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ORIGINAL PAPER

A methodology for mapping of quick clay in Sweden

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Abstract

Landslides may cause severe destruction that affects both the individuals and functions vital for society. Minor landslides in an area with quick clay may trigger secondary slides, influencing a much greater area compared to slides in areas with no quick clay. Today's expanding societies demand new areas for exploitation. To effectively meet this demand, there is an increased need to identify areas where quick clay may occur. Direct or indirect methods for assessing the presence of quick clay have previously been presented as well as a strategy for site investigations in quick clay areas. In this article, a methodology for mapping quick clays for the Swedish conditions with methods commonly available in this area is presented. The methodology presented in the article is structured in steps with different levels of detail and visualized with two conceptual flowcharts. Depending on the stage of planning, different types of surveys are recommended. The methodology has been applied at four sites where integrated interpretation of airborne and ground geophysical measurements as well as geotechnical investigations have been carried out. The results from two of these sites are presented here. The study reveals that all the methods used have their advantages and limitations. However, a combined use of the information provides much more accurate interpretation that can be used for a more cost-effective future planning and decision-making.

Keywords Methodology · Mapping · Quick clay · Landslide · Site investigations · Electrical resistivity

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1 Introduction

Landslides may affect large areas very rapidly. In an area with quick clay, even a minor landslide may trigger secondary slides, influencing a much greater area compared to slides in areas without quick clay. Quick clay slides happen primarily in Scandinavian countries (Sweden and Norway), Russia, and North America (Canada and the United States in Alaska). Examples of landslides in quick clay that have been reported in the literature include the Rissa landslide in Norway (Gregersen 1981), as well as the Tuve and Småröd landslides in Sweden (Larsson and Jansson 1982; Rosvall and Kjellberg 2009) and Mint Creek in Canada (Geertsema and Torrance 2005). A relatively recent quick clay landslide in Sweden that had a major impact occurred in Småröd, Munkedal 2006, involving a highly trafficked motorway that caused huge damage to infrastructure but fortunately resulted in no fatalities (Fig. 1). In Norway, a quick clay landslide occurred in the early hours of the 30th of December 2020 at Ask village, the administrative centre of Gjerdrum. In this event there were 10 persons who lost their lives and several buildings, mainly houses and apartments, were destroyed (OED 2021).

Quick clay occurs in coastal and low-lying areas which were covered by marine or brackish waters at the end of the last glaciation, about 10 000 years ago. Areas with quick clay have subsequently risen above sea level due to the land uplift caused by isostatic rebound. Hydrogeological factors that favour leaching of salt are necessary for the development of quick clay in areas with saltwater deposited clays. Quick clays have a mineral skeleton, which collapses during heavy remoulding, such as a landslide. As a result, the shear strength of the clay is severely reduced.

In southwestern Sweden, the margin of the Fennoscandian ice sheet retreated while in contact with the North Sea. Following the retreat of the ice sheet, glaciomarine clay was deposited in salt water below the marine limit. Therefore, quick clays occur

Fig. 1 Quick clay landslide in Småröd, Munkedal, Sweden, 2006 (foto SGI)

frequently in this area. Along the Baltic coast, in the eastern parts of Sweden, the situation was more complex. The development of the Baltic Sea included periods with lacustrine (freshwater) as well as brackish marine environments. As a result, the potential for quick clay is quite limited except in two regions (Fig. 2).

A clay is defined as quick based on its sensitivity (the ratio of undisturbed shear strength over remoulded shear strength) and the remoulded shear strength. For a clay to be defined as quick in Sweden, the sensitivity must be greater than 50 and the remoulded undrained shear strength not greater than 0.4 kPa (SGF 2016). The term high-sensitive clay sometimes used is defined as sensitivity greater than 30 (SGF 2016). In Norway, quick clay is defined as clay with a remoulded shear strength less than 0.5 kPa and high-sensitive clay is defined as having a sensitivity greater than 30 (e.g. Sandven et al, 2015).

