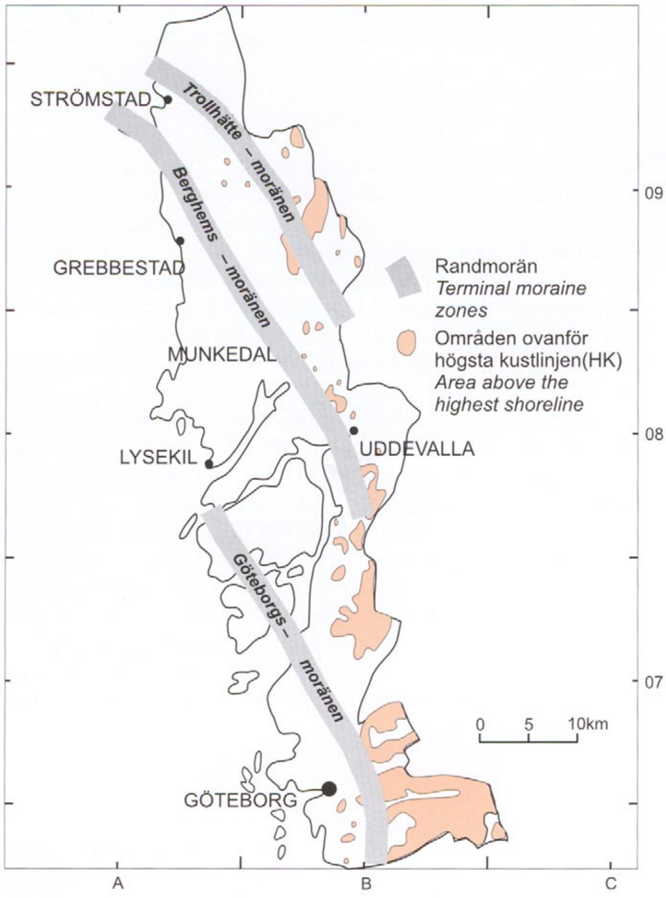


Fig. 2.8. Larger ice-marginal deposits in the county of Västra Götaland. (After Engdahl et al., 1999).

Highest shoreline

The area is located well below the highest shoreline and the sediments were deposited in sea water.

Thickness of clay sediment

The soil is characterised by extensive deposits of glacial clay sediments, whose thickness increases from the foot of the hills on the western side of the valley towards the river. The uppermost layers consist of glacial fine to coarse silt, fine sand and silty clay. Below the clay, a moraine layer is assumed to exist on top of the bedrock. Sandy till is found close to the outcropping hillocks to the north and the hills to the west of the Utby area.

The thickness of the clay depth is assumed to be approximately 40 metres below the riverbanks and then decreases gradually toward the hillocks and the valley sides.

Cambrian-Silurian bedrock
The bedrock in this part of the valley consists of grey, usually veined, homogenous or banded gneiss. No limestone exists in the vicinity.

Underlying coarse-grained material
The clay has been assumed to be resting on a layer of till on top of the bedrock. No investigations have been made to determine the thickness of the till layer. On the hydrological map, the area is designated as an area with continuous thick clay. Water-conducting sand and gravel may occur within and beneath the clay.

Peak in the bedrock surface
Directly upstream of the site, the river makes a sharp turn around a couple of small outcropping hillocks. The existence of buried hillocks below the ground surface cannot be excluded on the basis of the geological and hydrological maps and descriptions alone.

Artesian ground water
The bedrock slopes downwards from the hills in the west to the central part of the valley. Water may infiltrate the presumed till layer where it surfaces at the hill sides and flow towards the central part of the valley, creating artesian pressures there. Infiltration may also occur at the hillocks directly upstream of the site, although the catchment area is very small here. In higher ground, the till layer would provide conditions for a possible downward pore pressure gradient.

Larger fracture zones are found in the bedrock within the area. These zones stretch in the same direction as the river. A fault line is also found in a north-east and south-west direction.

Slightly artesian ground water pressures have been measured at the riverbanks.

Layers with high permeability within the clay
A thin and very hard layer of coarse soil has been found approximately 40 metres below the ground surface (see also Part 3 of this report).

Height above present sea level
The area is located about 30 metres above the present sea level.

Organic soils
No organic soils have been found in the area.

Catchment area
The catchment area for the clay deposit extends to the hill ridge at a height of 150 m above the present sea level on the west side of the valley. The size of the catchment area is about 600 ha. However, much of the run-off water is led down to the river through the small streams and gullies.

3D effects
No specific 3D effects exist in the area.

Results
According to the conditions described above, quick clay could mainly be expected in higher ground towards the valley sides and close to the hillocks where the thickness of the clay layers is limited. Geotechnical investigations have shown that quick clay is present in the area, as shown in Fig. 3.48. As can be seen, the deduction that quick clay may be found in areas with limited thickness of the clay layers is correct. The same areas also have preconditions for a significant downward gradient in pore pressure and are flat enough to prevent efficient surface run-off. No provisions for surface drainage have been installed in the area, which is used solely as pastureland.

No quick clay is found in parts of the area with very thick clay layers and hydrostatic or only slightly artesian pore pressures.

2.2.3 Agnesberg

In 1993, a landslide occurred at Agnesberg on the east side of the river Göta älv. The event is believed to have started as a small underwater slide in the steep slope towards the fairway. The landslide at Agnesberg has been described by Larsson et al. (1994).

The river valley in the area of Agnesberg is characterised by a wide valley with a flat ground surface surrounded by steep, high hills. The difference in elevation between the ground in the valley and the hill ridges is up to 100 metres. A side valley at an orientation of about 90° to the main river valley reaches some distance into the eastern hill ridge here. The difference in elevation between the water level in the river and the ground surface at the end of the side valley is about 50 metres.

The river outside Agnesberg is shallow, only 1–2 metres deep. There is then a steep slope down to the dredged fairway, in which the depth is about 8 metres.

Information from the “Hydrological map of the county of Västra Götaland (westen part)” (SGU, Serie Ah nr 12), the geological map (SGU, Serie Ae nr 72), the bedrock map of the (former) county of Göteborg and Bohus (SGU, Serie Ah nr 12) and from Larsson et al. (1994) has been used in the following description.

Highest coastline

The area is located well below the highest shoreline and the sediments were deposited in sea water after the latest glaciation, which ended about 12,000 years ago.

Thickness of clay sediments

The clay sediments have a thickness of about 35 metres in the central part of the valley and become thinner towards the valley sides. Fluvial deposits of sand are found on top of the clay sediments in some places.

Cambrian-Silurian bedrock

The bedrock in the area consists of grey and usually veined gneiss. No limestone exists in the vicinity.

Underlying coarse-grained material

The ice regression from the west coast of Sweden is characterised by temporary stops and re-advancements of the ice front. During such periods, ice-marginal deposits were formed and layers of coarse-grained material sedimented on top of previously deposited clay sediments. An extensive ice-marginal deposit of till (the Göteborg till, see Figure B10) is found beneath the clay sediments in the Agnesberg area. This till deposit becomes visible close to the bare rock in the hills at the valley sides. Here, rain water has a possibility to infiltrate the till beneath the clay.

Peak in the bedrock surface
The surrounding topography indicates that the bedrock surface varies below the clay**.** However, no depression could be detected in the ground surface.

Artesian ground water
The pore pressure distribution in the clay is probably affected by the high permeability in the underlying till. Prominent fracture zones in the bedrock are found within the area and run parallel to the river. In the side valley, a prominent fracture zone is also found in the bedrock, which stretches towards the main valley.

Artesian ground water pressures have been measured in the till. The pressure corresponds to a pressure level 6–8 metres above the mean water level in the river, see Fig. 2.9.

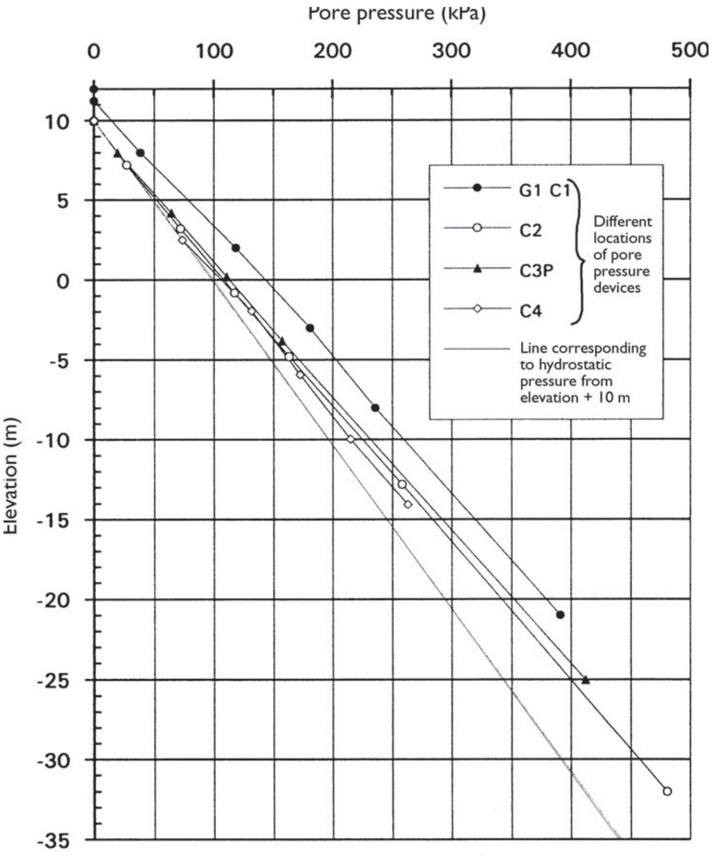


Fig. 2.9. Measured ground water levels and pore pressures close to the river Göta älv in the Agnesberg area (after Larsson et al., 1994).

Layers with high permeability within the clay
No layers with significantly higher permeability have been found in the clay in the area.

Height above the present sea level
The clay area is located between just a few metres and up to about 50 metres above the present sea level. The higher levels refer to the side valley.

Organic soils
No organic soils have been found in the area.

Catchment area
The catchment area for the clay deposit extends to the hill ridge at a height of 100 m above the present sea level on the eastern side of the valley. The hills are steep and are situated close to the area. Water is led directly from the hill sides into the till beneath the clay and also via the side valley. The size of the catchment area is about 400 ha.

3D-effects
Because of the side valley, the area is affected by water infiltrating from more than one direction.

Results
According to the description given above, quick clay could be expected to be found along the sides of the main and side valleys. Due to the high artesian ground water pressures, quick clay could possibly also be found closer to the central part of the valley, mainly in the lower parts of the clay deposit.

Resistivity measurements done in the area showed a lower salt content in the upper and lower layers. Accordingly, geotechnical investigations showed occurrence of quick clay in layers close to the ground surface, in deep seated layers and right below thhe bottom of thr river. Large deposits of quick clay were also found in the side-valley.

2.3 DISCUSSION

From the description given in Chapter 2.2, it is seen that there are a number of main prerequisites for the formation of quick clay. They are:

- limited thickness of the clay deposit
- large thickness (i.e. large water-conducting capacity) of the underlying coarse sediments
- possibility for infiltration of water into the water-conducting layer and
- clay sediment deposited in sea water

Quick clays are thus found mostly in areas:

- close to valley sides where bare rock becomes visible
- above (and below) thick and continuous deposits of coarse sediments (sometimes only in parts of the clay layers which are located close to the coarser layer)
- close to outcropping (and buried) hillocks

As part of the project, a search was made for an area in western Sweden where the prerequisites existed but no quick clay could be found. However, the search was unsuccessful. In this region, it is thus relatively unusual for all the prerequisites to be fulfilled, but without finding quick clay. This fact has been confirmed by Hellgren (2004).

In general, all clays which have been deposited in salt water may become quick as a result of leaching. The main restrictions are the availability of water, the conditions governing water seepage through the clay, and the duration of leaching. On certain occasions, the ion composition of the leaching water is also a restriction. Moum et al. (1971 and 1972) presented an area in Drammen, Norway, where quick clay was found only in the central part of the clay deposit, see Figure 20. The explanation given by the authors was that the clay had probably been quick in the lower parts but had reverted to non-quick clay through weathering of two valid ions. An analysis of the ion composition in clays deposited in or adjacent to areas with Cambrian-Silurian bedrock would be interesting for understanding the influence of polyvalent ions on the formation of quick clay. However, this is beyond the limits for this project.

The main factors preventing the formation of quick clay in areas where the main prerequisites exist are weathering and consolidation. Weathering releases ions bonded to the clay minerals and counteracts the leaching process. Quick clay is thus never found in or directly beneath weathered dry crusts. Consolidation reduces the natural water content in the soil. If this is reduced to values close to or below the lowest liquid limit that can result from leaching, the clay will neither be quick nor will it become so.

Chapter 3.
Mapping of quick clay formations by geotechnical and geophysical methods

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3.1 EXISTING METHODS OF QUICK CLAY MAPPING

3.1.1 General

There are no generally adopted methods of quick clay mapping in Sweden. In most cases, the existence of quick clay is observed in the results of the ordinary geotechnical investigations for different projects, mainly in the routine laboratory investigations which includedetermination of the sensitivity. The extent of the quick clay formation is then estimated from the existing results of the investigation and various arbitrary considerations.

3.1.2 Geotechnical methods

Correlations between sounding resistance and sensitivity were investigated by Möller and Bergdahl (1982) for the most commonly used sounding methods in Sweden at that time*. These methods were the traditional weight sounding test and static pressure sounding. Since quick clays occur most frequently in western Sweden, a study was made of a local variant of the static pressure sounding test in which a weight sounding tip is connected to 25 mm rods and pushed down at a constant rate. The investigation was based on previous Norwegian observations that the slope of the penetration resistance versus depth curve in clay could be linked to the sensitivity (Rygg 1978), see Fig. 3.1.

* The sounding methods that are relevant for this report are described in Chapter 31.2.

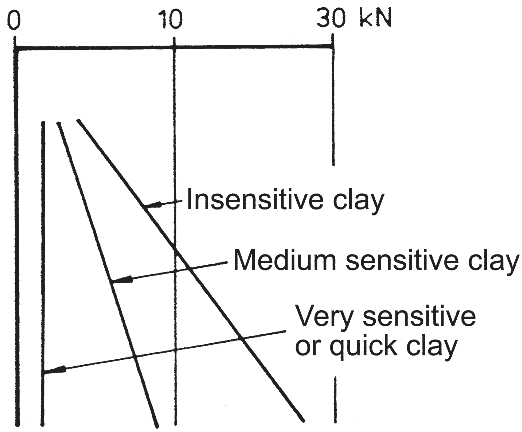
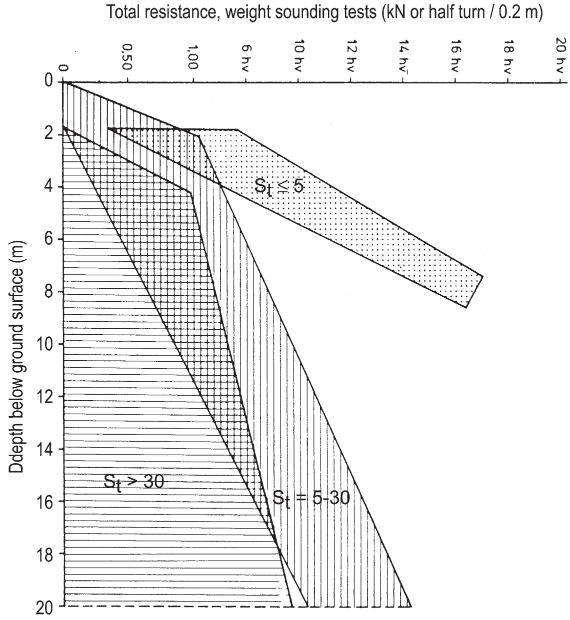


Fig. 3.1. Schematic correlation between slope of penetration resistance versus depth and sensitivity (Rygg 1978).

Certain correlations were found also in the Swedish investigation. Tentative charts were proposed for sounding resistances versus depth with certain fields assigned for certain ranges of sensitivity, Fig. 3.2. However, these fields presuppose that the soil is fairly homogeneous throughout the profile and that there is a "normal" dry crust but no other layers causing high rod friction which lie on top of or are embedded in the clay. The utilisation of these charts has therefore been limited.

For the static pressure sounding, another correlation was presented, in which the slope of the static force – depth curve was related to the sensitivity, Fig. 3.3. It was stated that if this curve had an inclination of less than 4 degrees from the vertical, the clay was likely to be highly sensitive or quick. With the standard scales for presentation, this limit corresponds to an increase in penetration force of 0.07 kN/m. This type of correlation has been used to some extent in subjective estimates of the relative sensitivity, although no specific limits have normally been applied.

In Norway, there is an accepted method for establishing the presence of quick or highly sensitive clays in connection with slope stability assessments. This involves rotary pressure soundings at uniform distances of about 150 metres along a slope crest and at points located up to 75 metres behind the crest (Løken, 2002). Possible quick clay formations at greater distances from the slope are normally not considered. The results of the rotary pressure soundings are scrutinised along the guidelines presented by Rygg (1978) and any parts of the curves that are smooth and almost vertical are designated as very sensitive clay. The actual sensitivity is then checked by field vane tests, if required.



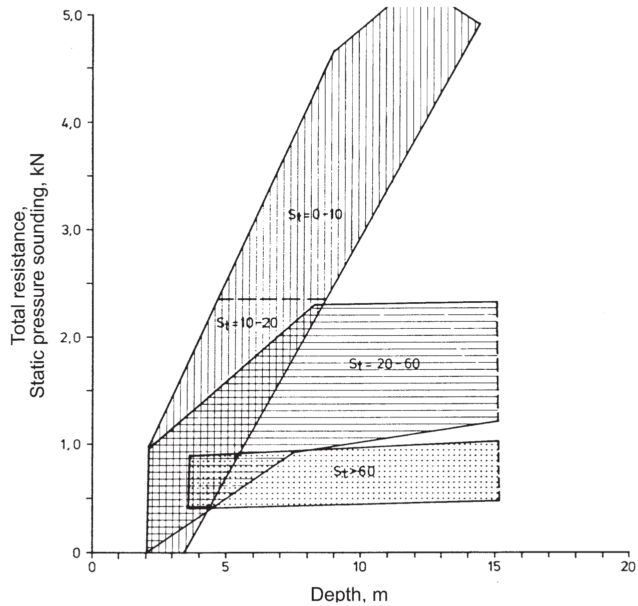


Fig. 3.2. Proposed areas in diagrams of penetration force versus depth for different ranges of sensitivity (Möller and Bergdahl 1982).
a) Weight sounding test
b) Static penetration test

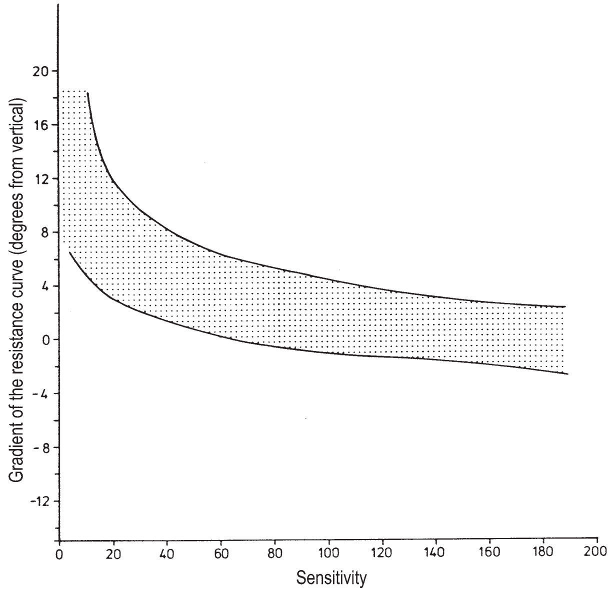


Fig. 3.3. Slope of penetration resistance versus depth in relation to the sensitivity of the penetrated clay (Möller and Bergdahl 1982).

The Norwegian method is not straightforward in regard to its application in Sweden. The rotary pressure sounding method is rarely used here. The crest of the slope is not easily defined in a gently sloping and undulating terrain, and several large landslides have started in quick clays located far from the most pronounced crests. The field vane test has also been found to be inappropriate for accurate determinations of the sensitivity owing to thixotropic effects as well as insufficient accuracy and resolution of the measurements.

3.1.3 Geophysical methods

In marine clays that have been leached by fresh water, there is often a link between the salt content and the sensitivity of the soil, as well as between the salt content and the electrical resistivity of the soil. However, a low salt content does not necessarily imply that the clay is quick but only that a precondition for this exists. Torrance (1974) found that the salt content had to be reduced below 2 g/litre (0.2%) before quick clay can be formed, Fig. 3.4. The corresponding resistivity varies somewhat with the porosity of the soil since it is mainly the pore water that is conductive (Penner, 1965). Laboratory studies on a typical Swedish clay have shown that a content of 0.2% NaCl corresponds to a resistivity of between approximately 6 and 13 Ωm for the range of bulk densities of interest for quick clay formation in Swedish clays, Fig. 3.5. Clays with lower densities are normally organic and clays with higher densities normally have water contents well below their liquid limits. In both cases they are not quick.