For larger areas, it can be useful to carry out a geophysical survey prior to more detailed geotechnical measurements. Combined use of geophysical and geotechnical methods for assessment of relationships for quick clay have been presented in several studies. Long et al. (2017) provide a detailed assessment of the applicability and accuracy of the various geophysical methods in the study of sensitive clays in Norway. Their study aims to analyse the parameters affecting the measured bulk resistivity. They analyse the limitations of finding a direct relationship between the remoulded shear strength and electrical resistivity data collected using various methods such as electrical resistivity tomography (ERT), resistivity cone penetration testing (CPTu-R), and airborne electromagnetic (AEM). Analysis of data from 30 Norwegian sites showed that the porewater salt content, with minor additional influence by clay content and plasticity, and porosity control the measured bulk resistivity. A very important and interesting finding they report is that "a relationship exists between the resistivity and remoulded shear strength, which is limited to material deeper than the dry crust and deep weathering zone (around 7.5 m). High resistivity (>10 Ωm) may indicate quick or weathered clay and low resistivity (<10 Ωm) conclusively points to stable, unleached clay.

In a very recent paper, Christensen et al. (2021) showcase an interesting and state-of-the-art method utilizing a machine learning-based algorithm to map sensitive glaciomarine clays in Norway. They combine the airborne electromagnetic (AEM) and geotechnical data where the use of the latter is made as training points to link the resistivity variations extracted from the resistivity models from 1D inversion of AEM data. The work is an example demonstrating how the developed methodology has a high potential to make quick clay hazard mapping reasonably efficient. This provides valuable "early phase insights" that result in efficient time saving leading to cost-effectiveness, and a harmonized methodology adapted for both infrastructure planning and regional hazard mapping.

In Sweden, most of the geophysical surveys carried out for mapping and modelling of quick clays have been limited to the use of ground geophysical measurements in rather small areas. In this context, Malehmir et al. (2013a, b) demonstrate the geophysical survey made with various ground geophysical methods in the same area. The methods used include reflection seismic, radio magnetotelluric (RMT), electrical resistivity tomography (ERT), and ground-penetrating radar (GPR). Shan et al. (2014) provide a detailed summary of the geophysical studies done on the quick clay sites in Sweden, Norway, and Canada. In the work presented by Salas-Romero et al. (2016) the results of geophysical downhole physical property measurements and borehole sediment sampling were compared with the other existing data (geophysical and geotechnical) along three seismic profiles reported by Malehmir et al. (2013a). They conclude that a combination of complementary geophysical methods, such as reflection seismic and electrical resistivity, extends the quality and