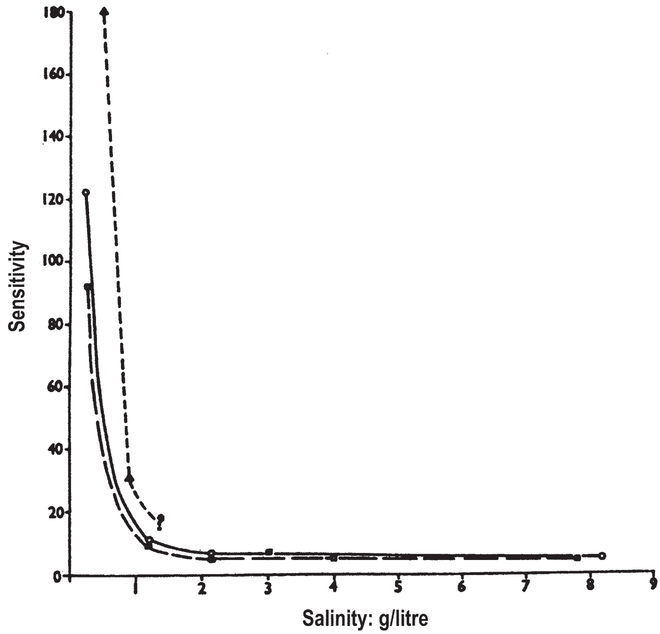


Fig. 3.4. **Sensitivity as a function of salinity at leaching of marine clays (Torrance, 1974).**

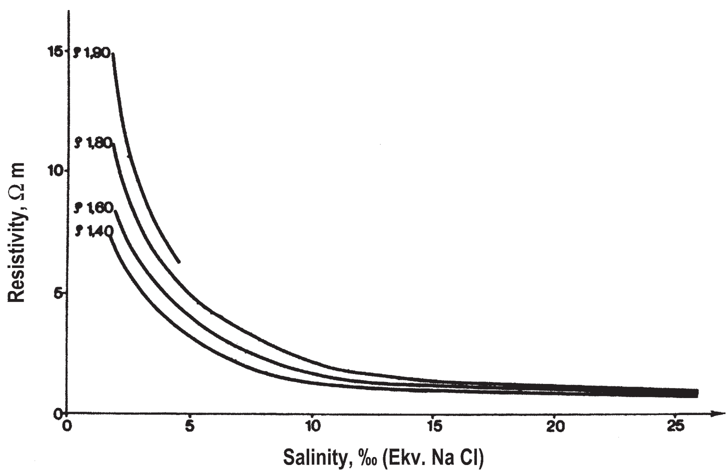


Fig. 3.5. **Resistivity in typical Swedish clay as a function of salinity and bulk density (Larsson, 1974).**

During the 1950's, a special "salt probe" was developed (Söderblom, 1969). The probe was pushed down into the soil and the resistivity was measured throughout the profiles. The method appeared to work satisfactorily and certain relations were established. Söderblom found that the resistivity was higher than 5 – 10 Ωm in quick clays. However, when using the salt probe, data were only obtained at individual points and the method was not very rational with the measuring and data processing techniques of that time. A resistivity higher than the given limit also only indicated that the clay could be quick, but a high resistivity could correspond to any sensitivity.

Recent investigations using surface resistivity measurements have shown that good continuous two-dimensional pictures can be obtained of the variation of the resistivity in whole sections of an investigated area (Dahlin et al., 2001). By combining several sections and cross-sections, a continuous three-dimensional picture can be obtained of the whole soil volume. Since the variation in resistivity largely reflects the variation in salt content in marine clays, also a good picture of this variation can be obtained. The results of one investigation showed tentatively that a good picture of the variation in sensitivity could be inferred from the picture of the variation in resistivity and in the particular case the limit for possible quick clay was at 7 Ωm. It was therefore recommended that the method be tested further.

3.2 Methods of quick clay mapping used in this project

3.2.1 Soundings

Rotary pressure sounding

Rotary-pressure sounding is a Norwegian method developed in the 1960's (see Statens vegvesen, 1997). It uses a twisted tip that is similar to the tip in the weight sounding test but larger. The tip is manufactured from a steel bar with a rectangular cross-section of 25 x 41 mm, which is twisted and then shaped into a conical tip at the lower end. One of the outer ridges of this screw is supplied with an extra hard welded top. The length of the tip is 225 mm and the projection of the cross-section has a diameter of 55 mm, Fig. 3.6.

The tip is attached to ϕ 36 mm sounding rods and pushed down into the soil at a rate of 3 ± 0.5 m/min while rotating at 25 ± 5 rpm. The drill rig shall provide a pushing force of at least 30 kN and a torque of about 1 kNm.

Rotary pressure sounding was extensively used in Norway up to about 1990. Thereafter it has been gradually replaced by the now predominant total sounding method (Hagberg 2003).

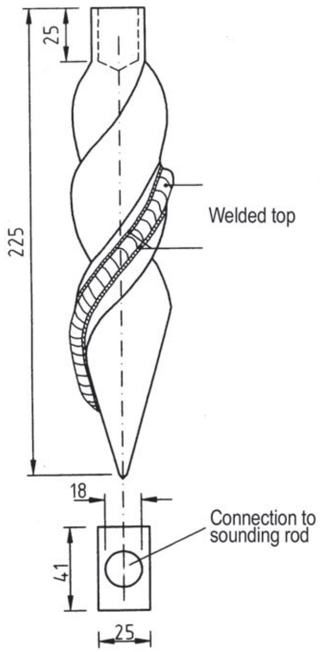


Fig. 3.6. Rotary pressure sounding tip.

Total sounding

The total sounding method was developed in Norway in order to obtain a method that is sensitive enough to register all significant strata in a soil profile and their relative stiffness, and which is still able to penetrate all types of fills and soil layers as well as large blocks and bedrock (Statens vegvesen 1997, Hagberg 2003). The equipment is therefore supplied with a tip consisting of a specially designed drill bit with a diameter of 57 mm. This contains a spring loaded ball valve for the flushing medium, which prevents soil from entering the drill bit when this is driven without flushing but allows the flushing medium to flow out when so desired, Fig. 3.7.

The drill bit is connected to hollow ϕ 45 mm steel rods of the same type as those used for soil-rock drilling (so-called geo-rods). The equipment can be driven into the soil in different ways depending on the penetration resistance. In soft soil layers, it is advanced in the same way as in rotary pressure sounding, i.e. at a rate of 3 ± 0.5 m/min and a rotation of 25 ± 5 rpm. The required pushing force and torque are also the same, i.e. 30 kN and 1 kNm.

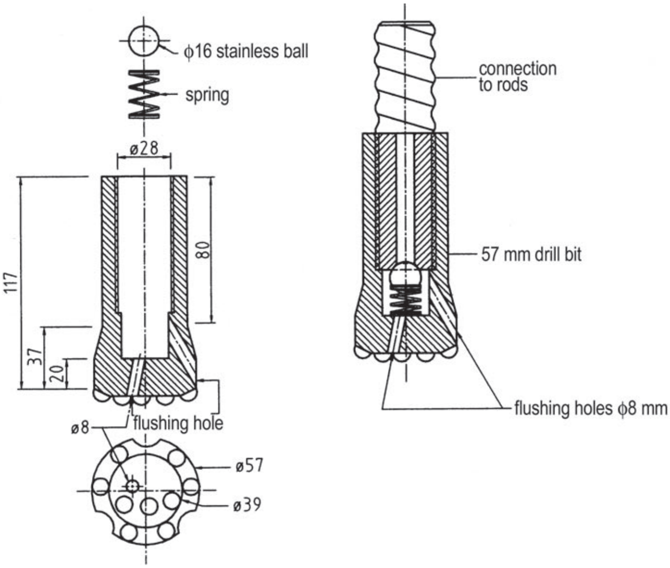


Fig. 3.7. Drill bit for total sounding.

When this driving work becomes insufficient to penetrate the soil, the rate of rotation is increased to 50 – 70 rpm. If this is insufficient, the rotation speed is returned to normal, flushing is commenced and driving continues at the normal rate of penetration. If this in turn proves insufficient for penetration, the pushing force is reduced and percussion drilling with simultaneous rotation and flushing is started. Whenever a stiffer layer is penetrated and softer underlying layers are encountered, the drilling mode is returned to only pushing and rotation.

Control to ensure that bedrock has been reached is normally performed by drilling 3 metres into the rock.

The method requires a heavy drill rig (for Scandinavian conditions). It must be able to provide a regulated rate of rotation of 0 – 100 rpm, a hammer effect of 8 kW, a blow frequency of at least 1000 blows/min and a flushing-water pressure of 8 bars at a flow rate of 40 litres/min. Water is the normal flushing medium but may be replaced by compressed air. In this case, the compressor must deliver air at a pressure of 8 bars and volume of 7 m^3/min.

Static pressure sounding

Static pressure sounding was developed in Sweden during the 1950's (SGF 1996). The original equipment has a tip with a square cross-section of 34 x 34 mm giving a projected area of 1000 mm^2. The tip is connected to the drill rods through a slip coupling which enables the tip to move freely in relation to the rods over a distance of 50 – 100 mm in the pushing direction. The tip is pushed down into the soil at a constant rate of 20 mm/s, (1.2 m/min) and the total pushing force is measured. After each stroke of 1 or 2 metres, new rods are attached and the rod assembly is lifted a distance corresponding to the stroke of the slip coupling. At the next stroke, the friction along the rods is measured first, followed by the total penetration force after the coupling has been re-engaged. In this way, the rod friction can be separated and the tip resistance evaluated. After the maximum pushing force has been reached, the system is rotated to achieve further penetration, if possible.

The original equipment was of lightweight, manually operated design with a special crank-jack and mechanical recording. It used 22 mm rods and the maximum pushing force was 10 kN. Rotation was seldom used in the early days of the equipment.

Today, modern crawler rigs with hydraulic pushing and rotation devices are used. In this context, the pushing force has been increased to 20 kN and the rod diameter to 25 mm. The pushing force is reduced to 5 – 9 kN before rotation is started. Nevertheless, the original tip and the slip coupling have proved to be vulnerable parts in this application and, since these are expensive to replace, they are often exchanged for a standard twisted weight sounding tip. The latter has approximately the same projected cross-sectional area as the original tip, i.e. 1000 mm^2, see Fig. 3.8. This exchange does not allow separation of the rod friction from the total friction, which would be desirable for estimation of the sensitivity. However, the rod friction is only measured after making stops to add new rods and to raise the jack for a new stroke. Owing to the

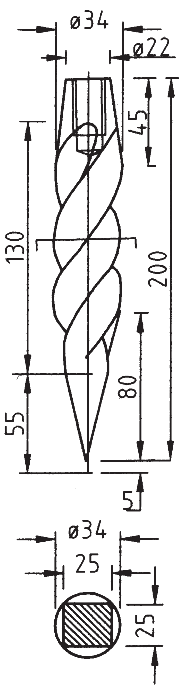


Fig. 3.8. Standard tip for weight sounding tests also often used in static pressure soundings.

reconsolidation and thixotropic effects occurring during this time, the measured value of the rod friction when resuming sounding may be highly erroneous and the stroke of the slip coupling is far too small to enable these effects to be eliminated.

Cone penetration tests

The cone penetration test, CPT, normally measures cone resistance, sleeve friction and penetration pore pressure (SGF, 1993a). The sleeve friction is measured along the perimeter of an approximately 133 mm long portion of the probe located just above its conical tip, Fig. 3.9. The probe has a diameter of 36 mm and a projected cross-sectional area of 1000 mm^2. It is attached to sounding rods, which in this case also had a diameter of 36 mm. The probe is pushed down into the soil at a rate of 20 mm/s (1.2 m/min).

The sleeve friction, like the friction along the rod system, should in principle be related to the remoulded shear strength of the soil in the shear zone between the penetrating equipment and the soil. However, the sleeve is located so close to the tip that, depending on the work required to completely remould the soil, the soil will normally be only partly remoulded here.

Because of practical limitations, the accuracy of the measurements is also restricted. In highly sensitive clays, most of the recorded friction is an effect of the pore pressures acting on the end surfaces of the sleeve. Even after careful calibration and correction for all known sources of error, the accuracy of the measurements will not be better than ± 2 kPa. This accuracy refers to the most accurate application class used in Sweden. For most probes, the accuracy will be considerably less. This should be put in relation to the limit in the classification, where quick clay has a remoulded shear strength of ≤ 0.4 kPa and a proper calculation of the sensitivity would require an accuracy of approximately 0.1 kPa.

The total penetration force is normally not measured in a CPT test. However, this can be done fairly easily if the drill rig is equipped for any penetration test where the pushing force is

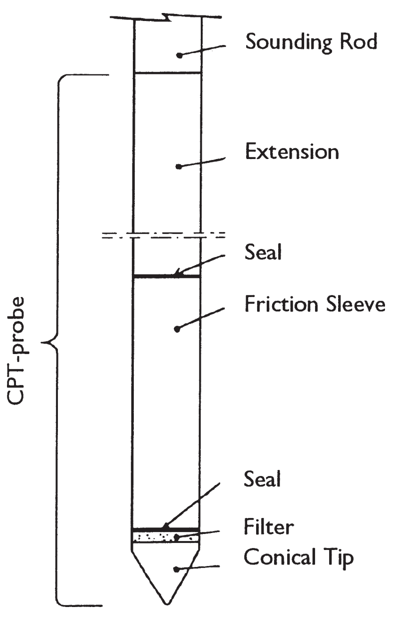


Fig. 3.9. Geometry of a CPT probe.

measured in the rig itself, e.g. rotary pressure sounding, total sounding or static pressure sounding. In this case, the weight of the equipment can be added and the tip resistance subtracted from the total penetration force. A sounding is obtained in which both the friction at the tip and the friction along the perimeter of the whole equipment are obtained as functions of penetration depth.

3.2.2 Comparison of the sounding methods

The static pressure sounding test uses the simplest and most easily operated equipment. Since the twisted tip with an overall diameter of 35 mm is pushed straight down, it causes a considerable remoulding of the soil. As it is considerably larger in diameter than the ϕ 25 mm push rods, it also acts as a friction reducing expander of the drill hole. Although it uses the lightest type of equipment, it has in this investigation also proved to be the type that is most prone to sink under its own weight without any extra pushing force in profiles with quick clays.

The rotary pressure sounding equipment is similar in appearance, but with a ϕ 55 mm overall diameter of the tip and ϕ 36 mm sounding rods. The equipment is thus heavier, but the test takes less time since the penetration rate is 3 m/min compared to 1.2 m/min. The pitch of the twisted tip and the rate of rotation match approximately the rate of penetration, and the equipment is thereby more or less screwed down into the profile. The remoulding of the soil and the relative expansion of the hole by the tip are thereby reduced. On the other hand, the simultaneous rotation and pushing entails that only part of the friction force along the rods is taken up and recorded as a vertical force. The test method is in most cases being replaced by total sounding, but experience in estimating the sensitivity of the soil is larger with this method.

Total sounding uses the heaviest equipment, which apart from a heavy drill rig also requires a supply of high-pressure flushing water or compressed air. The rate of penetration is the same as for rotary pressure sounding and the ability to penetrate also coarser and firmer layers widely surpasses that of any of the other methods. Because of the adapted modes of penetration during sounding, the resolution in the soft layers can be expected to be about the same as that for rotary pressure sounding. The diameter of the drill bit is 57 mm and the rods have a diameter of 45 mm. The drill bit thereby expands the hole and reduces the friction along the rods. The rotating drill bit also causes remoulding, but it is difficult to estimate how much.

All these three methods measure the total penetration force, whereas the remoulded shear strength and indirectly the sensitivity are linked to the rod friction only. At start of the test and in superficial layers, the accumulated rod friction is low and the recorded penetration resistance is mainly related to the tip resistance. This changes gradually with depth, and at great depths the friction along the rods will normally be totally dominating. The friction along the rods in a homogeneous clay profile is normally highest close to the tip, unless large friction-reducing effects occur here because of a considerably larger tip diameter. The friction in the soil layers higher up decreases gradually because of further remoulding as the rod system passes through and a certain decrease can also be expected as the hole becomes enlarged by wobbling effects from rotating rods, particularly in friction soils. On the other hand, there may be a certain migration of pore water from the smeared zone along the rods and thereby a gradual increase in remoulded strength. When studying the trend of total force versus depth, it has to be assumed that these effects are negligible and that variations in the tip resistance due to variations in the nature of the clay are also negligible. This is not always the case, particularly in transition zones between the dry crust or any other stiffer or coarser overlying soil and the soft clay below or when entering the more silty and varved bottom layers that occur frequently in the Swedish clay profiles.

The CPT test with additional measurement of the total penetration force is a considerably more elaborate method, which requires time for preparation of the probe. On the other hand, it yields much more detailed information on the soil in the profile than any of the other methods. Once the test is started, it continues at the same rate as static pressure sounding, i.e. at 20 mm/s. The test is performed without rotation and, when the rods have the same diameter as the probe, it creates the least disturbance. The friction measured against the sleeve just above the tip is therefore normally measured in only partly remoulded soil. Since the tip resistance is measured and subtracted from the total penetration force, all errors in the rod friction related to the tip resistance and its variations are eliminated. The dual measurement of the friction, at the tip and along the rod assembly respectively, makes it possible to check that variations in the total rod friction that are assumed to be related to additional friction at the lower end of the assembly are matched by a similar pattern of the friction measured here.

3.2.3 Field vane tests

The field vane test (SGF 1993b) is the only type of in situ test that has so far been used to estimate both the undisturbed and remoulded undrained shear strength and thereby also the sensitivity. The method is well established for determination of the undisturbed undrained shear strength in clay. Measurement of the remoulded shear strength is a possible addition, which because of cost and insufficient reliability is often omitted. The required accuracy of the shear strength determination in soft to medium stiff clay is normally ± 1 kPa. To achieve this accuracy, the friction in the system and along the rods has to be measured, usually by means of a slip coupling between the rods and the vane. This is the case also for vane equipment using a casing around the rods. For an accurate estimate of the remoulded shear strength in highly sensitive clay, the accuracy should be about 10 times better than what is normally required and achievable. In the normal procedure of measuring the remoulded shear strength, the recording instrument is disengaged after determining the undisturbed shear strength. The rods and the vane are then rotated about 20 turns, after which the rods are turned back to open up the slip coupling. The recording instrument is then re-engaged and the rods are turned slowly to measure the rod friction before the slip coupling is closed and the total torque recorded. The operations from the end of rotation of the vane until remoulded failure for vane and rods is reached take a certain time, during which various thixotropy effects also take place. A large number of parallel investigations with both field vane tests and fall-cone tests have been performed in the extensive Göta Älv investigation in soft sensitive Swedish clay (see Statens offentliga utredningar 1962). From the results of this investigation it can be observed that the field vane tests generally underestimate the sensitivity, particularly in quick clays. Field vane tests to estimate sensitivity have therefore been excluded in the present investigation.

3.2.4 Fall-cone tests

The usual way of estimating the remoulded shear strength in clay in Sweden is to use the fall-cone test (Swedish Standard 02 71 25). This test can be used to determine both undisturbed and remoulded shear strength, and the former determination requires undisturbed samples. If such samples are available, the sensitivity can be determined based on the fall-cone test results alone.

However, undisturbed sampling is time-consuming and costly, particularly in quick clays. A possible alternative is therefore to take disturbed samples and use the fall-cone test to determine the parameters remoulded shear strength and liquid limit, which are not sensitive to disturbance. The remoulded shear strength can then be compared to the undisturbed shear strength that is evaluated from field vane tests or CPT tests, after which the sensitivity can be calculated. When checking the estimated sensitivity from sounding tests in quick clay mapping in this way, use of the CPT test is more rational.

3.2.5 Surface resistivity measurements

The general principle for measuring electrical surface resistivity is to use a string of evenly spaced electrodes pushed into the ground surface along a measuring line. In a measurement, two of these electrodes are used for injecting electrical current into the ground, the electrical potential being measured between another pair of electrodes, and possibly between several other pairs.

The measured potentials are influenced by the magnitude of the current and of the conducting properties of the underlying soil. The depth and volume of the soil that influences a measurement are dependent on the spacing and position of the electrodes. By collecting measurements for a large number of electrode positions and spacings, a set of data is obtained that makes it possible to interpret and present an image of the electrical resistivity in the ground beneath the measuring line.

In the present project, the ABEM-Lund imaging system was used for measuring the resistivity (Leroux and Dahlin, 2003). The version employed comprises a current transmitter, a multi-channel measuring and logging instrument, and an electrode selector. The whole system is controlled by a microcomputer, which scans the given combinations of input and measuring electrodes. These combinations are selected according to patterns that from experience provide good, informative data coverage and at the same time speed up the measurements (Dahlin and Zhou, 2003). The system has seven measuring channels, which makes it possible to acquire measurements from seven pairs of electrodes at a time.

For interpretation, a finite element program is used, which compares the measured values with those that theoretically should be obtained for a model of the underlying soil. The errors between the measured and the theoretical values are calculated, and the model is adjusted to obtain the best fit to the measured values. In this case, the Res2Dinv program (Loke, 2003) has been used.

The quality of the measured data depends greatly on the homogeneity of the ground and the contact between the electrodes and the ground. Natural ground, homogeneous clay profiles, thin crusts and fairly wet conditions are thus beneficial factors for the measurements. Fills, pavements, overlying layers of coarse soils with low ground water tables, thick dry crusts, buried objects in the ground such as cables, pipes, piles and walls, as well as a highly irregular ground surface, are factors that reduce the quality of the measurements. In the latter case, certain criteria may therefore have to be applied when evaluating the measurements in order to eliminate apparently erroneous data. Alternatively, less weight can be given to such data in a new interpretation. The procedure is then to make an evaluation using all the data and then to repeat the process after selecting and amending erroneous measurements. Data removal has to be performed with caution and must be limited because the procedure is not straightforward and any removal also means a loss of information.

The interpreted resistivity sections can be presented separately and can also be compiled to form a three-dimensional view of the whole soil volume investigated. In this case, this has been done by using the “Rockware” program, which presents a view of the intersecting images. The view can be rotated and inspected from any direction.

It is not yet possible to perform true three-dimensional surveys of sites with dimensions such as those investigated in this study. With the desired resolution, it would take far too long to perform the measurements and the computations would be almost impossible. For the time being, the method is therefore limited to measurements in a number of more or less parallel lines and intersecting perpendiculars, and to present the results in quasi 3D images of intersecting 2D sections. The main limitation of this process is that the interpretation of the two-dimensional sections assumes that the conditions in the underlying soil are the same in the horizontal direction across the measuring line. This is not a major problem in fairly homogeneous soil conditions, but the uncertainty increases with the complexity of the geological environment.

3.3 SCOPE OF THE INVESTIGATION

3.3.1 General

The present investigation has aimed at obtaining sufficient data to evaluate different methods of quick clay mapping. For this purpose, three different areas with known occurrence of quick clay were selected. The investigation programme was designed to cover parts of the areas with quick clay as well as parts without such formations and thereby to enable establishment of the limits of the quick clay formation. There was thus a priori information in all three areas that quick clay was present, although it was not sufficient to provide more than a rough idea of its extent. All three areas are located in western Sweden and the clays have been deposited by sedimentation in a marine environment after the latest glaciation.

From the existing information, a rough outline of a probable border for the quick clay deposit was drawn on the plan for each area. A geophysical investigation using surface resistivity measurements was then designed to cover an area extending far out on both sides of this tentative border.

When the results from the geophysical investigation were at hand, they were compared to the priori information and were found to match this fairly well. New, adjusted and more detailed tentative borders for the quick clay deposits were then outlined and the geotechnical mapping and control programmes were designed.

The geotechnical mapping programme consisted of 9 – 10 static pressure soundings and 3 – 4 rotary pressure soundings, total soundings and CPT tests at each site. The static pressure soundings were located in both quick clay and non-quick clay, and were placed to verify the assumed border of the quick clay formation. Based on these results and the previous information, 3 – 4 of the investigation points were selected to cover the range quick clay – highly sensitive clay – normally sensitive clay. At these points, parallel tests were performed with the other three sounding methods and undisturbed samples were taken. In one of the test areas, the static pressure soundings were supplemented with results from a previous investigation using the same type of equipment and at another site sampling was limited because of fairly extensive sampling in a previous research project.

3.3.2 The test site in Skepplanda

Area and previous tests

The Skepplanda test site is located northwest of the community of Skepplanda, about 40 km north of Gothenburg. The test area is an area of farmland beside a small industrial estate. The terrain slopes gently over a distance of about 500 metres towards a steeper slope down to a small river, *Grönån*. The soil consists of soft marine clay below a relatively thin, dry crust. The upper border of the area is defined by a road, which runs where the clay layers have thinned out and the coarser soil overlying the bedrock reaches the surface. The thickness of the clay layer then increases to about 40 metres at the centre of the area. The investigations further down have generally been limited to depths of about 30 metres and the actual depth of the clay layers there is unknown. In the area now investigated, and probably over the whole area, there is a layer of coarse friction soil between the clay and the bedrock. Its thickness varies between almost zero and a couple of metres, but can generally be assumed to be about 1 metre. The layer is permeable, and the water pressures in this layer are artesian because of the sloping terrain and bedrock.

The free groundwater level is located in the dry crust and varies seasonally from the ground surface to about 1 metre below. Because of the artesian water pressure in the bottom layers, there is an upward gradient and pore water flow in the soil mass.

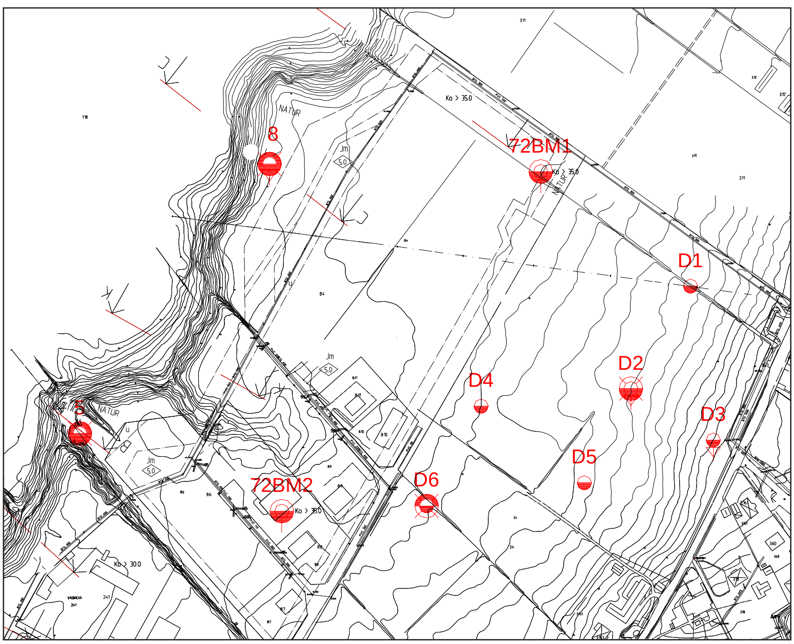


Fig. 3.10. The test site at Skepplanda.

The soil conditions close to Grönån have been investigated in connection with the establishment of the industrial estate and because of stability problems along the steeply sloping riverbanks. No quick clay has been found in this part of the area. However, in a new investigation further up the slope, which was performed for a planned extension of the industrial industrial estate, extreme quick clay with higher than measurable sensitivity was found during undisturbed sampling in one borehole designated D2 (GF 2003). An inspection of the results from the various soundings in the area indicated that this could be the case for a large part of the upper slope.

Investigations marked 72 BM refer to an investigation in 1972 using the original static pressure sounding, i.e. with a square tip and a slip coupling. Investigations marked D or by a number alone refer to investigations by GF in 2002 – 2003.

Geophysical tests

The resistivity measurements were performed in six lines about 300 metres long from just below the road in the upper part of the slope to well below the central parts of the area. Two cross lines of the same length running on opposite sides of the centre of the first six lines were also measured. The positions of the lines are shown in Fig. 3.11.

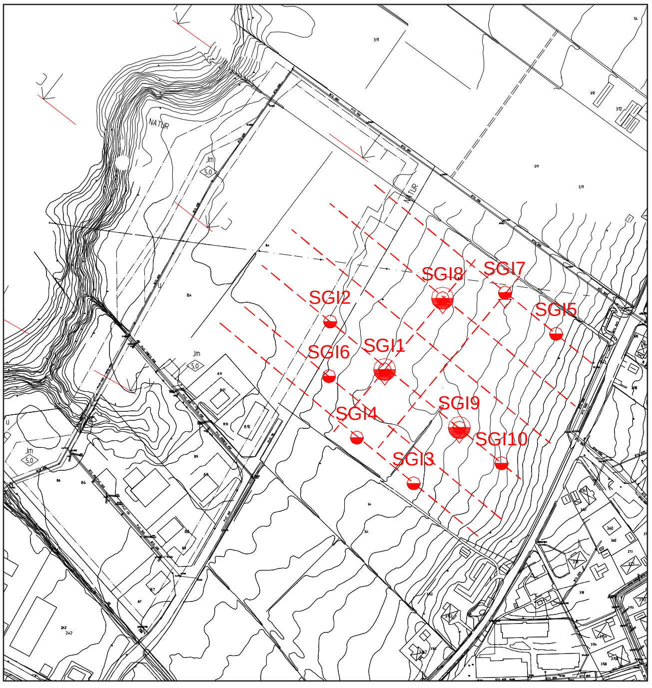


Fig. 3.11. Lines for resistivity measurements and location of test points in the current investigation at Skepplanda.

Geotechnical investigations

The geotechnical investigations in the present project were performed at ten points numbered 1 to 10. Static pressure soundings were performed at all of these, rotary pressure soundings and CPT tests were performed at points 1, 7, 8 and 9, and undisturbed sampling was performed at points 1, 8 and 9. The total soundings were limited to points 1 and 9 after these tests had shown that the level of the bedrock mainly coincided with the stop levels in the other types of sounding and that problems with artesian water pressure had been encountered in these two holes.

Results

The results of the laboratory tests, together with the results from the previous investigations in the area, showed that the undrained shear strength in the farmland was about 5 kPa just below the very thin dry crust and increased by about 1 kPa per metre depth. The crust effect is more pronounced close to the river and in the industrial estate, where the undrained shear strength is more or less constant at around 12 kPa down to 10 metres depth and then increases by about 0.8 kPa per metre depth, Fig. 3.12. A certain anomaly is that the highest shear strength is measured at point D2, where the sensitivity is highest.

Also in other respects, the clay appears to be somewhat different in the upper part of the area compared to that closer to the river. The density is thus higher and the water content and liquid limit are significantly lower. Some of these differences can be attributed to changes during leaching, but not all of them. However, the depths to bedrock vary considerably and it is not uncommon for the layering to follow the contour of the bedrock and for some of the top layers found in the central, deeper parts of the valleys to be missing at the valley sides. This has been illustrated previously, e.g. by Cato et al. (1981) in SGI Report 11 on the geology of the Tuve area. It is thus possible that the same type of clay as in the upper parts of the area will be found at greater depths closer to the river.

The relation between the natural water content and the liquid limit is often a good indication of the sensitivity of the soil, (Statens offentliga utredningar 1962). It has been found that this quasi liquidity index normally has to be above 1.15 in western Sweden if the clay is to be quick (Larsson and Åhnberg, 2003). This was also observed in the results from Skepplanda and the high quasi liquidity indexes were found solely in the upper part of the area, Figs. 3.13 and 3.14. At point 8, which is located about midway from the upper boundary of the area to the river, the clay in the lower half of the profile is of the same type as that at the points further up, but here it has a lower liquidity index and is not quick down to 35 metres depth, which

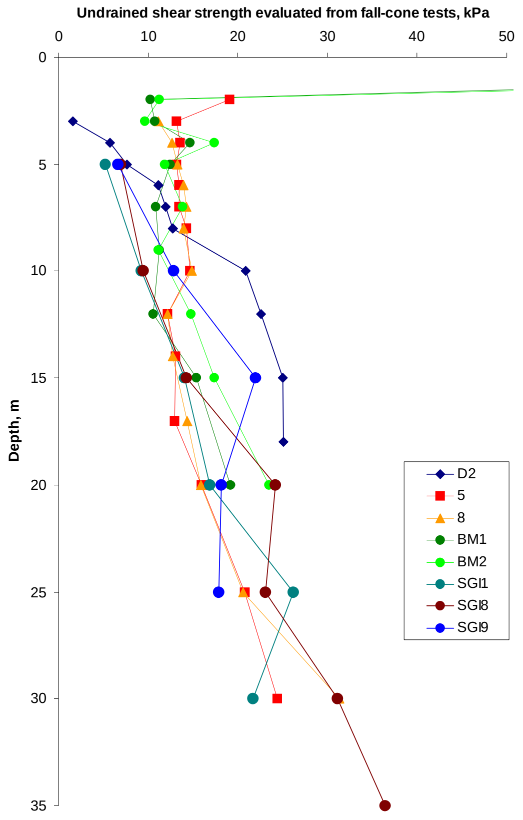


Fig. 3.12. Undrained shear strength at Skepplanda.

was the lowest sampling level. The total depth of the clay profile here is about 42 metres. According to the laboratory results, the quick clays are confined to the upper part of the area and ultra quick clay with sensitivity values of several hundred is found at point D2, Fig. 3.15. It may also be noted that the clay tends to be more quick in deeper layers at point 9, which is located somewhat lower down in the area, and that quick clay is found only in the bottom layers at point 1, which is located even further down towards the river.

The resistivity measurements showed high values in the upper part of the area, whereas gradually lower resistivity was found further down towards the river. Lower resistivity corresponds to a higher salt content and the resistivity sections indicate that leaching occurs from the bottom upwards, which should correspond to the artesian groundwater conditions, Fig. C16.

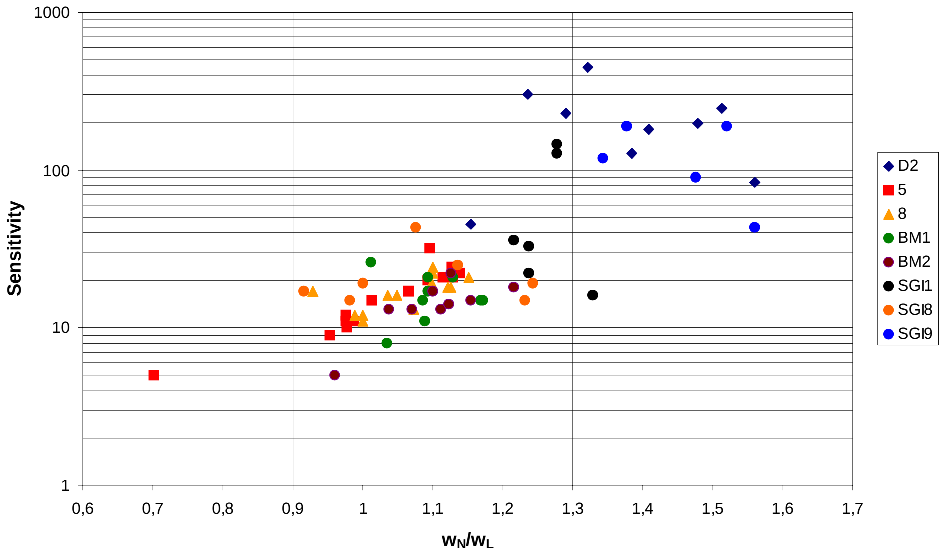


Fig. 3.13. **Relation between quasi liquidity index w_N/w_L and sensitivity at Skepplanda.**

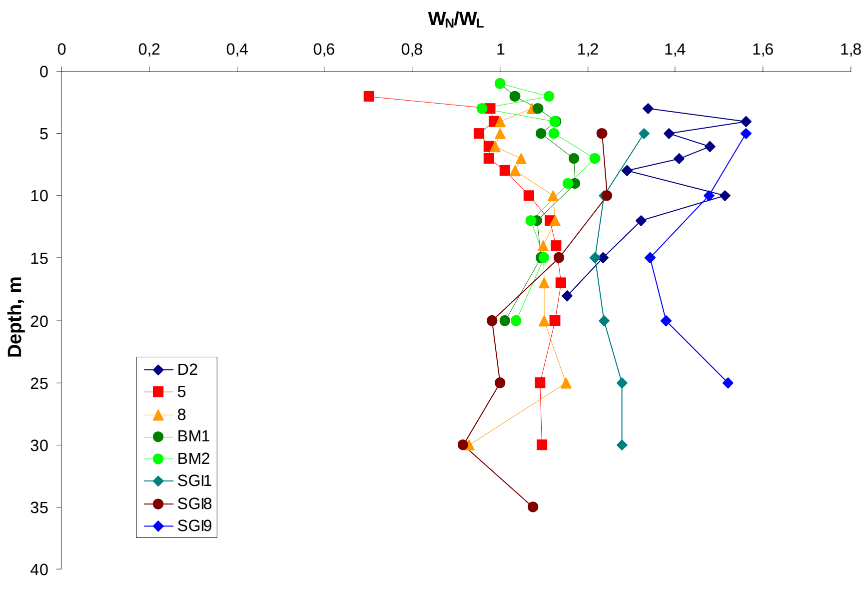


Fig. 3.14. **Quasi liquidity index versus depth at different points at Skepplanda.**

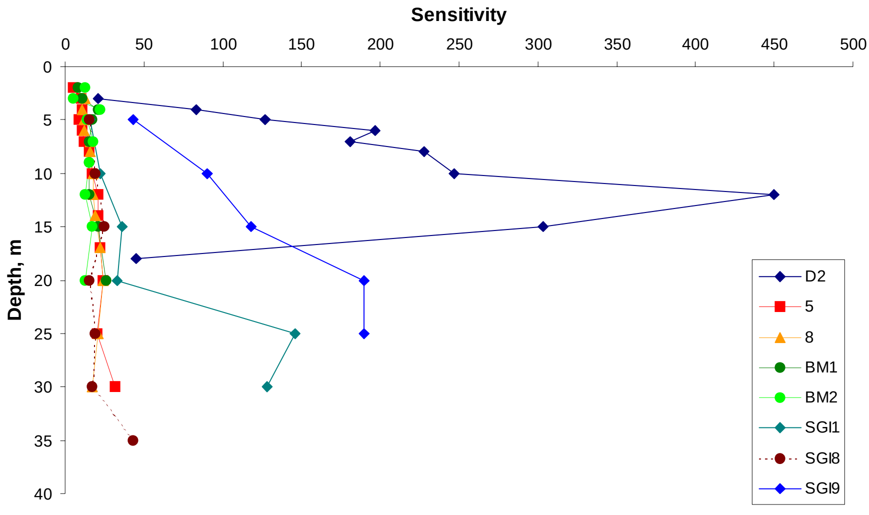
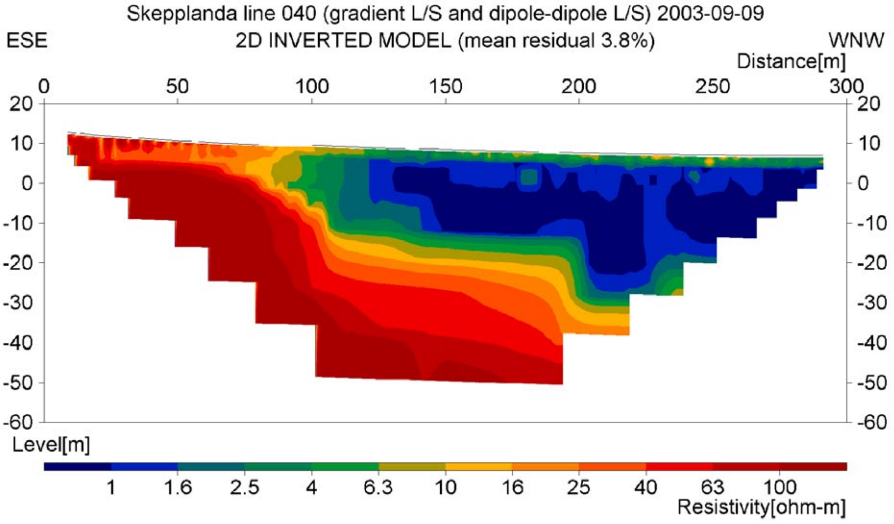


Fig. 3.15. Sensitivity versus depth at different points at Skepplanda.

The results of the static sounding tests confirmed the general picture in that the inclination of the curve for sounding resistance versus depth was almost vertical or even negative in the depth intervals with quick clay. At points 9 and 10, where there is quick clay almost throughout the profile, the equipment sank under its own weight for large depth intervals. In those parts where the sensitivity was lower, it was observed that the sounding resistance increased each time the penetration was stopped to add new rods and raise the pushing yoke. It then took almost a metre of further penetration before all the effects of the stop were erased. The results of the static pressure soundings in this project are presented as smoothed curves after removal of the stop effect in Fig. 3.17. Even a first glance of the results provides a good relative picture of the distribution of the sensitivity in the soil mass. From the results it can be observed that in the upper part of the slope each profile is quick throughout and that further down there is only a zone in the lower part of each profile which is quick. This zone follows the bottom contour and decreases in thickness with distance from the upper area and increasing thickness of the clay layer.

The results from the previous static pressure sounding have been included in Fig. 3.18. These results have not been smoothed and the increases in sounding resistances after each stop can be observed. Apart from this, they supplement the general picture in order to make it more complete.



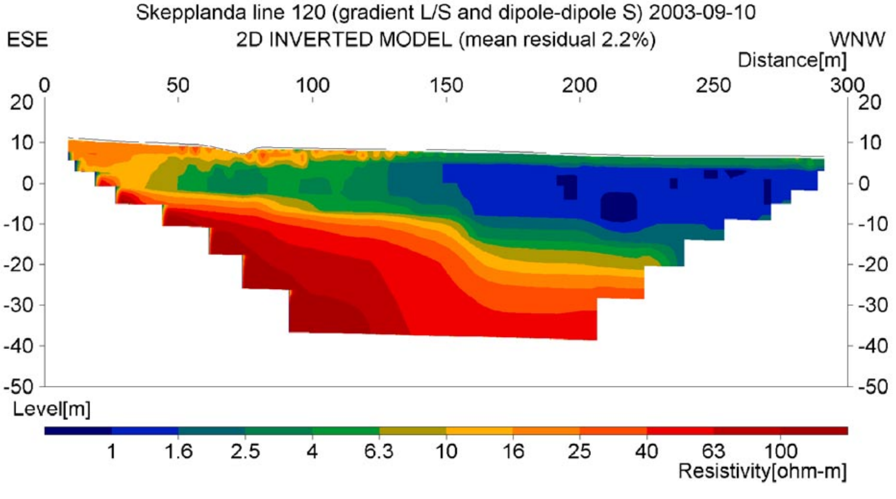


Fig. 3.16. Resistivity sections for lines 040 and 120. The uppermost thin high resistivity layer corresponds to the dry crust and bedrock is found somewhere in the red – dark red zones.

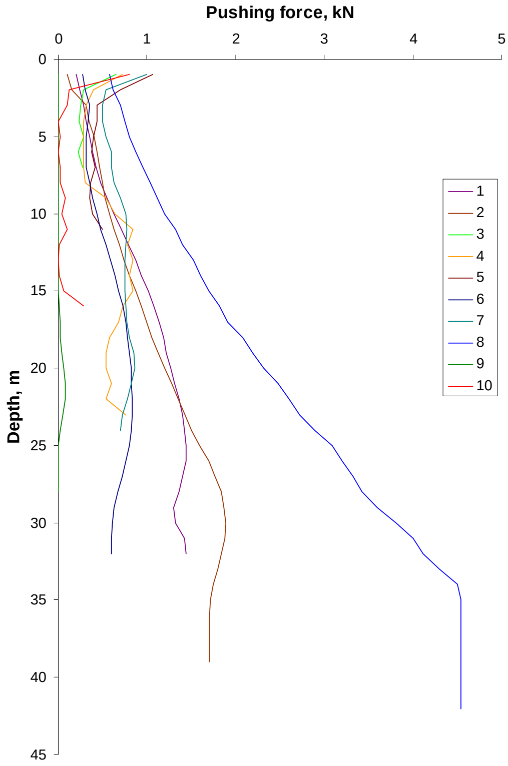


Fig. 3.17. **Results from the static pressure soundings in the present investigation at Skepplanda.**

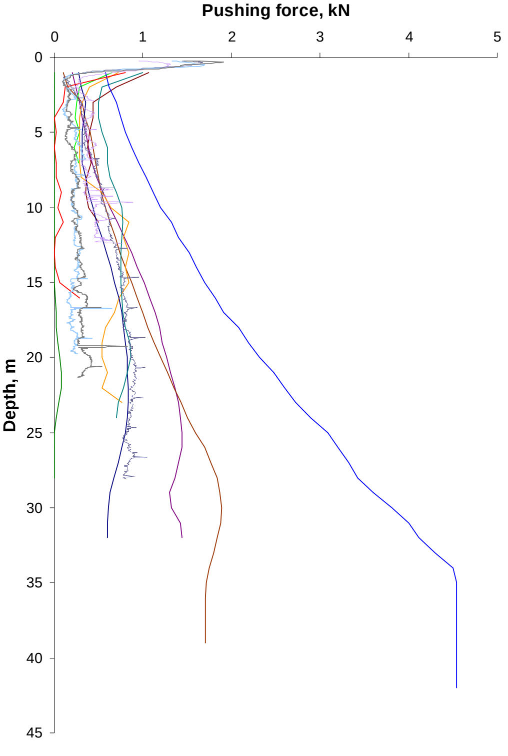


Fig. 3.18. **Results from all relevant static pressure soundings at Skepplanda.**

The results from the rotary pressure soundings were similar, with higher resistances after each stop. The curves were also more jagged since the noise in the registered values became considerably higher when rotation was applied. The smoothed curves are shown in Fig. 3.19. Approximately the same picture as for the static pressure soundings appears, but with somewhat less detail. Also in this case, the equipment sank under its own weight for a large part of the profile in the most sensitive clay.