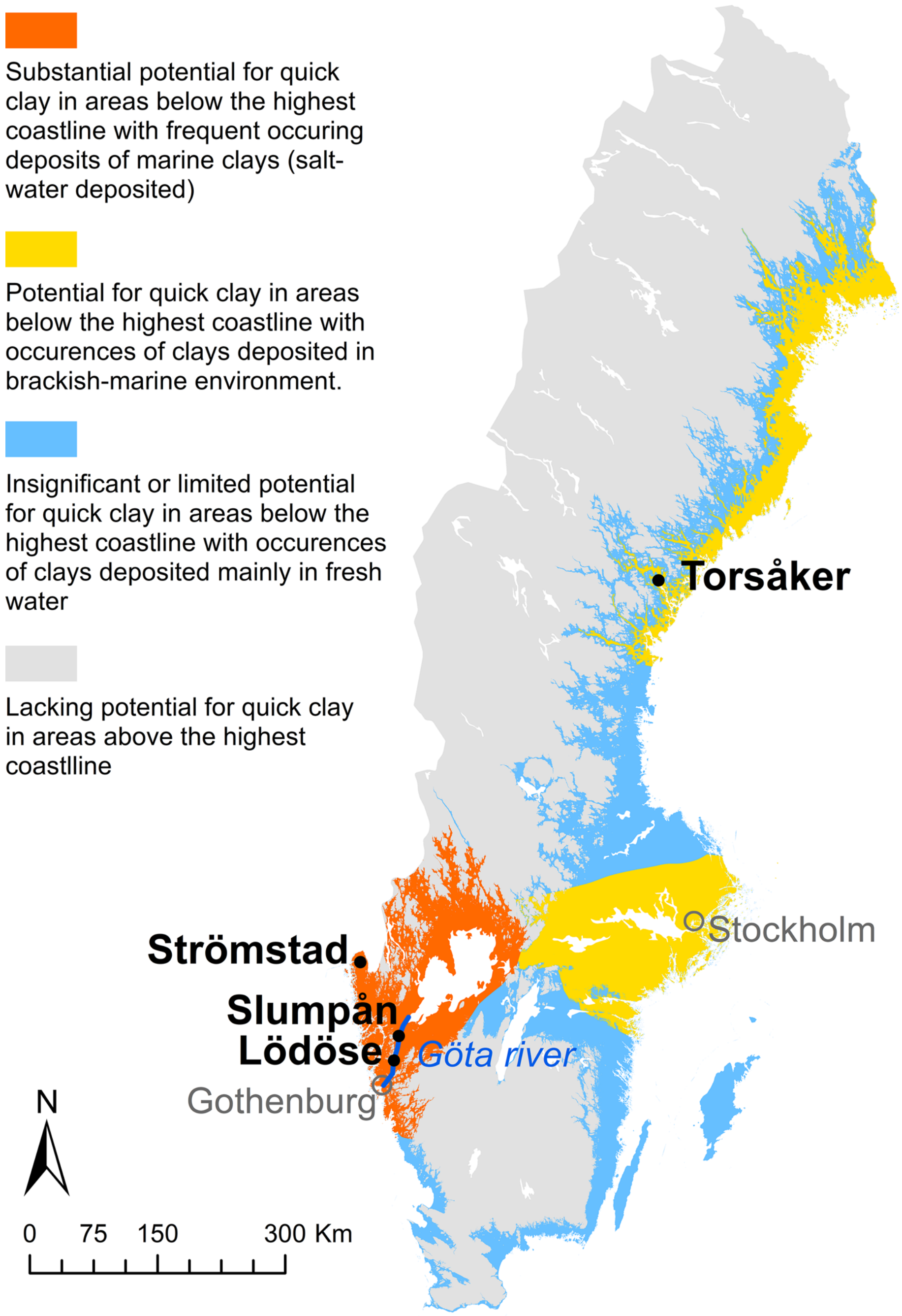

Fig. 2 Potential for quick clay in Sweden based on the deposition environmental (salt, brackish or fresh-water) of clays (modified after Schoning 2016). The study areas in Sweden are shown by black dots on the map

accuracy of the geological and stratigraphical interpretations made from the borehole data to larger areas covered by such methods.

In the last decade, the airborne geophysical data acquisition systems have been developed considerably which has enabled accurate measurements of the electromagnetic signal onboard an aircraft (see Pfaffhuber et al. 2017 and references therein). Such systems cover large areas in a reasonably short amount of time, and the high-resolution data contain valuable information about the distribution of the electrical resistivity of the ground down to depths where quick clays are formed. As is discussed later, variation of the electrical resistivity can be coupled to the variation of clay types, by integrating various information such as geological and geotechnical data.

Both in Norway and Sweden geotechnical sounding methods have been evaluated for assessment of quick clay as a complement to laboratory tests. Rankka et al. (2004), Lundström et al, (2009), Löfroth et al. (2012) evaluated the use of both geophysical and geotechnical methods for detection of quick clay at Swedish test sites. The methods included rotary weight sounding (DT), rotary pressure sounding (DRT), total sounding (TOT), static pressure sounding (Tr), cone penetration test (CPTu), and field vane test. They found a general correlation between the slope of the pushing force – depth curve and the remoulded shear strength of the soil at the same depth. Similarly, Sandven et al. (2015, 2016) evaluated the use of geophysical and geotechnical methods in Norway including DT, DRT, TOT, CPTu/CPTu-R, and field vane test for detection of quick clay and brittle materials. They conclude that conventional methods in Norway (DT, DRT, TOT) will continue to be important, but they recommend using information from several boring methods for evaluating the presence of quick or sensitive clays. All the studies conclude that soil sampling and laboratory tests will be required for verification.