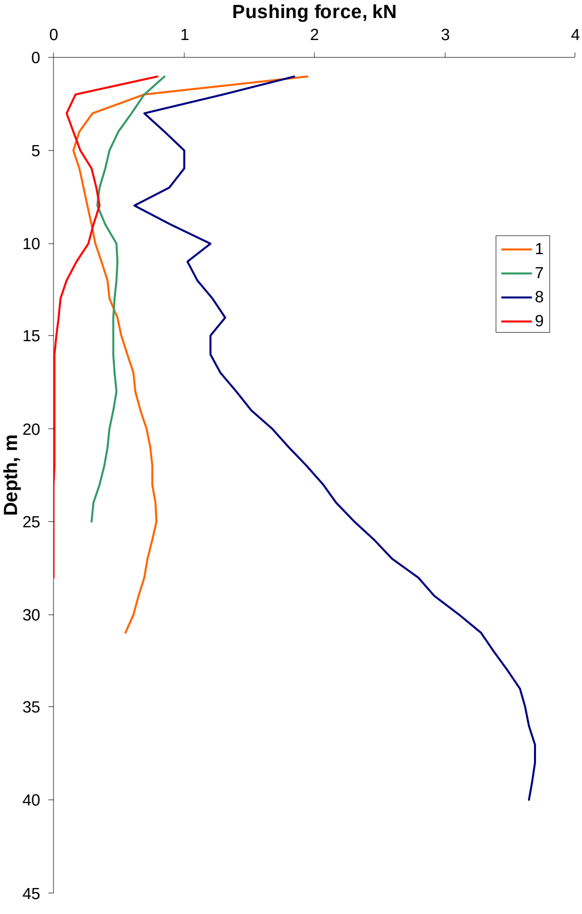


Fig. 3.19. Results from the rotary pressure soundings at Skepplanda.

The total soundings show a similar picture, although there are only results from two points, Fig. 3.20. Also this equipment sank under its own weight for part of the profile in the most sensitive clay.

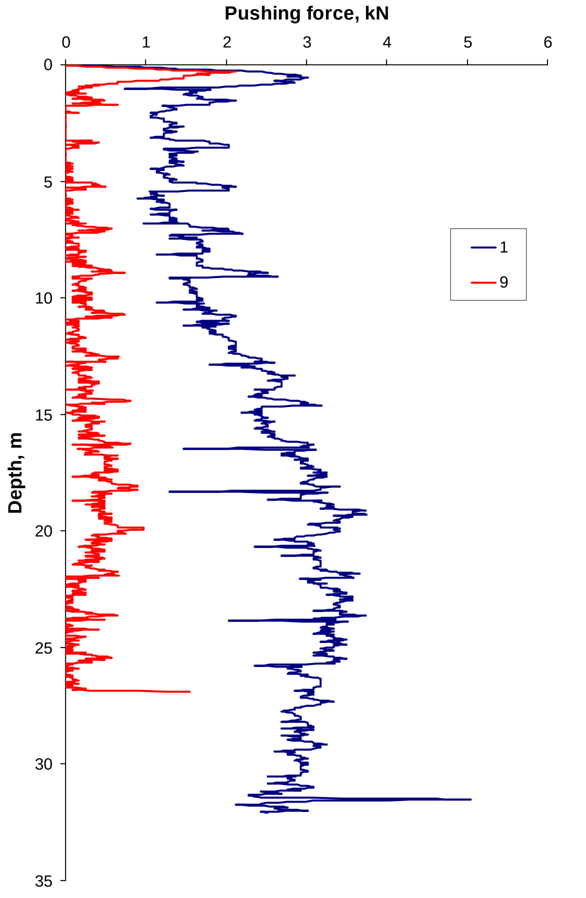


Fig. 3.20. Results from the two total soundings at Skepplanda

For the CPT tests, the results have been corrected by subtracting the measured tip resistance from the total penetration force and adding the weight of the rods, Fig. 3.21. The curves have also been smoothed to remove the enhanced friction due to temporary stops in the penetration. The rod friction is generally higher than for the other sounding methods, which can be attributed to the considerably lower remoulding by the tip. The pattern of the rod friction versus depth is the same as for the other test methods, but the curves are not quite as steep.

In the plot in Fig. 3.21, a guiding line corresponding to an average rod friction of 1 kPa has been inserted. An inclination steeper than this line indicates that the clay is highly sensitive and probably quick, and parts in which the curves are vertical or almost vertical indicate quick or ultra quick clays. The general picture is verified

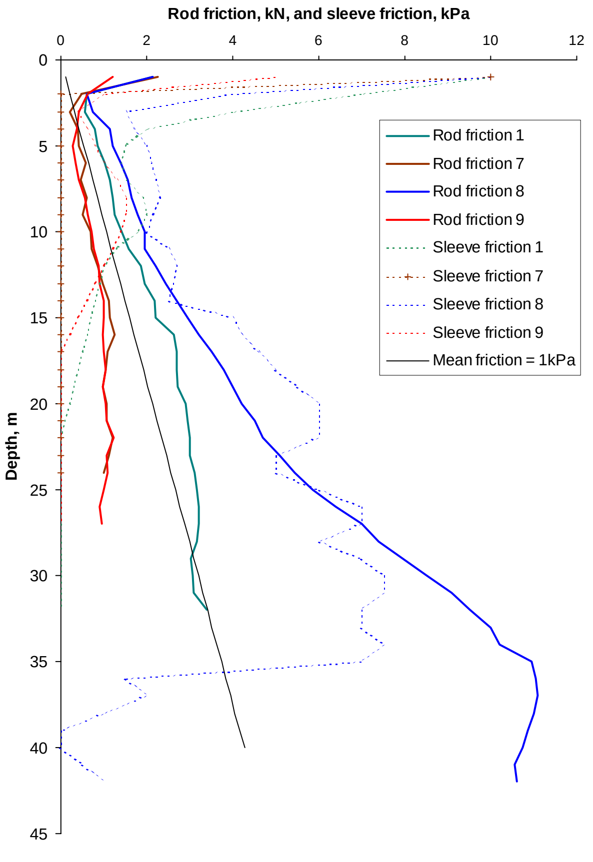


Fig. 3.21. Results from the CPT tests at Skepplanda in terms of rod friction and sleeve friction versus depth.

by the measured sleeve friction, which is zero or almost zero in the parts with ultra sensitive clays and generally less than 2 kPa in the parts with highly sensitive – quick clays. When judging the absolute values of the sleeve friction, it should be considered that these may be expected to be considerably higher than the completely remoulded shear strength and that the measuring accuracy is normally ± 2 kPa at best. However, the pattern should match the estimated sensitivity from the total rod friction, which it clearly does here. The results of the CPT tests also indicate that there is coarser clay at the bottom of the clay profiles, with embedded thin silt layers at the very bottom. The quick clay in the deeper clay profiles is located mainly in this layer.

3.3.3 The test site in Utby

Area and previous tests

The test site at Utby is located on the western bank of the river *Göta Älv* about 10 km north of the community of Lilla Edet. The river makes a sharp turn around a couple of small outcropping hillocks just upstream of the site. The area is a rural area with farmland all the way from the riverbank up to the nearest buildings and the public road about 1 km away. The area closest to the river is used solely as pastureland. Most of the area is flat or slopes only gently towards the river and then turns into steep slopes down to the river or in the ravines at its tributaries. At the test site, there is a depression in its south-western part reaching about 200 metres in from the riverbank as a result of an earlier landslide. There are no installations in the area except for farm tracks and an erosion protection of rock fill along the riverbank.

The banks of the Göta Älv were investigated during the late 50's – early 60's in an extensive investigation of the stability conditions along the river (see Statens offentliga utredningar 1962). The investigations were confined to the area extending from the river that could be involved in a primary slide and areas further away towards the valley sides were normally not involved. The investigation points at the test site at Utby are shown in Fig. 3.22. It was then found that quick clay is present over the entire investigated strip along the river to the north of the bend at Utby. A

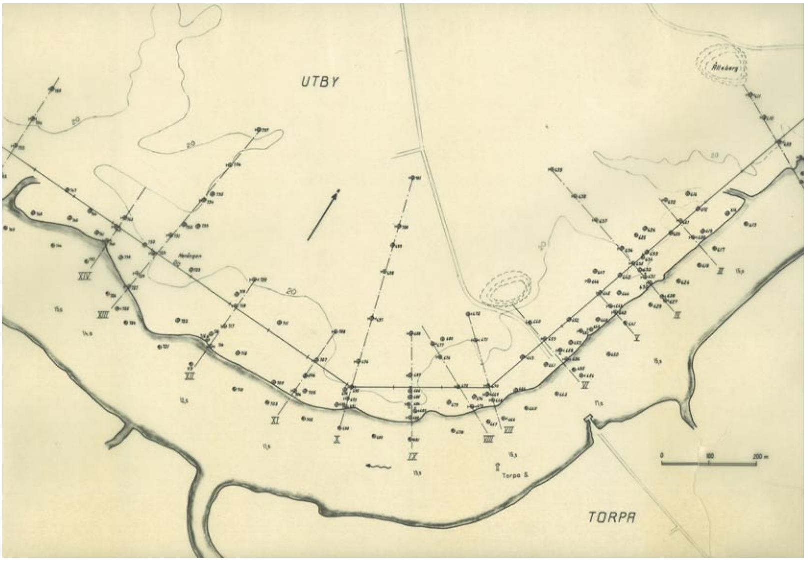


Fig. 3.22. Plan of the area with the investigation points in the Göta älv investigation.

short distance to the south of the bend, the quick clay formation seemed to disappear close to the river, where the investigations were concentrated and most detailed. However, coarser and more scattered investigations indicated that it was still present at greater distances from the river.

The clay in the area is marine clay that has been assumed to be resting on a layer of till on top of bedrock. The top of the assumed till layer below and close to the river was encountered about 40 metres below the surrounding plateau. It then sloped gently towards the valley sides and more steeply towards the outcropping hillocks. The depth of the clay layers was thus assumed to range from about 15 metres below the eroded river course to about 40 metres at the crest of the steep slopes above the riverbank and then decrease gradually towards the valley sides and hillocks. The sounding results from a single test point, one of about 80 in that particular area, indicated that the clay depths could be considerably deeper south of the bend.

The pore pressure measurements performed in the earlier investigation indicate free ground water levels close to the ground surface. Below the upper plateau, there is then a downward gradient with less than hydrostatic pore pressures. Below lower ground at the river banks, this has turned into artesian water pressures with somewhat higher than hydrostatic pore pressures. Considering the topography, the pore pressures below the river may be assumed to be even more artesian.

Geophysical tests

The test site in the present investigation was located with the intention of finding the border of the quick clay formation. Since the location of this was more uncertain than at Skepplanda, the investigated area was made somewhat larger. The resistivity measurements were thus performed in six parallel lines about 400 metres long running perpendicularly to the river and starting just above the crest of the steep slope at the riverbank. A cross line approximately 500 metres long running parallel to the river and at the centre of the first six lines was also measured. The positions of the lines are shown in Fig. 3.23.

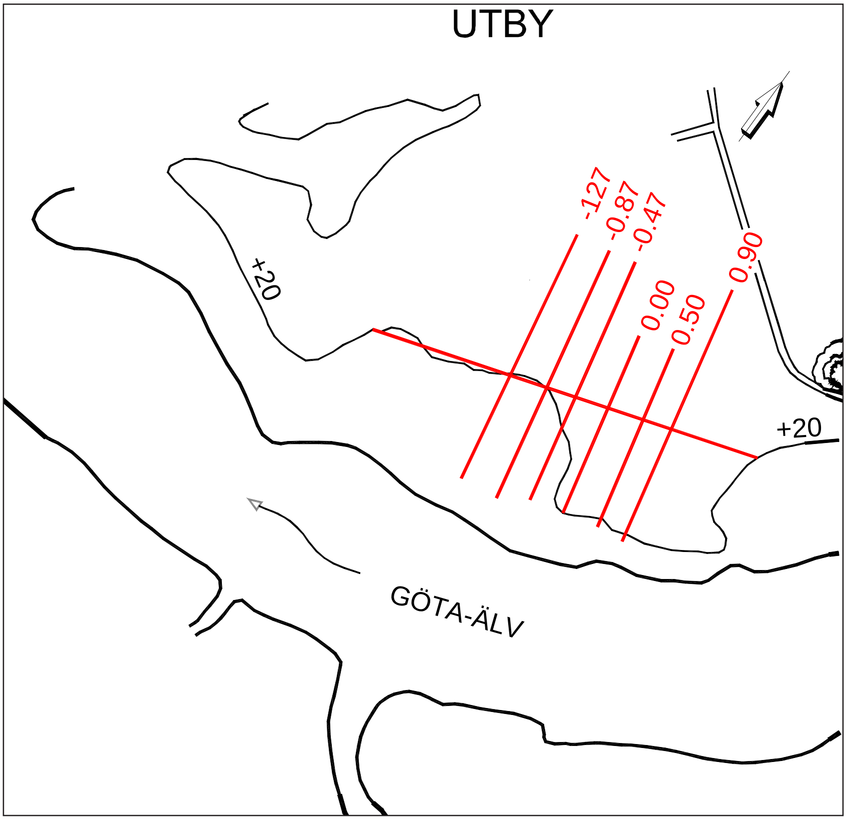


Fig. 3.23. Lines for resistivity measurements and new investigation points at Utby.

Geotechnical investigations

The geotechnical investigations in the present project were performed at nine points numbered 1 to 9. Static pressure soundings were performed at all of them, rotary pressure soundings were performed at points 1, 3, 5 and 6, and CPT tests and undisturbed sampling were performed at points 1, 5 and 6. All these soundings stopped at approximately the same levels as those in the previous investigation and in what appeared to be a very firm bottom or bedrock. The total soundings were performed at points 2, 5 and 6. The reason for switching to point 2 for these tests was that the tests at points 5 and 6 had shown that the assumed firm bottom was an approximately 0.5 metre thick very hard layer of coarse soil and that the clay layers continued to very large depths below this layer. The test at point 2 was then performed to ascertain that the assumed bedrock at the shallower bottom at this point really existed.

Results

The results of the laboratory tests, together with the results from the previous investigations in the area showed that the undrained shear strength was approximately 20 kPa just below the level of the plateau and then increased by approximately 1 kPa /metre, Fig. 3.24. However, there is a considerable scatter in the results, particularly in the previous investigations. The dry crust is only about a metre thick.

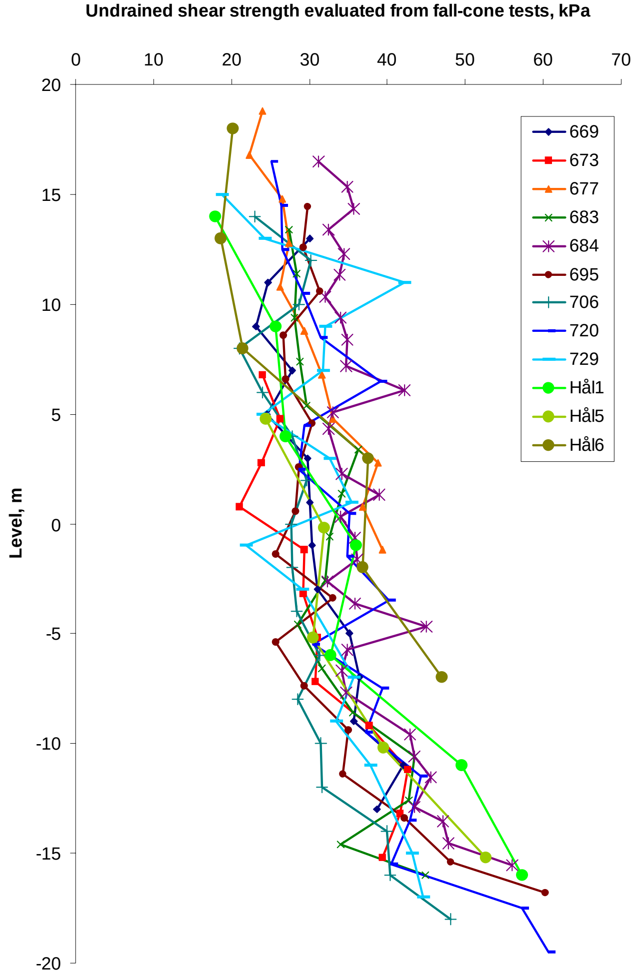


Fig. 3.24. Undrained shear strength at Utby.

The measured densities and water contents do not indicate any large differences in the clay in the area. The scatter in the results mainly obscures possible variations due to factors such as the slide in the south-western part of the area. The scatter in liquid limit is even greater, and also for this parameter it is difficult to discern a clear pattern.

However, the values of the quasi liquidity index, the remoulded shear strength and the sensitivity all show that the clay is different over the area. The clay with high quasi liquidity index and sensitivity is thus found in the north-eastern part of the area, whereas the clay in the south-western part has lower values, Figs. 3.25 and 3.26. Correspondingly, the opposite pattern is found for the remoulded shear strength, Fig. 3.27. It is also found that the thickness of the highly sensitive layers generally increases with distance from the river and towards areas with lower thickness of the clay layers. Here, it must be observed that the clay layers below the river are probably considerably thicker than previously assumed.

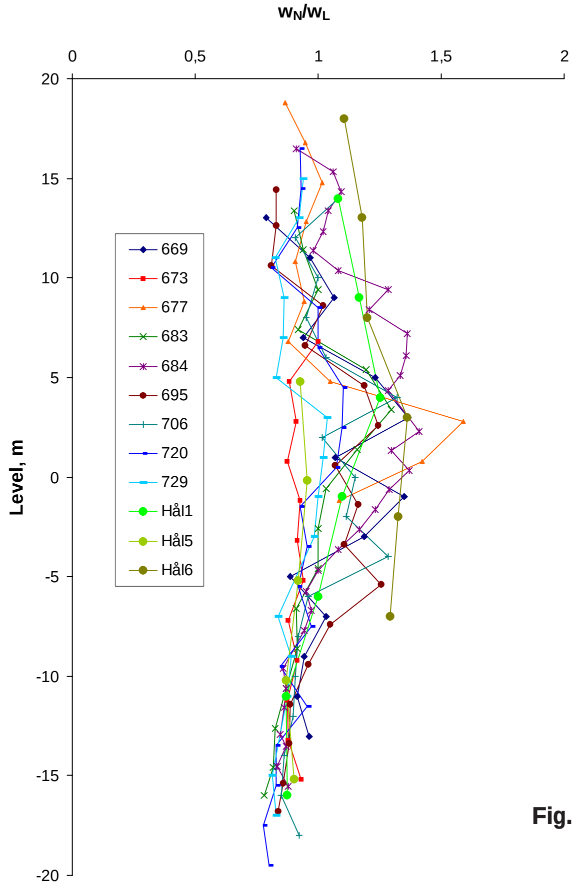


Fig. 3.25. Quasi liquidity index versus level at different points at Utby.

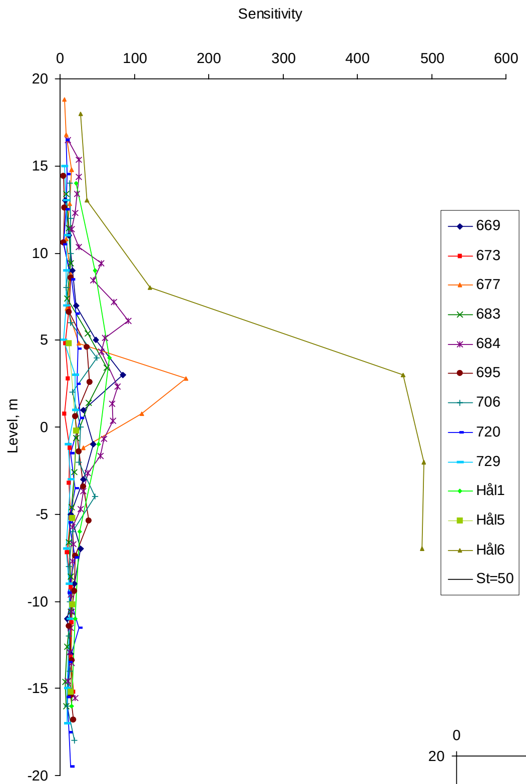


Fig. 3.26. Sensitivity versus level at different points at Utby.

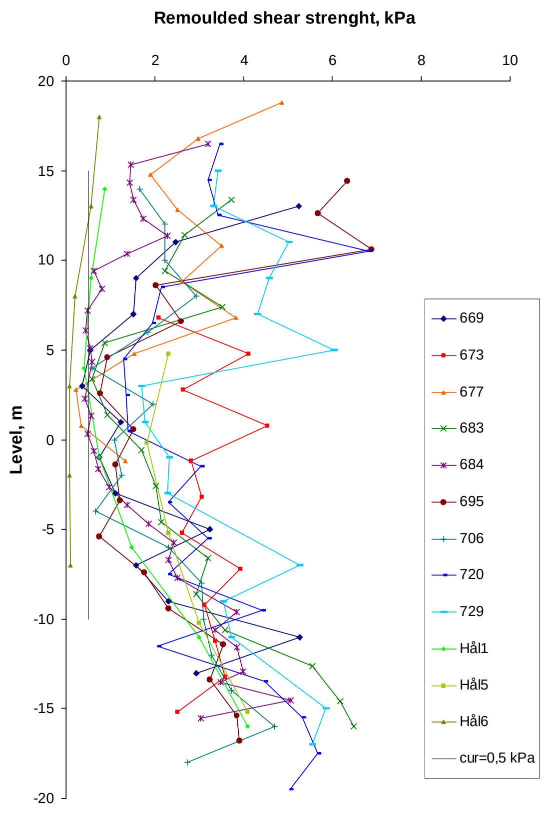


Fig. 3.27. Remoulded shear strength versus level at different points at Utby.

The usual type of correlation between quasi liquidity index and sensitivity was found for the results from Utby. The relations for the earlier results and those from the present investigation differ somewhat, possibly as a result of different sampling equipment and sample qualities, and possibly also because ultra-sensitive clays were not encountered in the earlier investigation. Nevertheless, the results show that the quasi liquidity index should be higher than approximately 1.15 for the clay to be quick, Fig. 3.28.