There are several methodologies used for hazard zoning related to quick clay landslides. The Norwegian Water Resource and Energy Directorate (NVE) has issued guidelines for the planning of land use along with water courses (NVE 2009; Aunaas et al. 2016) in Norway. The guidelines contain hazard zonation with regards to quick clay and include work carried out by the Norwegian Geotechnical Institute (Gregersen 2008). It is stated that the level of hazard depends on the consequence and probability of a landslide occurrence. The work includes a method for mapping areas with quick clay, where local geological conditions are studied based on topographical criteria (inclination > 1:15 and minimum height difference > 10 m). Wherever needed, rotary pressure soundings are deployed while conducting geotechnical site investigations. In addition, other methodologies for mapping of hazard zones for estimation of maximal retrogression distance of potential quick clay landslides in Norway have been presented (Haugen et al. 2017). In the methodology for landslide risk mapping carried out in Sweden, estimation of the landslide extent, and consequently, the size of the hazard zones depend on the areas with quick clay. The extent of landslide retrogression is determined for slopes with an initial slip surface that has a safety factor of 1.3 or lower in an undrained analysis or 1.2 or lower in a combined analysis, if this slip surface includes a soil volume with a sensitivity of 50 or higher (SGI 2012; Åhnberg et al. 2014). In the landslide hazard mapping carried out in Quebec, Canada, the susceptibility of the terrain is classified taking into account slope angle, slope height, and the existence of erosion. The constraint maps produced also include soil types and the potential for landslide retrogression. The conditions for an initial landslide to become retrogressive are assessed on the basis of the sensitivity of the clay (Hungr and Locat, 2015).

Strategies for mapping of the presence and extent of sensitive and quick clay, not including landslide hazard, have been presented in Norway by Solberg et al. (2011), Sauvin et al. (2013), and Sandven et al. (2015). Sandven et al. (2015) present both geotechnical and geophysical methods for identifying quick clays and a strategy for site investigations in quick clay areas. The strategy is presented as a matrix where the size of the areas to be investigated are presented in columns together with examples of the type of projects. Proposed methods are presented in rows where each row has a different level of detail (Sandven et al, 2015). Some of the methods are similar to those proposed in this paper, whereas others are different. In Solberg et al. (2011) the focus is on the planning of projects where the resistivity method together with CPTu-R can be used to investigate an area where geological conditions for quick clay exist and, if possible, reduce the extent of the pre-defined hazard zones.

The aim of this paper is to present this methodology targeting Swedish conditions utilizing methods that are commonly available at a local level to map areas where quick clay may be present. The methodology includes an overview of topographical variation and geological settings together with geophysical and geotechnical methods. It is considered essential that the methodology promotes a cost-effective investigation depending on the stage of the planning process and the degree of accuracy in the mapping of quick clay that is required in that stage. Different types of surveys are therefore recommended, and the methodology is structured in steps with different levels of detail. These are visualized with two flow charts. The paper first presents the concept behind the methodology developed, and then, shows examples from two of the study areas where the methodology has been applied. The results from earlier studies in Sweden and Norway (e.g. Rankka, et al, 2004; Lundström et al, 2009; Löfroth et al, 2011a, b; Åhnberg et al, 2014; Solberg et al, 2012; Sandven et al, 2015) are also used for complementing and comparison. The results of this survey have earlier been presented in one report, one guideline and a web mapping service (Löfroth et al. 2018; SGI 2018a; SGI and SGU 2019), which are all in Swedish.

2 Proposed methodology

A methodology has been developed for mapping of areas where quick clay may be present. It targets Swedish conditions with methods that are commonly available at a local level.

The methodology is structured in steps with different levels of detail. Depending on the stage in the planning process, different types of surveys are recommended. The methods used consist of analysis of geological, geophysical and geotechnical investigations and data in the target areas. The purpose of a step-by-step methodology to successively gain a better understanding of the presence of quick clay in an area is to achieve cost-effective use of resources. The developed methodology is presented in two flow charts, Figs. 3 and 4.

A rough division of applicable methods can be done based on whether they are advisable to use in an early or a late stage of the planning process of a project. A figurative line may be the use of site investigations with land-based geophysical and/or geotechnical field investigations. Regional plans for counties may be associated with the early stage while planning for smaller areas such as a residential area may start in the later stage, depending on the size and prior knowledge.

At an early stage (Fig. 3), a first assessment can be made by analysing the geological information and conditions from using, for example, digital information and maps showing the areas where clays are deposited in saltwater or brackish water under the highest coastline. This provides a relatively quick picture of the prerequisites for the formation of quick clay in the area. A web mapping service has been developed to facilitate this assessment. It will be further presented later in this paper.