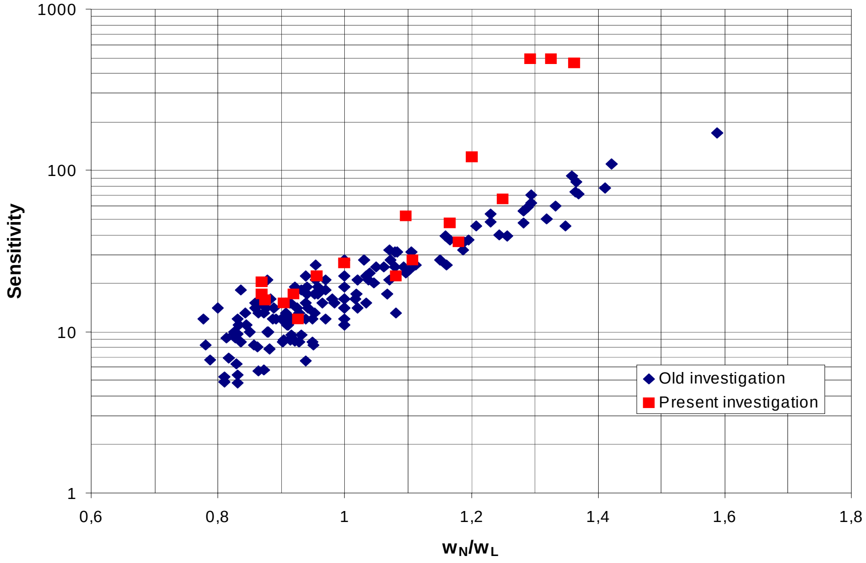
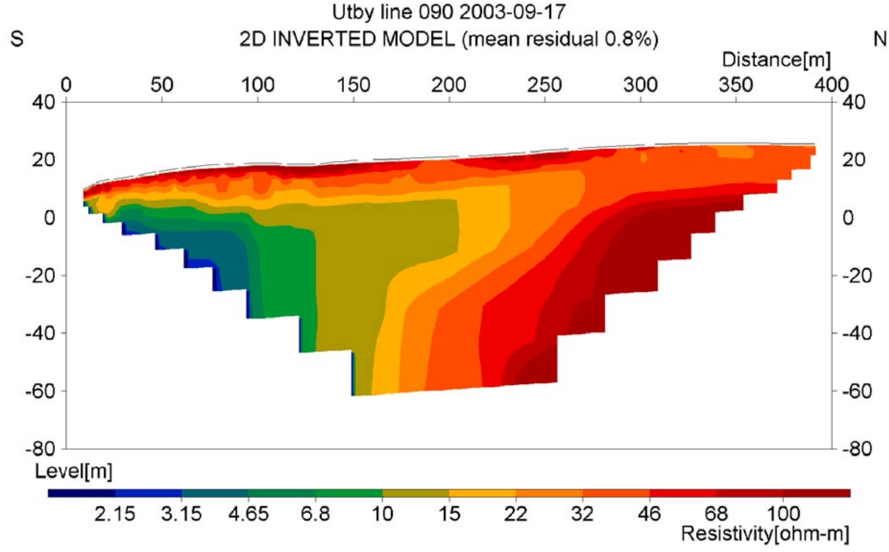


Fig. 3.28. Relation between quasi liquidity index w_N/w_L and sensitivity for Utby clay.

The resistivity measurements showed high values in the north-eastern part of the area, whereas gradually lower resistivity was found further down towards the river and southwest. The resistivity sections indicate that leaching has occurred from both percolation of water from the ground surface and diffusion from draining layers at the top and bottom, which corresponds to the groundwater conditions, Fig. 3.29.

The dark red zone in the upper part of the resistivity image for section 090 corresponds to bedrock, whereas no check of the bedrock level at great depths is available. The hard and coarse layer found in the geotechnical investigations at approximately elevation –20 metres does not show up in the resistivity images.



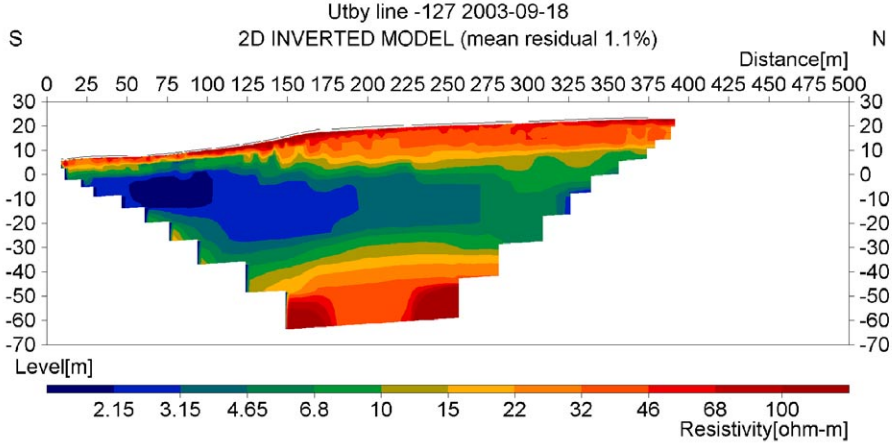


Fig. 3.29. Resistivity sections for lines 090 and –127. The uppermost thin high resistivity layer corresponds to the dry crust.

The results of the static sounding tests confirmed the general picture previously found at Skepplanda, Fig. 3.30. The curves showed the same pattern with increased resistances after each stop in the penetration and almost vertical penetration force – depth curves in the parts with quick clays. No quick clay was indicated at points 5 and 8 in the south-western part of the area, whereas such parts with increasing thickness towards the northeast could be seen at the other points. In this case, the crest and upper non-quick layers were thick enough to prevent the equipment from sinking under its own weight. Below this part, the layer of quick clay is limited to a certain depth interval except for points 6 and 7, in which quick clay appears to occur throughout the penetrated depth. At point 6, the latter corresponds to hitting the level of the hard layer, whereas it is uncertain whether this layer or bedrock was reached at point 7.

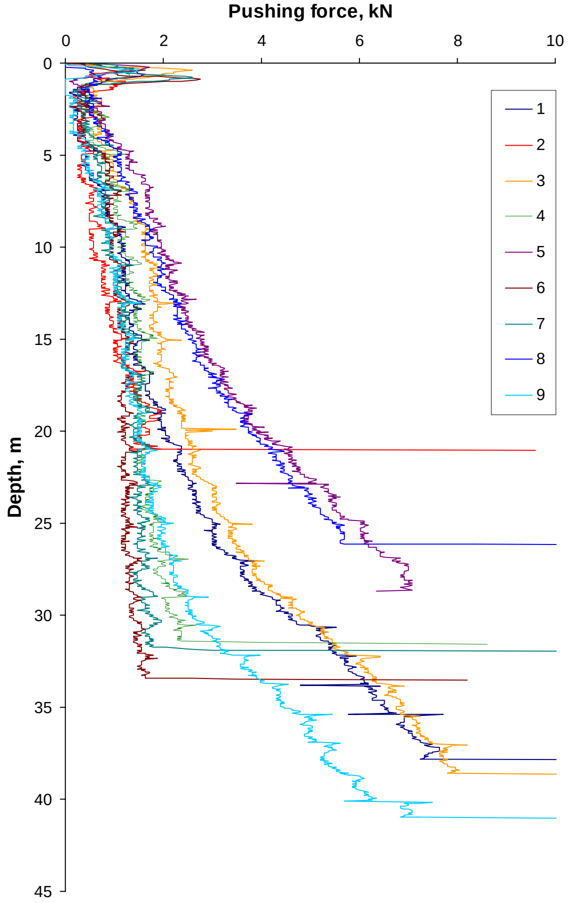


Fig. 3.30. Results from the static pressure soundings at Utby.

The results from the rotary pressure soundings yielded approximately the same picture as the static pressure soundings, Fig. 3.31. Also in this case, the equipment did not sink under its own weight at any of the points. However, the inclination of the penetration force-depth curve became negative for a large part of the profile at point 6, where the most sensitive clay was found.

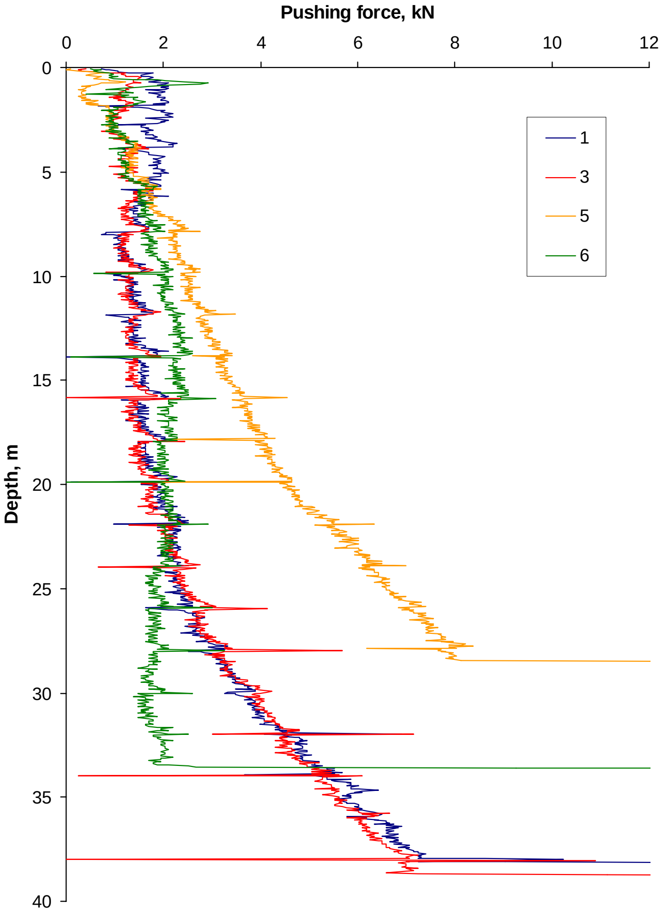


Fig. 3.31. Results from the rotary pressure soundings at Utby.

The total soundings show a similar picture, although there are only directly comparable results from points 5 and 6, Fig.3.32. The total soundings at points 5 and 6 using only pressure and rotation stopped at the same levels as the previous sounding tests. An increase in rotation and flushing did not increase the penetration. However, when activating the hammer, the equipment penetrated fairly rapidly and about 0.5 metre further down, the hammer was stopped and the penetration resumed for pressure and rotation only in what appeared to be a direct continuation of the clay layers above the hard layer. The soundings were continued as far as the drill rods at hand allowed, i.e. to about 40 metres depth.

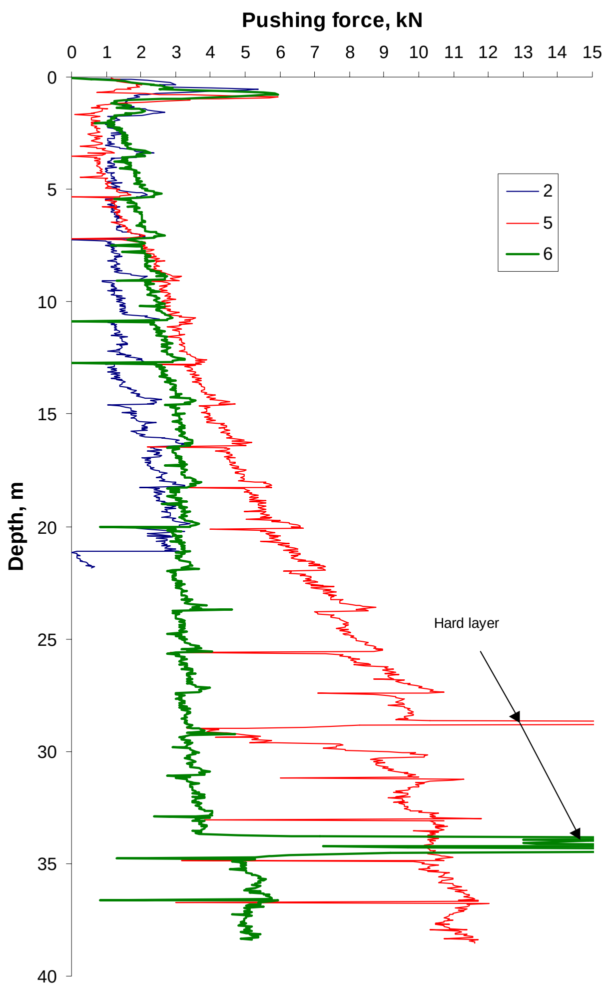


Fig. 3.32. Results from the total soundings at Utby.

An embedded coarser layer at approximately the same elevation as the hard layer at Utby has been found at Strandbacken approximately 10 km downstream on the Göta Älv, and at several other locations in the area (Larsson and Åhnberg, 2003). This is mainly attributed to temporary re-advancements of the retreating ice-front during the de-glaciation 10,000 – 11,000 years ago (Stevens, 1987). However, these layers are normally made up of sand and silt deposits and no layers as coarse and hard as that found at Utby have to the author's knowledge been reported before.

The evaluated rod friction and the measured sleeve friction in the CPT tests are shown in Fig. 3.33. The pattern of the rod friction versus depth is the same as for the other test methods and the measured trends for the rod friction are supported by the measured sleeve friction.

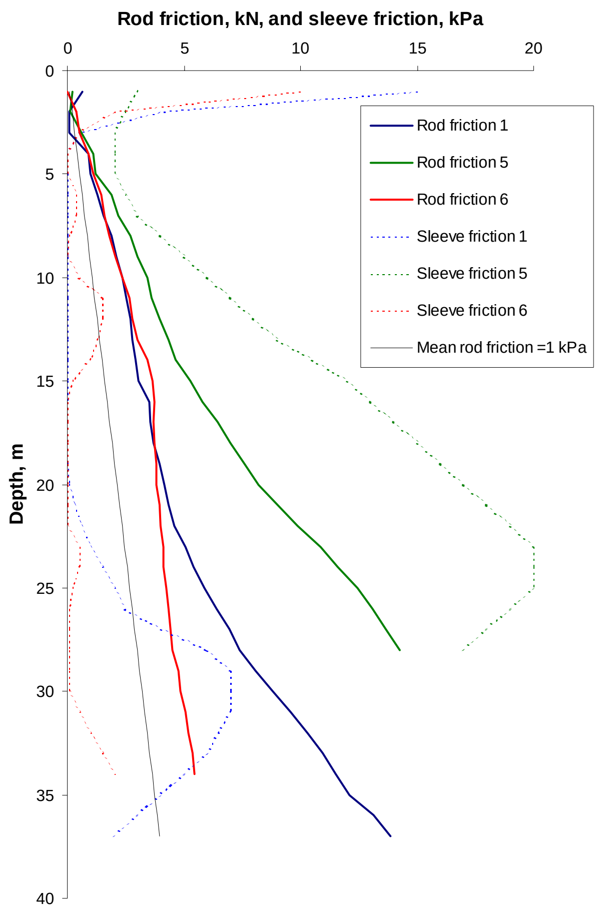


Fig. C33. Results from the CPT tests at Utby in terms of rod friction and sleeve friction versus depth.

The normal presentations of the results of the CPT tests in terms of total cone resistance, friction ratio, generated penetration pore pressure, pore pressure ratio etc. indicate fairly uniform clay down to the hard layer. The exception is at point 5, where there are sharp breaks in both cone resistance and generated penetration pore pressure at 7 metres depth, indicating a slip surface from the earlier landslide.

In all CPT tests, the pore pressure dissipation was recorded for about 5 minutes after stop against the hard layer. The dissipation curves indicate that the layer cannot be considered as a free draining layer but has a permeability of a magnitude that is typical for fine silt. Considering its thickness of only about 0.5 metre, the hard layer has thereby a very limited water conducting capability, and thus probably no significant influence on the leaching process.

3.3.4 Torp

Area and previous tests

The test site at Torp is located on the western bank of the river *Örekilsälven* in the southern part of the community of Munkedal. Here, there is a rise in the bedrock below the clay layers in the river valley and the river makes a couple of sharp turns around the area. The area was involved in the large Munkedal project to ensure stability along the riverbanks through the community. Before this, the area had been built-up, with several dwelling houses and a cement works. The stabilisation works involved large excavations at the crests of the slopes and every building except for a single dwelling house was demolished either during these operations or shortly afterwards. Nevertheless, the previous history entails that there are several fills and paved surfaces in the area. A number of earlier installations in the form of pipes and cables also remain in the ground, in addition to those serving the remaining building.

The topography of the area is more irregular than at the other sites. Its western border in a central west-east section is a steep hillside with outcropping bedrock along which runs the main railway in the area. The ground then slopes gently for about 150 metres down to a road running roughly parallel to the valley side. After passing the road, there is a plateau about 100 metres wide, followed by a steep excavated slope about 5 metres deep. The excavated terrace below is about 50 metres wide and is followed by a steep natural slope about 13 metres deep down to the riverbank, where erosion protection has been constructed.

The area further south has a similar topography but further north, both the river and the excavated plateau turn about 90 degrees to the west and create an uneven northern border of the site. Furthermore, the northern end of the road runs in a sloping depression in the ground towards the river, which indicates that a quick clay slide has occurred here some time long ago.

The area was investigated in connection with the stabilising works and more thoroughly in a recent project concerning the long-term effects of excavations in slope crests (see Larsson and Åhnberg, 2003). Also geophysical investigations were carried out by Dahlin et al.(2002). The geotechnical investigations showed that quick clay occurred in one of the investigated sections and the geophysical investigations in the same section indicated that this occurrence could be mapped by resistivity imaging.

The soil in the area consists of lateral fluvial sediments of organic sand and silt on top of marine clay. The thickness of the sand and silt layer at the site varies mainly within 2 – 5 metres, which means that all of it was removed from the excavated terraces. The total thickness of the sediments below the plateau in the central part of the site is about 25 metres. The bedrock appears to form a corresponding plateau here, but then slopes downwards towards the north, east and south. This means that the thickness of the sediments before the erosion of the river and the excavation was considerably greater in these directions. The original thickness at the river was at least 60 metres and in a section 230 metres to the south it is estimated to have been 80 – 90 metres. In the area between the road and the valley side, the thickness of the sediments decreases gradually.

During 1996 – 2001, the soil conditions from the river channel and up to the road were thoroughly investigated in two sections, of which one runs through the central part of the present test site and the other is located 230 metres further south, Fig. 3.34. The results are described in detail in Larsson and Åhnberg (2003). It was then found that quick clay occurred below the plateau in the northern section, but not further out towards the river and not in the southern section where the sediments were thicker. A thin layer of quick clay had also been reported at point S22 in the previous investigation.

The clay in the area is assumed to be resting on a layer of till on top of bedrock. From geophysical investigations, the thickness of this layer has been assumed to be between 1 and 10 metres and has at the few points where it has been checked by soil-rock drilling proved to be about 1 metre.

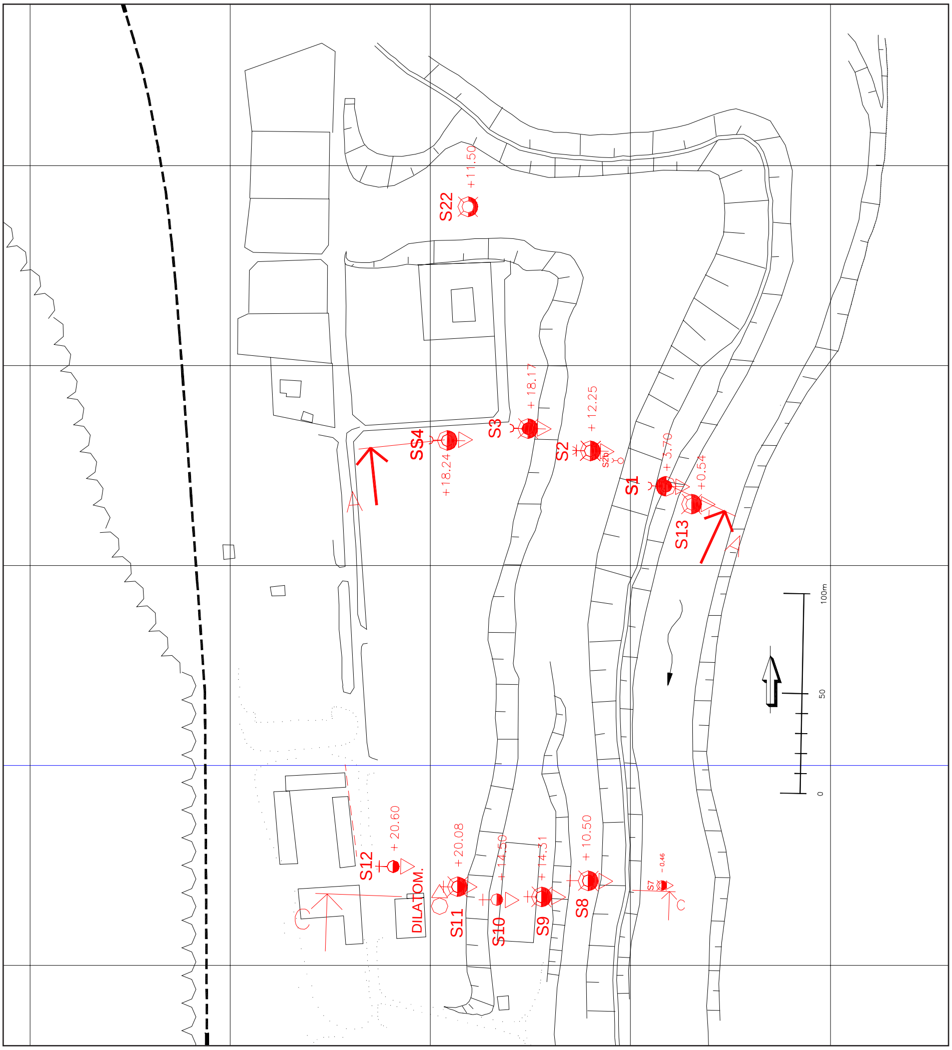


Fig. 3.34. **Plan of the area with the investigation points in the previous investigations.**

The pore pressure measurements indicate free ground water levels about 1 metre below the ground surface, except at the upper crests, where it dips in the more permeable layers of sand and silt. On the excavated terrace, the free ground water level is mainly at the ground surface. Below the upper plateau, there is a downward gradient with lower than hydrostatic pore pressures. This changes gradually down the slope and the pore pressures are artesian at the riverbank and below the riverbed.