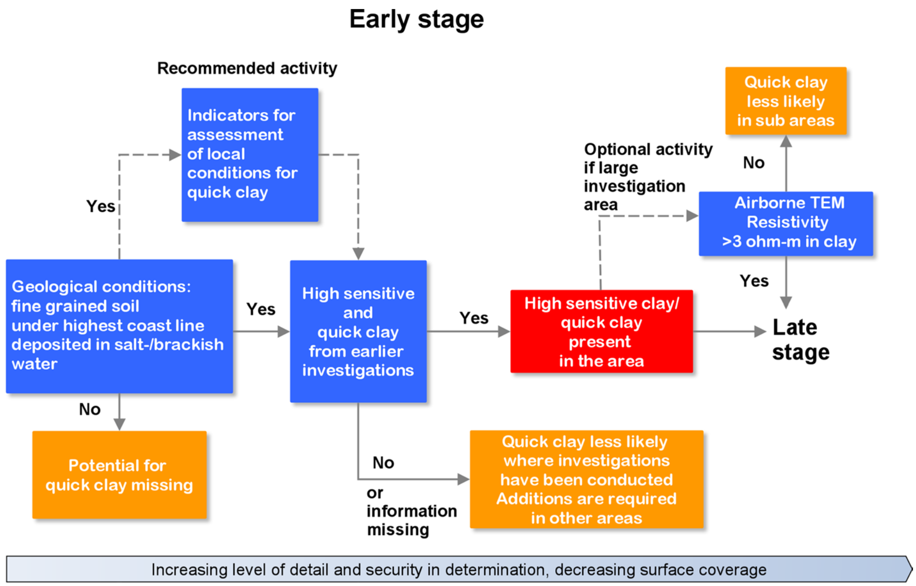

Fig. 3 The geological prerequisites for quick clay are identified at this stage by: a review of existing maps showing geological conditions for quick clay potential and a review of the conclusions in any investigations and surveys already carried out. Optionally, the substrate is supplemented with airborne TEM measurements. Based on SGI (2018a)

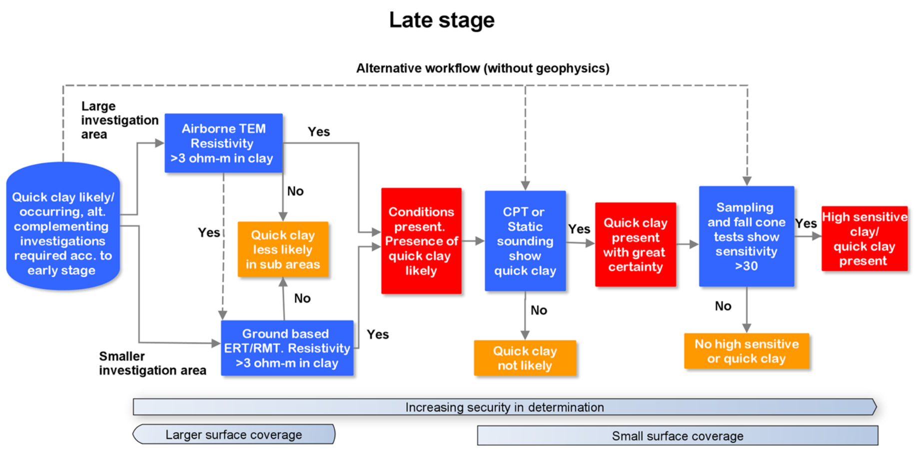

Fig. 4 The presence and extent of quick clay is clarified at this stage by field and laboratory investigations. Stepwise, the methods provide increased certainty in the interpretation but at the price of reduced surface coverage. Based on SGI (2018a)

If the interpretation of geological data indicated that there are favourable conditions for the formation of quick clay, then it is recommended to proceed to assess other factors that imply increased probability for the presence of quick clay within the area

(Rankka et al. 2004). This would give information of where it is most likely to find quick clay within the area, which can then be the basis for planning of investigations.

Early on, it is important to make an inventory of and review existing investigations. This can be done at various levels of detail. At an early stage, it may be a matter of getting an overview of the conclusions made from earlier studies. It may be advisable during the project to return and deepen the inventory and review the presence of quick clay from prior investigations.