Geophysical tests

Here again, the test site in the present investigation was located with the intention of finding the border of the quick clay formation. A rough idea of this was inferred from the previous investigations and resistivity measurements had already been performed in two lines. These lines were supplemented by five new ones, three mainly parallel to the road and two roughly perpendicular to it. Because of the topography and surface conditions, some of the lines were broken. The positions of the lines are shown in Fig.3.35.

Fig. 3.35. Lines for resistivity measurements and investigation points at Torp.

Geotechnical investigations
The geotechnical investigations in the present project were performed at nine points designated A–D, S2–S4 and S22. The designations A–D represent new investigation points in this project. S2–S4 and S22 are investigation points used also in the previous investigations, which have kept their previous designations to avoid confusion. Static pressure soundings were performed at all the investigation points, rotary pressure soundings were performed at points A, S2–S4 and S22, and total soundings and CPT tests were performed at points S2–S4 and S22. Results from undisturbed sampling and laboratory tests at points S2–S4 and S22 were already available and the sampling in this project was limited to two levels at point E, where the results from static pressure sounding indicated that highly sensitive clay might be present. The last three sounding types were thus mainly limited to the points where comparative laboratory results existed. The extra rotary pressure sounding at point A was performed because the upper layers at this point were so coarse that problems occurred owing to the relatively slender static pressure sounding equipment with bending and high friction at the top and an unusually jagged penetration curve throughout the profile.

Results
The results of the laboratory tests in previous investigations had shown that the clay throughout the area was mainly similar in character and had generally consolidated for an original ground surface level with the present plateau. The layering appears to be mainly horizontal with some tendency for the boundaries between different soil layers in the northern section to be influenced by the contour of the bedrock. The undrained shear strength is about 30 kPa directly below the upper sand and silt layer, after which it increases linearly with depth. The main exception from the general rule is the quick clay found at point S4, and to a lesser degree at point S22, where both preconsolidation pressures and undrained shear strengths are somewhat lower than at corresponding levels in the rest of the area.

The measured densities, water contents and liquid limits do not show any distinct differences between the different points, apart from a certain variation in level as mentioned above.

However, the values of quasi liquidity index and sensitivity all show that the clay varies across the area. The clay with high quasi liquidity index and sensitivity is thus found below the upper plateau and the thickness of this layer increases from about a metre at point S3 and a couple of metres at point S22 to more than half of the clay profile at point S4 closer to the valley side. Figs. 3.36 and 3.37.

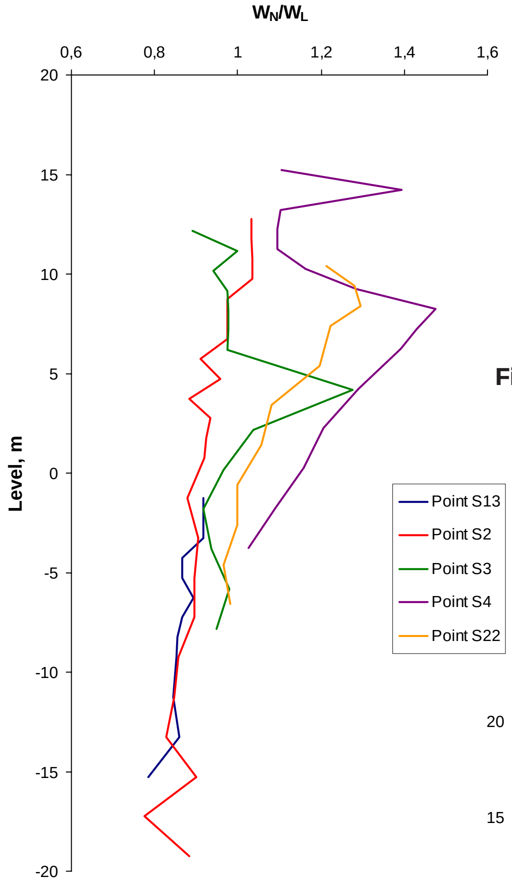


Fig. 3.36. **Quasi liquidity index versus level at different points at Torp.**

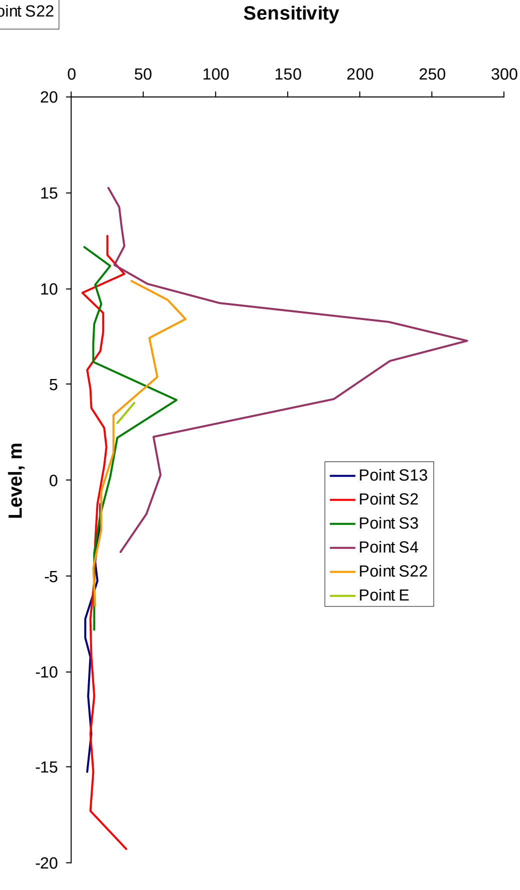


Fig. 3.37. **Sensitivity versus level at different points at Torp.**

The usual type of correlation between quasi liquidity index and sensitivity was found also here, and the results show that the quasi liquidity index should be higher than approximately 1.15 for the clay to be quick, Fig. 3.38.

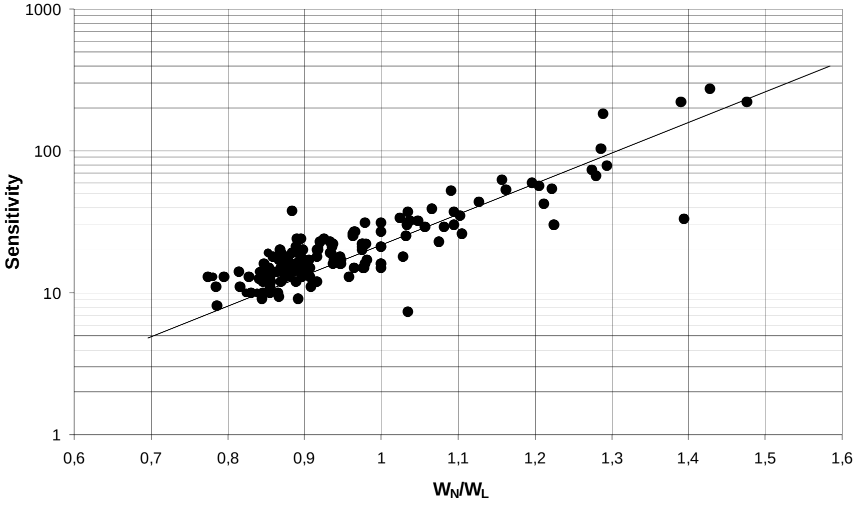


Fig. 3.38. Relation between quasi liquidity index w_N/w_L and sensitivity for Torp clay.

The resistivity measurements showed considerable scatter and more irregular images than at the other sites. This can be attributed to the conditions at the ground surface with poor electrical contact in the sand and silt layers and the fill materials, which are not completely saturated even below the free ground water level. Various buried objects in the upper soil profile can also be expected to affect the results. The extent to which the varying topography affects the interpretation is more difficult to estimate. However, in spite of this scatter a fairly clear picture was obtained with high resistivity below the upper plateau and further up towards the valley sides and lower values in all areas with thicker clay profiles. The resistivity sections indicate that leaching in the shallower clay profiles has occurred from both percolation of water from the ground surface and diffusion from draining layers at top and bottom, whereas leaching in the thicker clay profiles is mainly limited to the top layers where mainly diffusion from rainwater penetrating the coarser sand and silt layers may be assumed to have taken place.

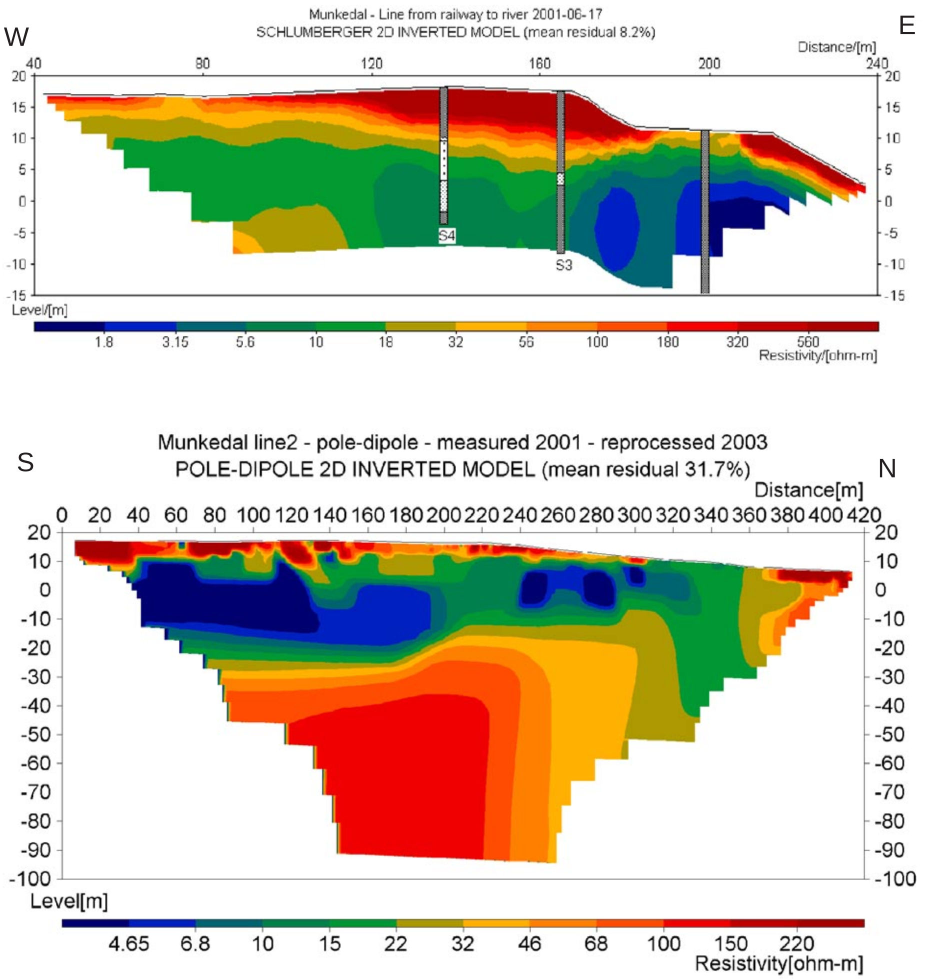


Fig. 3.39. Resistivity images for Section A (upper) and the cross line at the road.

The upper red zones in the images correspond to the sand and silt layers on top and the dry crust in the slope towards the river. The resolution at great depths is poor and results from depths greater than about 30 metres should be treated with great caution.

The results of the static sounding tests showed the normal pattern with increased resistances after each stop in the penetration and almost vertical penetration force – depth curves in the parts with quick clays, Fig. 3.40. Quick clay was thus indicated at all points along the road, A – C, and at point S4. Possible thin layers at other points could not be clearly discerned. However, there was an indication of a highly sensitive layer at 6 – 9 metres depth at point E. This led to a subsequent

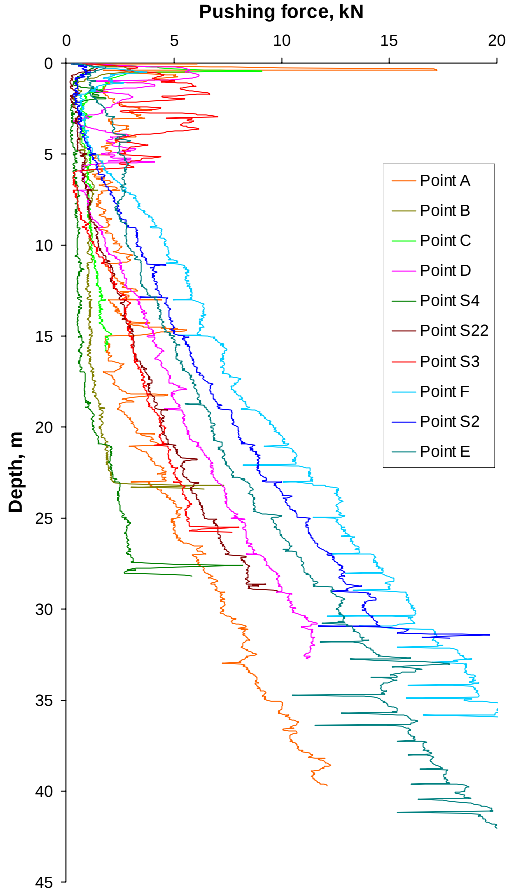


Fig. 3.40. Results from the static pressure soundings at Torp.

sampling at depths of 7 metres and 8 metres, and the laboratory tests showed that the clay here was highly sensitive but not quick. The overlying sand and silt layers created enough friction to prevent the equipment from sinking under its own weight at any of the points.

The results from the rotary pressure soundings yielded approximately the same picture as the static pressure soundings, Fig. 3.41. In this case, the results from the sounding at point A became more regular and easier to interpret, and indications of thin layers with highly sensitive clay could possibly be discerned also at points S3 and S22.

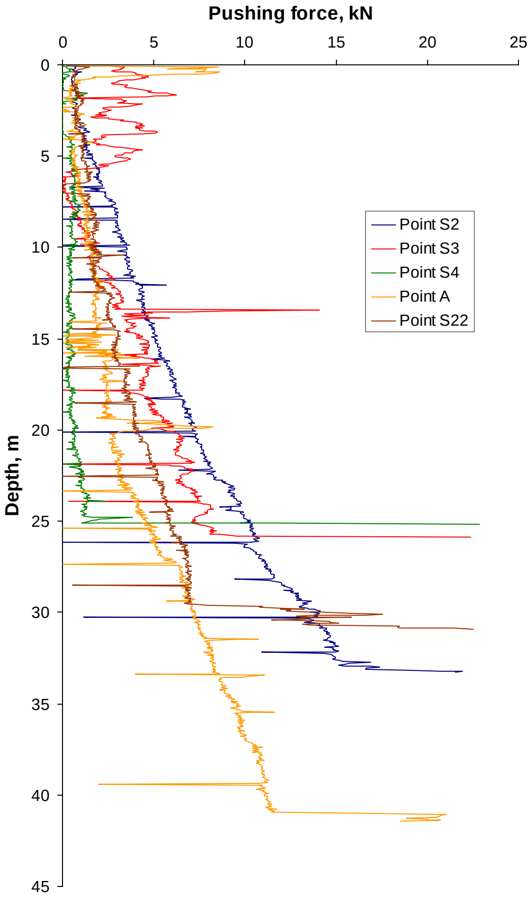


Fig. 3.41. Results from the rotary pressure soundings at Torp.

The total soundings also show a similar picture, although no clear indications of quick clay can be seen at any point expect for point S4, Fig. 3.42.

The evaluated rod friction and the measured sleeve friction in the CPT tests are shown in Fig. 3.43. The pattern of the rod friction versus depth is the same as for the other test methods and the trends for the rod friction are supported by the measured sleeve friction, although the scatter is fairly large for the latter parameter. Also these results show quick clay in the upper part of the profile at point S4. The thin, quick clay layers at point S3 and S22 are indicated, but not strongly enough to make a certain evaluation.

The results of the CPT tests indicate fairly uniform clay from just below the upper sand and silt layer, if still present, down to the firm bottom layers.

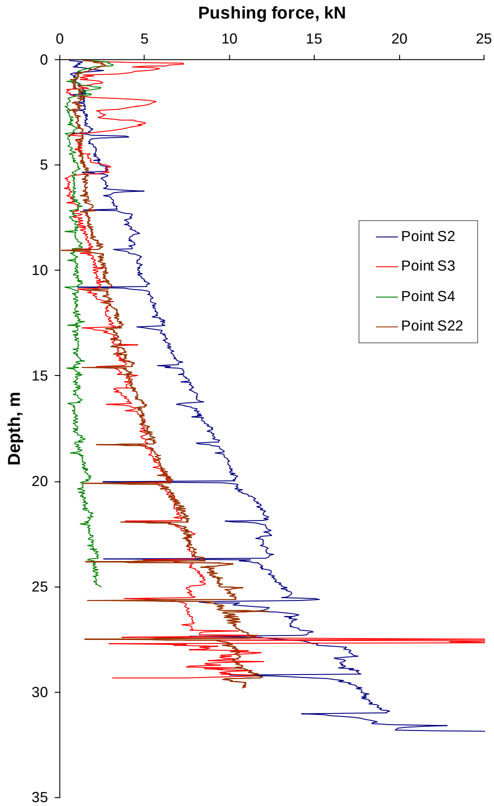


Fig. 3.42. **Results from the total soundings at Torp.**

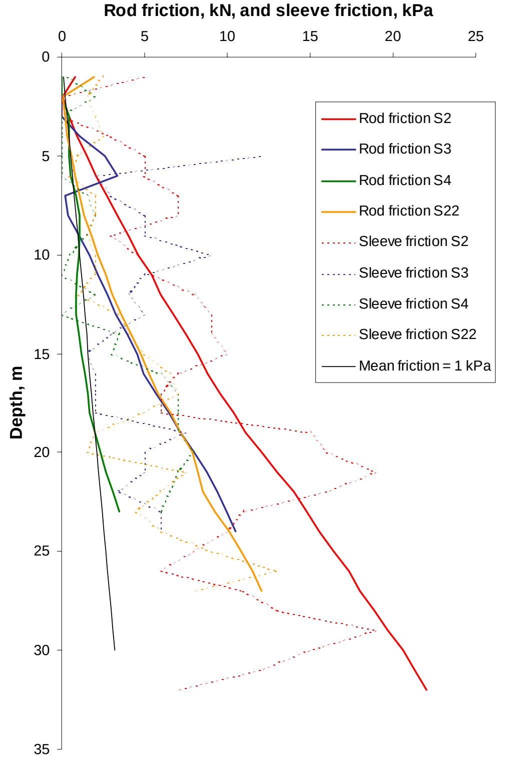


Fig. 3.43. **Results from the CPT tests at Torp in terms of rod friction and sleeve friction versus depth.**

3.4 GENERAL RESULTS FROM THE INVESTIGATIONS

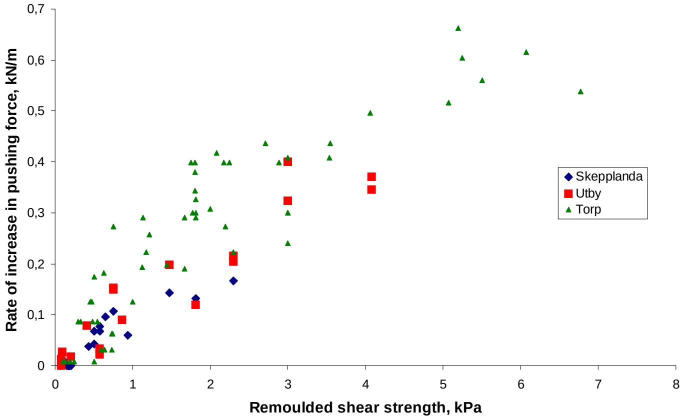
3.4.1 Correlations

The results of the sounding tests have shown a general correlation between the slope of the pushing force – depth curve and the sensitivity of the soil at the same depth. The pushing force is made up of two components; tip resistance and rod friction. The total penetration force also consists of two components; the measured pushing force and the weight of the equipment itself. It is only the rod friction that is related to the sensitivity, or more strictly the remoulded shear strength of the soil, and this parameter should preferably be used. However, it is not possible to separate the rod friction from the tip resistance, except in the CPT tests. On the other hand, the weight of the equipment and the tip resistance partly compensate for each other in this context. The rod friction is often also the main component in the types of soil profiles of interest for quick clay mapping, except at very shallow depths. It is thus to be expected that a certain correlation will be found between the pushing force measured at the top of the rods and the remoulded shear strength of the soil.

This correlation can, among other things, be expected to be dependent on the diameter of the rods, the shape of the tip, the diameter of the tip in relation to that of the rods, the rate of penetration and whether the equipment is rotated and in that case at what speed. As can be observed in the presented curves, the correlation also requires each penetration stroke to be long enough to overcome the thixotropic effects created at each stop for adding new rods.

The correlations between remoulded shear strength and pushing force found in this investigation are shown in Fig. 3.44. The correlations between the remoulded shear strength and the corrected rod friction and measured sleeve friction respectively in the CPT tests are also shown in Fig. 3.44d and 3.44e.