At the end of the early stage, investigations might be further complemented by conducting airborne electromagnetic measurement (e.g. TEM). This is a method that provides extensive coverage in a short period of time, however, it has a high start-up cost and is best suited for larger areas. By using such a fast method, the presence of quick clays can be further assessed by analysing the electrical resistivity of the ground to identify potential areas with the presence of quick clay. For example, as the first assumption for Swedish conditions, if prior knowledge is not available in the specific location, a certain resistivity threshold can be assumed as a limit over which conditions for the presence of quick clay may exist. For example, a lower limit value of 5 Ωm has earlier commonly been used in Sweden. However, formal recommendations have never been set for Swedish conditions. As it is shown later in this paper, quick clay may occur where lower resistivity than 5 Ωm are measured.

At a later stage (Fig. 4), ground-based geophysical and geotechnical investigations may be applied to specific areas suspected to contain quick clay based on results from early stage findings. Those are required to obtain more quantitative and qualitative material necessary to assess the presence of quick clay. By applying geotechnical investigations, the occurrence of quick clay at specific locations can be determined. In Fig. 4, a process to identify the areas with the presence of quick clays is presented. To determine the limit value for resistivity over which clay may be assessed as quick, it is required that results from site investigations are verified by sensitivity determined by fall cone tests from undisturbed samples retrieved from the site. The sensitivity determined by fall cone tests can then be supported by an assessment of the quasi-liquidity index (w_N/w_L). In the following sections, application of the methodology in the early and late stages and results from the two study areas, Lödöse and Strömstad, are presented.

3 Application of the methodology at Swedish sites

Field and laboratory measurements from four areas have been investigated to complement previous studies to test and verify the methodology. Results from the various methods are presented, evaluated and compared. The methods consist of analysis of geological and topographic data, airborne and ground geophysics, as well as geotechnical investigations. The selected sites are Lödöse, Slumpån, Strömstad and Torsåker (see Fig. 2).

The sites have been selected based on two criteria. First, part of each site should contain quick clay. Second, the four sites should collectively provide a diversity of geological settings. These settings comprised, but were not limited to, clay layers of different thickness, clay layers with and without embedded sand layers as well as topographical position. This provides both a good basis for the evaluation of the selected methods and the methodology.

3.1 Early stage: geological setting of study areas

Three of the study areas, Lödöse, Slumpån and Strömstad, are situated in the coastal region of southwestern Sweden, Fig. 2. The landscape is characterised by a moderate relief and a network of more or less pronounced valleys reflecting the fracture pattern of the crystalline bedrock. The bedrock is covered by thin till, generally not more than a couple of meters thick. The valleys are largely filled with glaciomarine and post-glacial clays with total thicknesses in the range of 10–100 m. Glaciofluvial deposits (eskers and deltas) also exist. All three study areas are situated below the marine limit in a region with saltwater deposited glaciomarine clays. The upland areas are characterized by bedrock outcrops and very thin surface layers of till, littoral sand, and peat.

In Figs. 5a, b, the simplified surficial deposits map of the study area Strömstad and Lödöse are shown. Parts of the geophysical and geotechnical results from investigations in these two sites are presented in this article to illustrate the advantages and limitations