The results show clear and linear correlations between sounding resistance and remoulded shear strength. The scatter is large for the sleeve friction in CPT tests, which can be expected because of the insufficient measuring accuracy and also because here the soil will be only partly remoulded. When ϕ 36 mm push rods are used in this method, the sleeve friction and the rods will have the same diameter as the tip and no extra remoulding from an enlarged tip will be created. The degree to which the soil just above the tip is remoulded probably varies between different soil types, but the results show that in principle the friction along the sleeve is higher than the remoulded shear strength, and the average ratio in the tested types of clay is roughly about 3:1. Also the corrected rod friction shows that the friction along the rods is generally higher than the remoulded shear strength, and indicates that a)



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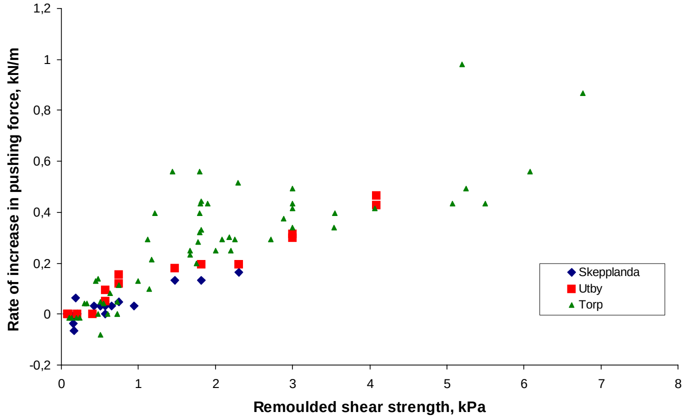


c)

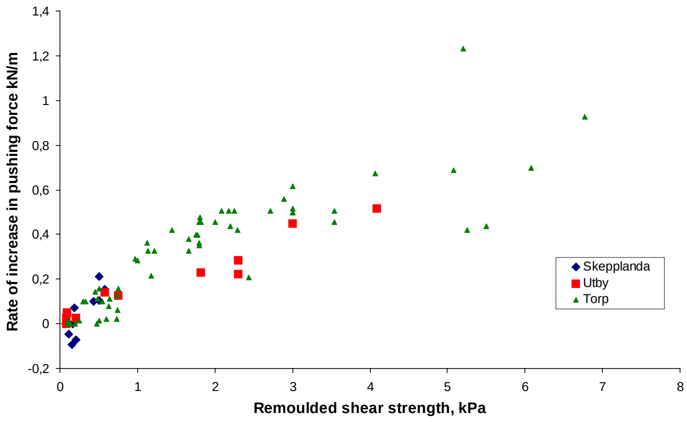
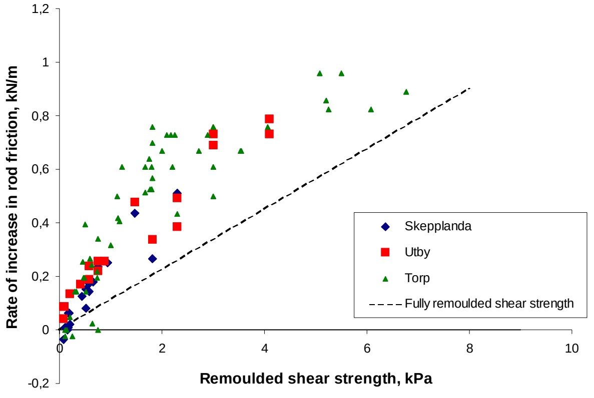


Fig. 3.44. Relation between sounding resistance and remoulded shear strength
a) Static pressure sounding
b) Rotary pressure sounding
c) Total sounding

d)



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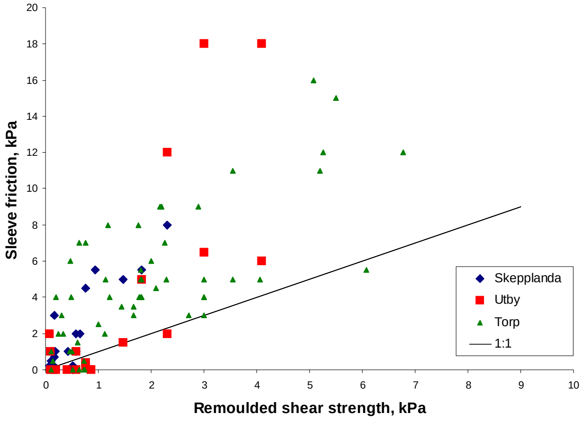
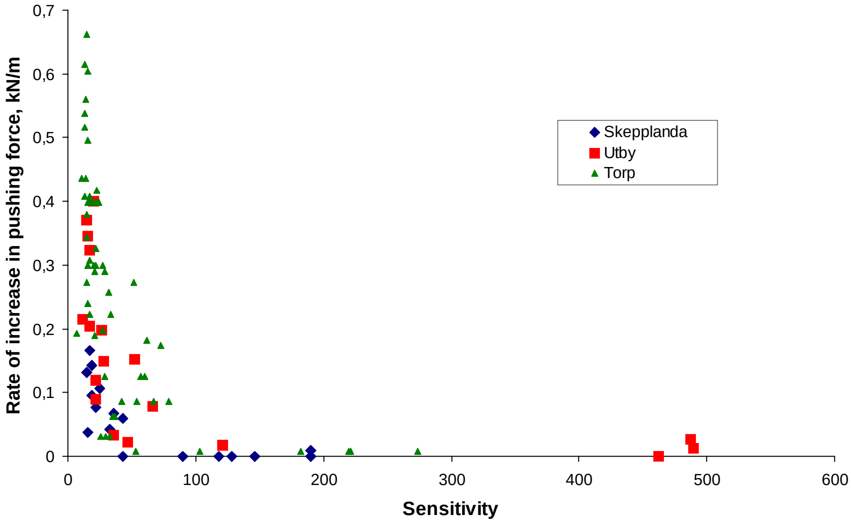


Fig. 3.44. Relation between sounding resistance and remoulded shear strength
d) CPT test, corrected rod friction
e) CPT test, sleeve friction

the average rod friction over a 1 metre interval is normally about 1.5 times the completely remoulded shear strength.

The corresponding correlations for the sensitivity are shown in Fig. 3.45. The results for all the methods show that all the relations obtained are similar to that proposed by Möller and Bergdahl (1982) for static pressure sounding. Quick clays are thus found to give almost no increase in pushing force or rod friction versus depth. However, since there is no direct connection between pushing force and sensitivity, there is a large variation in sensitivity for any given slope of the sounding curves, except for the very flattest. It is thus not possible to propose any useful mathematical expressions for these correlations.



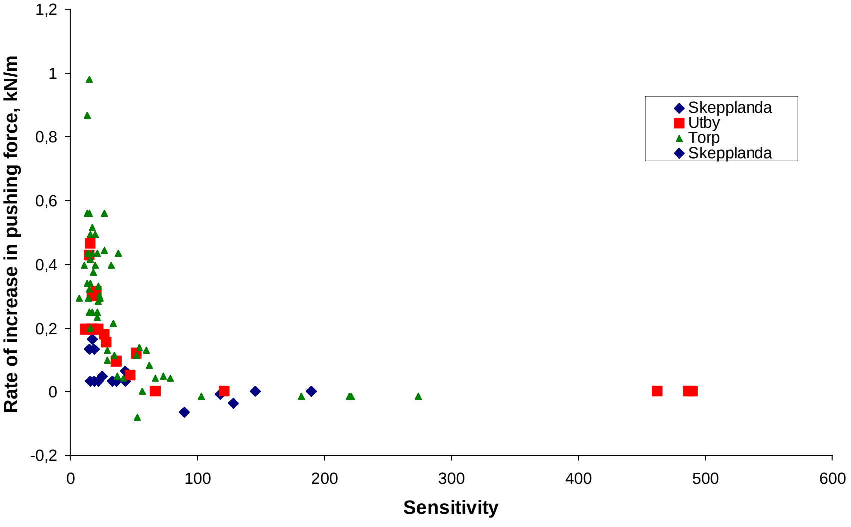
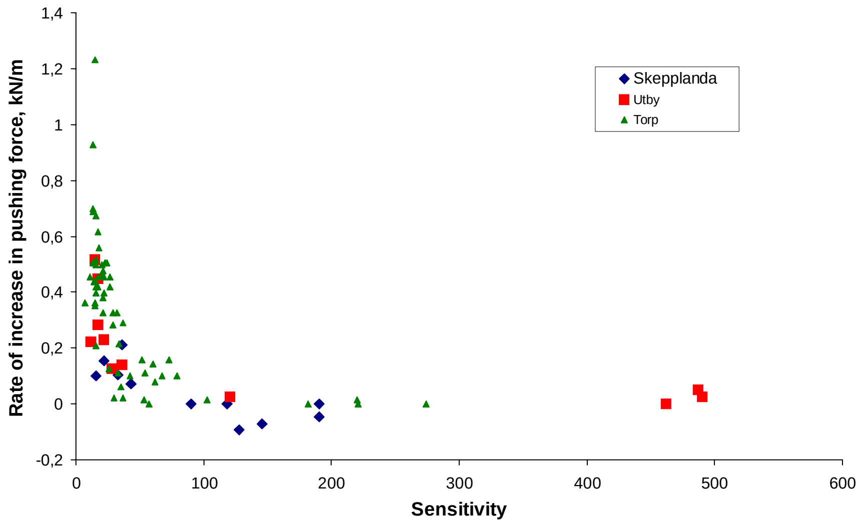


Fig. 3.45. Relation between sounding resistance and sensitivity
a) Static pressure sounding
b) Rotary pressure sounding



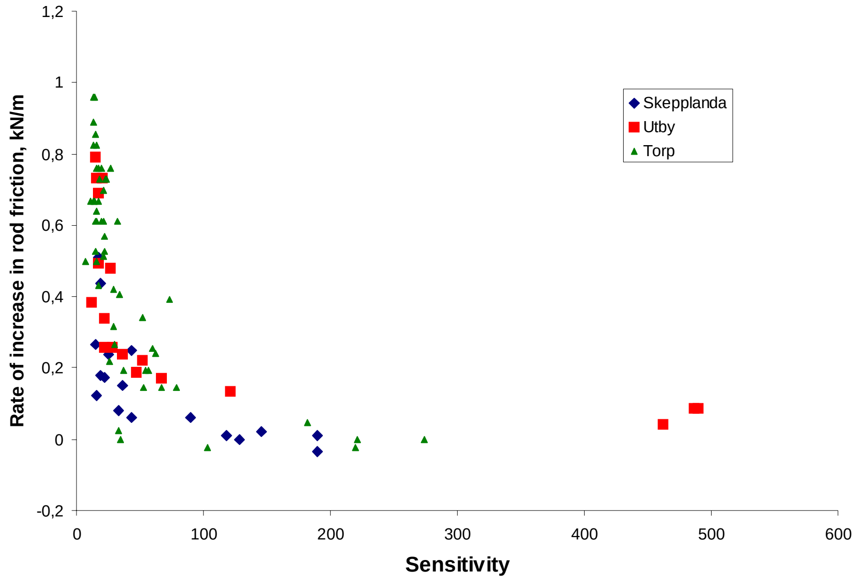


Fig. 3.45. **Relation between sounding resistance and sensitivity**
c) Total sounding
d) CPT test, corrected rod friction

Also the correlation between the resistivity and the sensitivity was investigated, Fig. 3.46. The results confirmed the earlier rule that the resistivity should be ≥ 5 Ωm if the salt content is to be low enough to allow the clay to be quick (Söderblom, 1969). They also confirmed that no other correlation could be found since high resistivity and low salt content does not automatically mean that the clay is

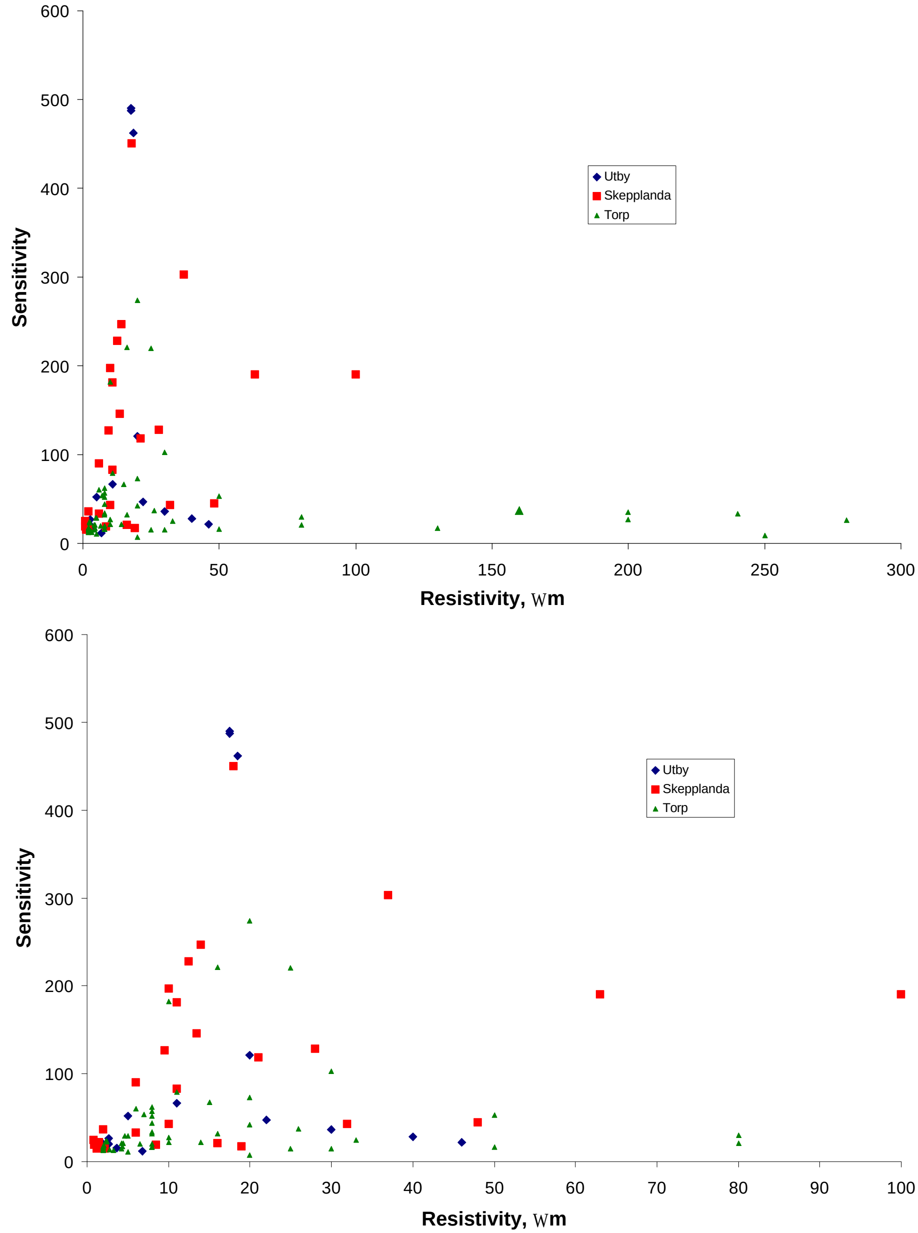


Fig. 3.46. Relation between resistivity and sensitivity.

sensitive. Thus, some of the highest resistivity values are found in the dry crust and weathered zone, where the clay is hardly ever highly sensitive because of an insufficient water content and chemical weathering effects. Also in other zones, the water contents are often too low because of compression of the soil, or the chemical composition of the soil and pore water entails that the clay is not particularly sensitive even at a high water content. Furthermore, organic soils are never quick.

3.4.2 Discussion

The correlations between sensitivity and electrical resistivity can be used only for separation of soil volumes in marine clays, which have been leached sufficiently to possibly form quick clay, from those volumes where the salt content remains high enough to prevent this. The actual sensitivity of the leached clay has to be determined by other methods, which can only provide sample tests. Certain general observations – for example, the soil in the dry crust and the weathered zone, as well as organic soils and heavily overconsolidated soils, is rarely quick – can also be used in the screening process.

The correlations between sensitivity and sounding resistance can be used mainly for a rough division of the soil into sensitivity classes. No precise rules can be given for the way in which this should be done because the correlation is only indirect and depends on soil type, equipment and test performance. However, an almost vertical pushing force–depth curve generally indicates highly sensitive clay. Provided that the same equipment and test method is used throughout the investigated area, a very good visual picture can also be obtained of the relative sensitivity of the soil by studying the penetration curves*. The slope of the curves can also be calibrated roughly against sensitivity values obtained from tests on samples taken at some of the test points.

It is possible to use any sounding method which uses a constant rate of advance into the ground and in which the penetration force applied on the top of the rods is measured. However, the stroke in each pushing operation should preferably be at least 2 metres in order to enable separation of the thixotropic effects that occur each time the operation is interrupted for the addition of new rods. It should be observed that the variations in total penetration force are not related to rod friction alone, but significant changes in tip resistance may distort the general picture. Thus, the large dip in tip resistance after passing through the stiffest part of the dry crust makes it impossible to draw any conclusions about the sensitivity in the layer just below the

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* This refers mainly to a limited area with the same geology.

crust. The same problem occurs when passing embedded stiffer layers in the soil profile. An almost constant or decreasing penetration force may also be a result of the tip entering soil layers with continuously decreasing plasticity, such as varved and silty bottom layers, in which also the tip resistance decreases.

Another source of error is that the rod friction away from the tip may change significantly. This can occur if high friction caused by coarse soil in the crust or any other large object is released when these objects are dislodged. It can also be caused by a wobbling motion of the rods leading to enlargement of the drill hole and local gaps between the rods and the soil.

Furthermore, any change in the rod diameter in the string of drill rods will create a change in the pattern of the penetration curve and cannot be permitted.

These potential errors can be avoided by using CPT tests with the additional measurement of the total penetration force. Provided that a sensitive probe is used, the rod friction can be separated and also checked by using the readings of sleeve friction at the very tip. The fact that there is no direct correlation between the rod friction (and sleeve friction) and the sensitivity still remains. On the other hand, a CPT test provides a fairly accurate determination of the undrained shear strength, which together with determinations of liquid limits and remoulded shear strength on samples can be used to calculate the sensitivity. The latter two determinations do not require undisturbed samples. Depending on other circumstances, such as the available data from other investigations and the scope of the investigation, the more laborious CPT test may therefore be a more rational test. The much more detailed information about the soil conditions also in other aspects than sensitivity alone should also be taken into consideration when selecting test methods.

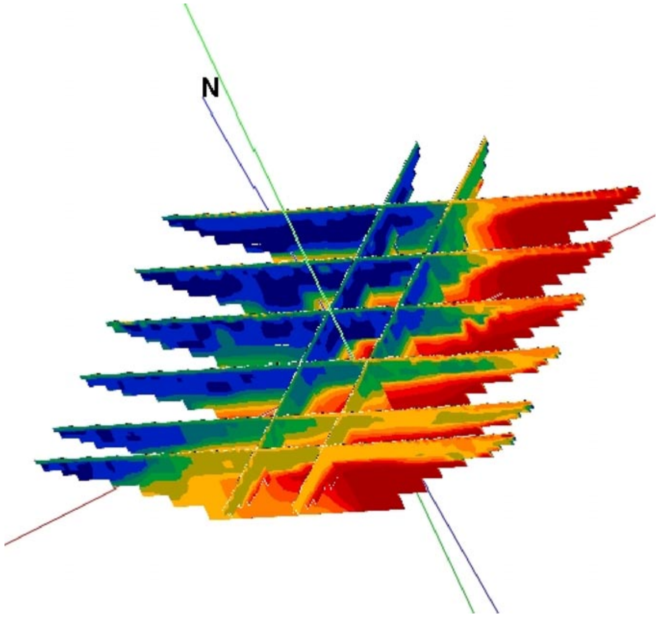
3.5 COMPARISON OF GEOPHYSICAL AND GEOTECHNICAL MODELS

The resistivity measurements provide continuous 2-dimensional images of the soil in the measured sections. There are also programs that allow these sections as well as the cross-sections to be combined into a quasi 3-dimensional picture of the whole investigated soil mass. This picture can be rotated and inspected from different directions and angles to obtain the best illustrative view.

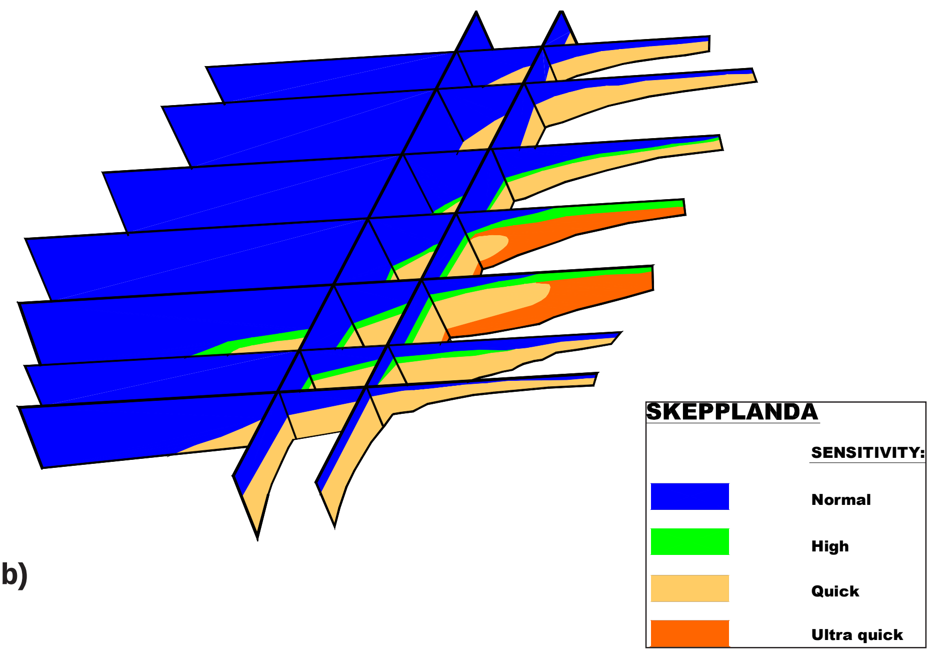
The geotechnical investigations are performed at single points and provide profiles only at these points. When several points are investigated along a line, a section can be drawn in which the different soil layers identified at the test points are connected by straight lines or otherwise estimated curves. There is no readily available program for connecting such geotechnical sections into 3-dimensional models. However, provided that there are sufficient investigation points to create such a model with reasonable certainty, a manual process can be used. In the actual cases, there are several test points in each limited area and the points have been located to enable such modelling. When creating the geotechnical models, the same views have been selected as those that were found to give the best illustration of the resistivity distribution. A direct comparison between the models can thereby be made.

The resistivity model and the geotechnical sensitivity model for the Skepplanda site are shown in Fig. 3.47. In the geotechnical model, the soil has been divided into four sensitivity classes. The blue colour represents normal sensitivity, which for the clays in western Sweden is up to about 30. The green colour represents highly sensitive but not quick clays with sensitivity values in the range of 30 – 50. The yellow colour represents quick clays with sensitivities above 50 and the red colour shows ultra quick clays with sensitivity values of several hundred and sometimes unmeasurable levels. The criterion that the remoulded shear strength must be less than 0.4 kPa in quick clay has also been checked.

It can be observed how the two models match with quick clay found in the significantly leached parts and that clay with normal sensitivity is found where the salt content remains high. The only discrepancy is the zone for the dry crust and the thin weathered zone at the top, where the resistivity is high but the clay is non-quick, but this is to be expected for other reasons, as previously explained. It can also be observed how the thickness of the clay layers, the permeable layer below the clay and the artesian water pressures have affected the leaching process and quick clay formation. The dark red zones in the lower right part of the resistivity presentation show the underlying bedrock.



a)



b)

Fig. 3.47. **Quasi 3-dimensional models of the soil at Skepplanda.**
a) resistivity model
b) geotechnical model

The same presentations for the site at Utby are shown in Fig. 3.48. Here again, there is a very good correlation between the two models, except for the depths of the profiles. All the geotechnical investigations, except for the total soundings, stopped at the embedded hard layer. On the other hand, the resistivity measurements did not

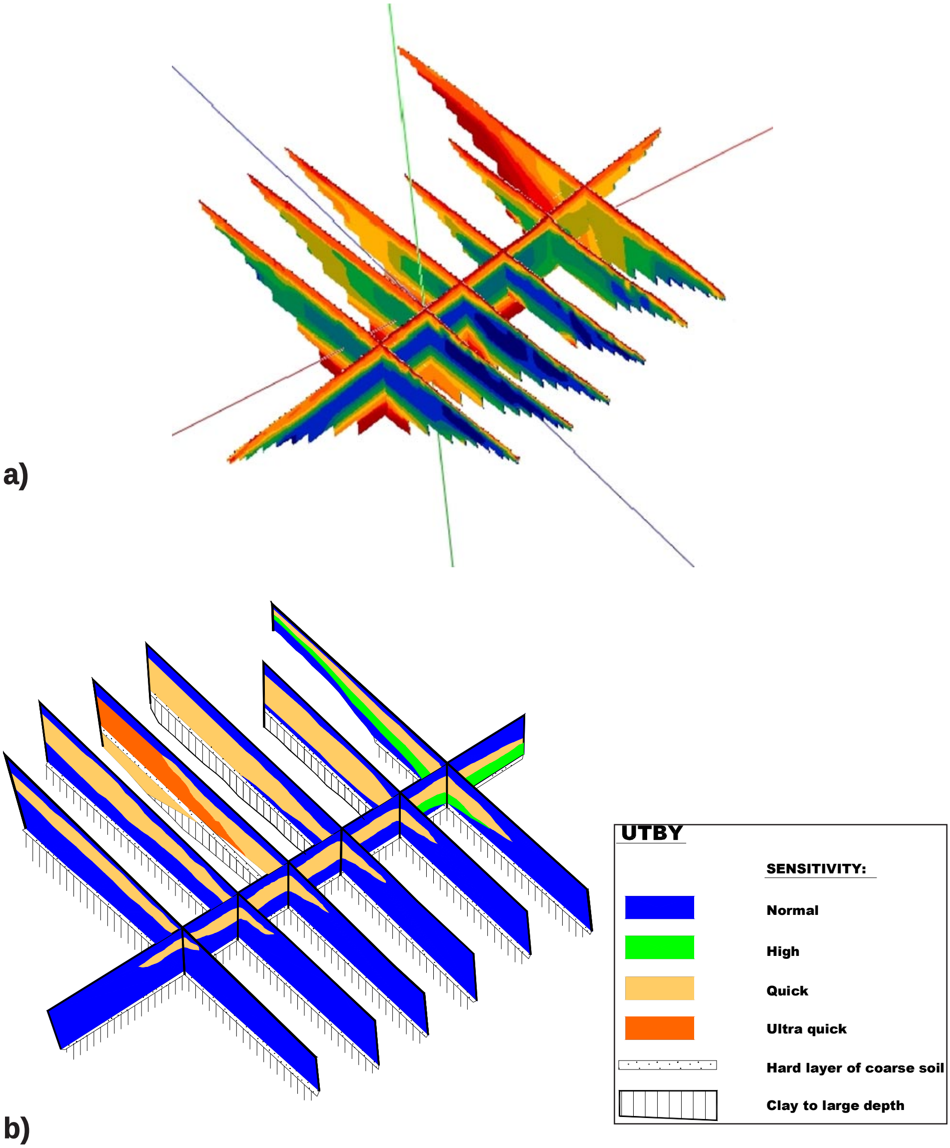
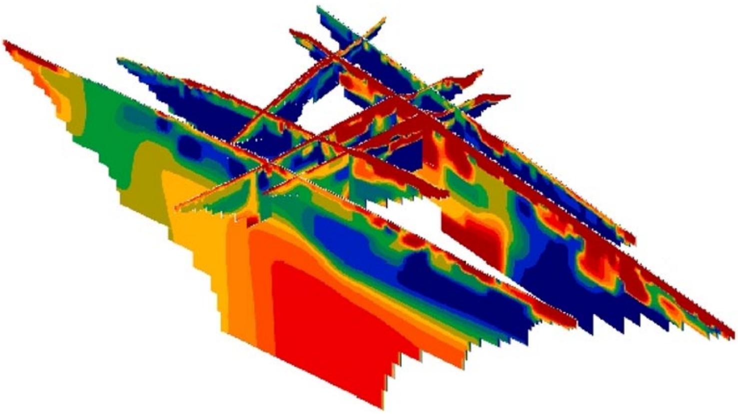


Fig. 3.48. Quasi 3-dimensional models of the soil at Utby.
a) resistivity model
b) geotechnical model

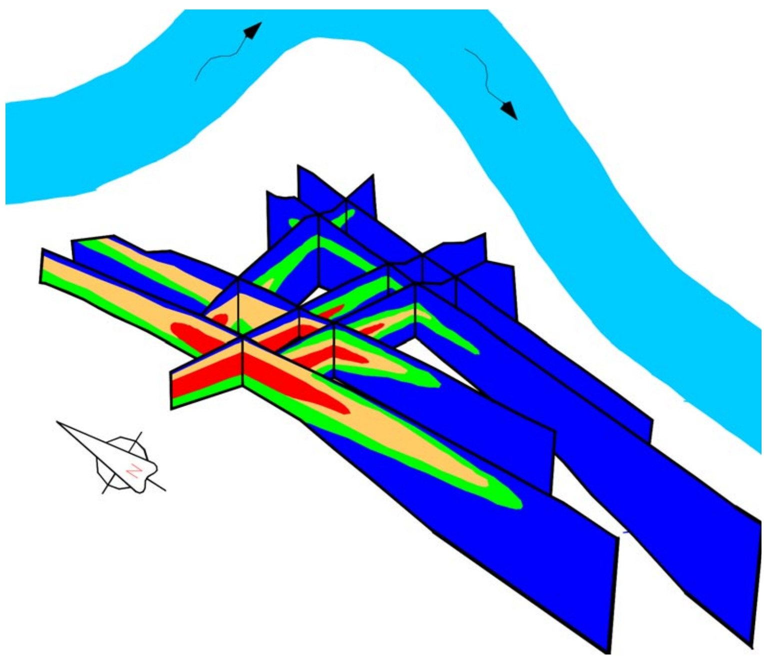
detect this layer and showed great depths to bedrock in most of the area. The resistivity in the hard but thin layer was obviously not sufficiently different to show up in the interpretation. Regarding depth, the two models thus only coincide in the upper left corner, where the depth to bedrock was less and the upper bedrock surface was located above the elevation of the hard layer, which was thus not present here. Also at Utby, the leached and highly sensitive zones are mainly found in the upper part of the slope, where the thickness of the clay layers is less. However, in this case the quick clay is found mainly in the upper parts of the profiles below the crust and the weathered zone. This reflects the ground water conditions with a downward gradient and water slowly seeping down from the ground surface in these parts.

Also the models for the Torp area are fairly consistent. In this case, there is considerably more scatter in the resistivity model, which reflects the less favourable conditions for these measurements at this site. Nevertheless, the model shows that the salt content is generally low enough for quick clay formation up towards the valley side and below the plateau in those parts where the depth to bedrock is relatively low. In areas with greater depths to bedrock, the salt content appears to be high enough to prevent quick clay formation, except for a zone in and just below the crust and overlying sand and silt sediments. Here too, there is a downward gradient in the pore pressure in the upper parts of the area.

The geotechnical model shows the corresponding distribution of sensitivity. The quick clay is concentrated to the area towards the valley side and below the plateau where the thickness of the clay layer is limited. Quick clay was found below the sand and silt layers at point S22 in the northern part of the area, but not at the other points outside the main quick clay formation. This upper quick layer thus appears to have a limited extent. The clay at the location of the assumed earlier quick clay slide was found to be quick. However, the extent to which the process of quick clay formation had advanced at the time of this slide and the causes of the limitation of this slide area cannot be estimated.



a)



b)

Fig. 3.49. **Quasi 3-dimensional models of the soil at Torp.**
a) resistivity model
b) geotechnical model

3.6 RECOMMENDATIONS

The methods applied in the mapping of quick clay should be selected with consideration to cost and benefit, the suitability of the method in the particular geology and environment and possible other uses of the results than quick clay mapping alone.

The use of resistivity measurements is mainly applicable when large areas are to be investigated since these measurements provide continuous sections, whereas sounding methods only provide point information. The latter operations can therefore become fairly extensive if large areas are to be covered, the borders of the quick clay formations clarified and no pockets of quick clay left undetected. The resistivity measurements are also mainly applicable in rural areas with a minimum of surface pavements and installations in the ground. Fills and thick overlying layers of unsaturated sand are also unfavourable for these measurements. A complex geology could also be a restriction for this type of measurement, but this is not normally the case in the Swedish areas of main interest.

The results of resistivity measurements always have to be supplemented by geotechnical investigations, but these may be considerably limited in relation to those in a traditional geotechnical investigation.

The simple static pressure sounding is normally sufficient for mapping quick clay. The use of the heavier rotary pressure sounding method did not show any particular advantage in the investigations in this project, except possibly that the method is somewhat faster. This could be beneficial since a large number of soundings have to be performed for a detailed mapping of an area. Rotary pressure sounding also better penetrates any coarse fills and layers overlying the clay.

Both these methods can be replaced by the total sounding method, which yields corresponding results and also has the ability to penetrate stiffer layers and to verify the level of the bedrock. The benefit of this was illustrated at Utby, where the soil layers proved to be much thicker than estimated by any of the other methods. However, the equipment for total sounding is much heavier and requires a large drill rig and access to high-pressure flushing water or compressed air. The injection of a flushing medium under high pressure in the bottom layers in areas on or close to slopes with low or uncertain stability must also be performed with great caution. Drilling with a flushing medium will also always involve potential additional problems in areas with artesian ground water conditions.

The CPT test with simultaneous measurement of the total penetration force gives the most reliable picture of the variation in sensitivity. However, the time and cost for each test are considerably higher and the interpretation more laborious. This may be more than compensated if the results are to be used for more than quick clay mapping, such as determination of the detailed stratigraphy, the undrained shear strength and other parameters. The need for high quality undisturbed samples is thereby also reduced, which may be taken into consideration in the cost-benefit analysis. In any case, it is always recommended to measure the total penetration force in areas where there may be quick clay deposits. The extra cost for this measurement is insignificant and enables a better evaluation of the sensitivity if this should prove to be of importance.

References

Appelo C.A.J. & Postma, D. (1994). Geochemistry, groundwater and pollution. A.A. Balkema, Rotterdam.

Atkins, P.W. (1982). Physical Chemistry, Oxford University Press. Oxford.

Berggrundskarta över Göteborgs och Bohuslän (Bedrock map of the county of Göteborg and Bohus) (1990). Swedish Geological Survey, SGU, Serie Ah nr 12. Uppsala. (In Swedish)

Berggrundskarta över Älvsborgs län (Bedrock map of the county of Älvsborg) (1986). Swedish Geological Survey, SGU Serie Ah nr 13. Uppsala. (In Swedish)

Bjerrum, L. (1954a). Geotechnical properties of Norwegian marine clays. Geotechnique, Vol 4, 49-69.

Bjerrum, L. (1955). Norske marine leirers geotekniske egenskaper. Norges Geotekniske institutt. Publikasjon 7. Oslo. (In Norwegian)

Bjerrum, L. & Rosenqvist, I.,T. (1956). Some experiments with artificially sedimented clays. Geotechnique, Vol. 6, pp 124-136.

Bjerrum, L. (1967). Engineering geology of Norwegian normally-consolidated marine clays as related to settlements of buildings. Seventh Rankine Lecture. Geotechnique, 17, pp 81-118.

Brand, E.W. & Brenner, R.P. (1981). Soft clay engineering. Elsevier.

Cato, I., Fredén, C., Häger, K.O. & Miller, U. (1981). Rekonstruktion av sedimentationsförhållandena vid Tuve. In Tuve-skredet – Geologi, Statens geotekniska institut, Rapport No. 11b, Linköping. (In Swedish)

Dahlin, T., Larsson, R., Leroux, V., Svensson, M. & Wisén, R. (2001). Geofysik i släntstabilitetsutredningar. Rapport 62. Statens geotekniska institut. Linköping. (In Swedish)

Dahlin, T. & Zhou, B. (2003a). A numerical comparison of 2D resistivity imaging with ten electrode arrays, accepted for publication in *Geophysical Prospecting*.

Engdahl, M., Fogdestam, B. & Engqvist, P. (1999). Beskrivning till kartan över grundvattnet i Västra Götalands län, västra delen f.d. Göteborgs och Bohus län (Description of the hydrological map of the county of Västra Götaland). Swedish Geological Survey, SGU Serie Ah nr 12. Uppsala. (In Swedish)

Fällman, A-M, Holby, O. & Lundberg, K. (2001). Kolloiders betydelse för hållfasthet och föroreningstransport i jord. Statens geotekniska institut, Rapport 60. Linköping. (In Swedish)

Geologisk karta över Vänersborg (Geological map of Vänersborg) (1982). Swedish Geological Survey, SGU, Serie Ae nr 48. Uppsala. (In Swedish)

Geologisk karta över Marstrand SO och Göteborg SV (Geological map of Marstrand SO and Göteborg SV), (1985). Swedish Geological Survey, SGU, Serie Ae nr 72. Uppsala. (In Swedish)

Geologisk karta över Fjellbacka (Geological map of Fjellbacka). (1901). Swedish Geological Survey, SGU, Serie Ac nr 3. Stockholm. (In Swedish)

GF (2003). Geoteknisk undersökning Skepplanda, Grönåns industriområde. GF Konsult AB, Uppdrag 32102301, Göteborg.

Hagberg, K. (2003). Föredrag på SGF Temadag i Stockholm. (Unpublished)

Hansbo, S. (1975). Jordmateriallära. Almqvist & Wiksell, Uppsala. (In Swedish)

Hellgren, L-G. (2004). Personal contact with Lars-Gunnar Hellgren, the City Planning Authority of Gothenburg. Göteborgs Stadsbyggnadkontor, Göteborg.

Hydrologisk karta over Västra Götalands län, västra delen, före detta Göteborgs och Bohuslän (Hydrological map of the county of Västra Götaland, Westen part, former Göteborgs and Bohus County). (1998). Swedish Geological Survey, SGU, Serie Ah nr 12. Uppsala. (In Swedish).

Hydrologisk karta över Älvsborgs län (Hydrological map of the county of Älvsborg) (1994). Swedish Geological Survey, SGU, Serie Ah nr 13. Uppsala. (In Swedish)

Jerbo, A. & Hall, F. (1961). Några synpunkter på högsensitiva bottniska sediment. Geologiska föreningen Stockholm. Förhandlingar. Stockholm. (In Swedish)

Karta över landisens avsmältning och högsta kustlinjen i Sverige (Map over the regression of the inland ice and the highest shore-line in Sweden) (1961). Swedish Geological Survey, SGU Specialkarta, Serie Ba nr 18. Uppsala. (In Swedish)

Kenney, T.C. (1976). Formation and geotechnical characteristics of glacial-lake varved soils. Laurits Bjerrum memorial volume. Norges geotekniska institutt.

Larsson, R. (1975). Konsolidering av lera med elektroosmos: En laboratoriestudie. Byggforskningen, Rapport R45:1975, Stockholm. (In Swedish)

Larsson, R., Ottoson, E. & Sällfors G. (1994). The landslide in Agnesberg (in Swedish). Swedish Geotechnical Institute. Report 44. Linköping.

Larsson, R. & Åhnberg, H. (2003). Long-term effects of excavations at crests of slopes, Pore pressure distribution – Shear strength properties – Stability – Environment. Swedish Geotechnical Institute, Report No. 61, Linköping.

Leroux, V. & Dahlin, T. (2003). Resistivity for mapping of quick clay –Field study at Skepplanda, Utby and Munkedal in Bohuslän, Sweden. Report 2003-10-24. Department of Engineering Geology, Lund University, Lund.

Loberg, B. (1980). Geologi. Material, processer och Sveriges berggrund. P A Norstedt & Söners förlag. Stockholm. (In Swedish)

Loke M.H. (2003). Manual for Res2Dinv, available at: www.geoelectrical.com.

Lundqvist, G. (1958). Beskrivning till jordartskara över Sverige. Sveriges geologiska undersökning. Stockholm. (In Swedish)

Løken, T. (1970). Recent research at the Norwegian Geotechnical institute concerning the influence of chemical additions on quick clay. Geologiska föreningen i Stockholm. Förhandlingar. Volume 92. Part 2. Stockholm.

Løken, T. (2002). Personal communication with Tor Løken, Norwegian Geotechnical Institute, Oslo.

Mitchell, J.K. (1976). Fundamentals of soil behaviour. John Wiley & Sons, Inc.

Moum, J., Løken, T. & Torrance, J.K. (1971). A geochemical investigation of the sensitivity of a normally consolidated clay from Drammen, Norway. Geotechnique 21, No 4, 329-340.

Moum, J., Løken, T. & Torrance, J.K. (1972). A geochemical investigation of the sensitivity of a normally consolidated clay from Drammen, Norway. Discussion. Geotechnique 22, No3, 542-544.

Möller, B. & Bergdahl, U. (1982). Estimation of the sensitivity of soft clays from static and weight sounding tests. Proceedings of the European symposium on penetration testing, 2, ESOPT, Amsterdam, May 1982., Vol. 1, pp.291-295.

Penner, E. (1965). A Study of sensitivity in Leda Clay. Canadian Journal of Earth science, 2, pp 425-441.

Pusch, R. (1962). Clay particles; their size, shape and arrangement in relation to some important physical properties of clays. Statens råd för byggforskning. Handling Nr 40. Stockholm.

Pusch, R. (1970). Clay microstructure. A study of the microstructure of soft clays with special reference to their physical properties. Swedish Geotechnical Institute, Proceedings No 24. Stockholm.

Pusch, R. (2002). Personal communication with Roland Pusch, Geodevelopment AB, Lund.

Rankka, K. (2003). Kvicklera – bildning och egenskaper – Litteraturstudie. Statens geotekniska institut, Varia Nr 526, Linköping. (In Swedish).

Rosenqvist, I.T. (1946). Om leirers kvikkagtighet. Statens Vegvesen. Veglaboratoriet. Meddelande Nr 4. Oslo. (In Norwegian)

Rosenqvist. I.T. (1955). Investigations in the clay-electrolyte-water system. Norwegian Geoteknical Institute. Publication No 9, pp 36. Oslo.

Rosenqvist, I.T. (1978). A general theory for the sensitivity of clays. Proceeding of the interdisciplinary conference held at the University of Luleå. Permont Press.

Rygg, N. (1978). Dreietrykksondering: Tolkning av sonderingsresultat. Vegdirektoratet, Veglaboratoriet, Intern rapport nr. 816, Oslo. (In Norwegian).

SGF (1993a). Recommended standard for cone penetration tests. Established by the Swedish Geotechnical Society June 15, 1992, Swedish Geotechnical Society. SGF, Report 1:93 E, Linköping.

SGF (1993b). Recommended standard for field vane shear test. Approved by the Board of the Swedish Geotechnical Society, April 7, 1993, Swedish Geotechnical Society. SGF, Report 2:93 E, Linköping

SGF (1996). Geoteknisk fälthandbok. Allmänna råd och metodbeskrivningar. Svenska Geotekniska Föreningen. SGF Rapport 1:96, Linköping, (In Swedish)

Skempton, A.W. (1953). Soil mechanics in relation to geology. Proceeding of the Yorkshire geological society. Hull.

Statens offentliga utredningar (1962). Rasriskerna i Götaälvdalen. Betänkande avgivet av Götaälvskommittén. Inrikesdepartementet. Stockholm. (In Swedish)

Statens vegvesen (1997). Feltundersøkelser – retningslinjer, Håndbok 015. Vegdirektoratet, Veglaboratoriet, Oslo. (In Norwegian).

Stevens, R. (1987). Glaciomarine fine sediments in southwestern Sweden: late Weichselian-Holocene lithostratigraphy, depositional environment and varve formation. Dissertation. Chalmers University of Technology/University of Gothenburg, Department of Geology, Publ. A54, Gothenburg.

Swedish Standard 02 71 25 – Geotekniska provningsmetoder – Skjuvhållfasthet – Fallkonförsök (Geotechnical tests – Undrained shear strength – Fall-cone test) (1991) (In Swedish)

Söderblom, R. (1969). Salt in Swedish clays and its importance for quick clay formation. Results from some field and laboratory studies. Swedish Geotechnical Institute, Proceedings, No 22. Stockholm.

Söderblom, R. (1974). Organic matter in Swedish clays and its importance for quick clay formation. Swedish Geotechnical Institute, Proceedings, no 26. Stockholm

Talme, O., Pajuste, M. & Wenner, C.-G. (1966). Secondary changes in the strength of clay layers and the origin of sensitive clay. Byggforskningsrådet, Rapport 46. Stockholm.

Talme, O. (1968). Clay sensitivity and chemical stabilisation. Byggforskningsrådet, Rapport 56. Stockholm.

Tan, T.K. (1957). Discussion on: soil properties and their measurements. Proceeding 4th International Conference on Soil Mechanics and Foundation engineering. Vol 3, pp 87-89. London.

Torrance, J.K. (1974). A laboratory investigation of the effect of leaching on the compressibility and shear strength of Norwegian marine clays. Geotechnique 24, No 2, pp 155-173.

Torrance, J.K. (1978). Post-depositional changes in the pore-water chemistry of the sensitive marine clays of the Ottawa area, eastern Canada. Engineering Geology, no 14, 135-147.

Tovey, N.K. (1971). A selection of scanning electron micrographs of clays. CUED/CSOILS/Tr5a. University of Cambridge, Departure of Engineering.

Troedsson, T. & Nykvist, N. (1980). Marklära och markvård. Almqvist & Wiksell Läromedel. Uppsala. (In Swedish)

Van Olphen, H. (1977). An introduction to clay colloid chemistry. John Wiley & Sons. New York.

Whitehouse, U.G., Jeffrey, L.M. & Debrecht, J.D. (1969). Differential settling tendencies of clay minerals in saline waters. Proceedings 7th national conference on clays and clay minerals. Washington, D. C., pp 1-79. Pergamon, Oxford.

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