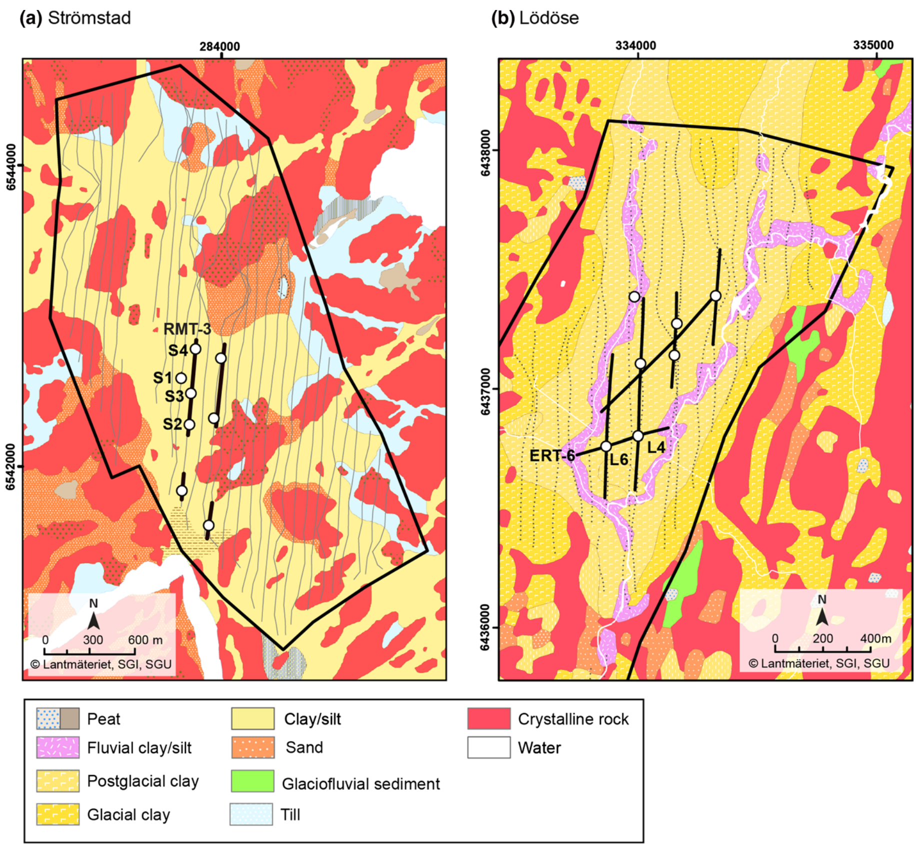

Fig. 5 Surficial deposits map of the two study areas Strömstad (**a**) and Lödöse (**b**). Location of flight lines are shown with thin grey/dotted grey lines. The black lines show the location of ground geophysical profiles measured by the ERT and RMT method. The white circles show the location of geotechnical soundings. The black polygons mark the area surveyed by the airborne electromagnetic measurements. Note that in the Strömstad site there are four RMT profiles and one ERT profile (northeast), and in Lödöse site, there are six ERT profiles and no RMT

of different methods and how the methods can complement each other. The location of flight lines, ground geophysical profiles, and geotechnical boreholes are superimposed on the maps. Within the study areas, there are no documented traces of landslides.

One of the study areas, Torsåker, is situated in the Ångermanälven river valley in central Sweden. This valley is of preglacial origin. It is 50–100 m deep and in crystalline bedrock. The valley is filled, from the bottom to the top, with Quaternary deposits: till, glaciofluvial sand-gravel, glacial clay-silt, and post-glacial fluvial sediments. The thickness of the sediments exceeds 100 m in some locations. Some of the more organic-rich post-glacial sediments are sulphide-bearing. Bedrock outcrops and till deposits are found on the valley slopes and the surrounding uplands.

3.2 Early stage: geological, hydrogeological and topographical methods

Overview assessment of the potential for quick clay are based on geological/topographical settings and existing traces of landslides.

The presence of marine clays (deposited in salt- or brackish water under the highest coastline) in the investigation (target) area is the most important condition. This means that if there are glaciomarine clays, there is a potential for quick clay. If there are not, the potential for quick clay is negligible. The map in Fig. 2, in combination with maps of surficial deposits published by SGU, could be used as a basis for this determination.

If glaciomarine clay is present, the spatial distribution of the potential for quick clay may be assessed from local geological/hydrogeological conditions, such as the existence (observed or inferred) of hydraulically conductive layers within or beneath the clay deposit.

By studying the morphometry of existing traces of landslides (scars) in or near the target area, it is in some cases possible to get an indication of the potential of flow slides (indicating quick clay).

A method based on analysis of over 1800 landslide scars in fine-grained soil was proposed by (Melchiorre et al. 2014). Landslide scars in Sweden were classified in four classes based on the form of the scars indicating flake or flow slide based on (Quinn et al. 2011), see Fig. 6. The inclination of the ground within the scar was calculated for the landslide scars in the database with sufficient size, i.e. less than half of the scars. An inclination of the ground less than 5–10° could indicate flow and an inclination higher than 10–20° could indicate flake (Melchiorre et al. 2014).

Based on the geological and topographical conditions and the classification of the landslide scars in the areas, it could be verified that prerequisites for quick clay were present in the study areas.

3.3 Early stage: review of earlier investigations

Geotechnical investigations had been carried out adjacent to the study areas in connection with the upgrading of roads in the area. These investigations showed that quick clay was present close to the study areas.

3.4 Early stage: geophysical methods

According to studies by Solberg (2007), marine clays with the salt content below 5 g/l in the pore water are generally either high-sensitive or quick. The leaching process causes

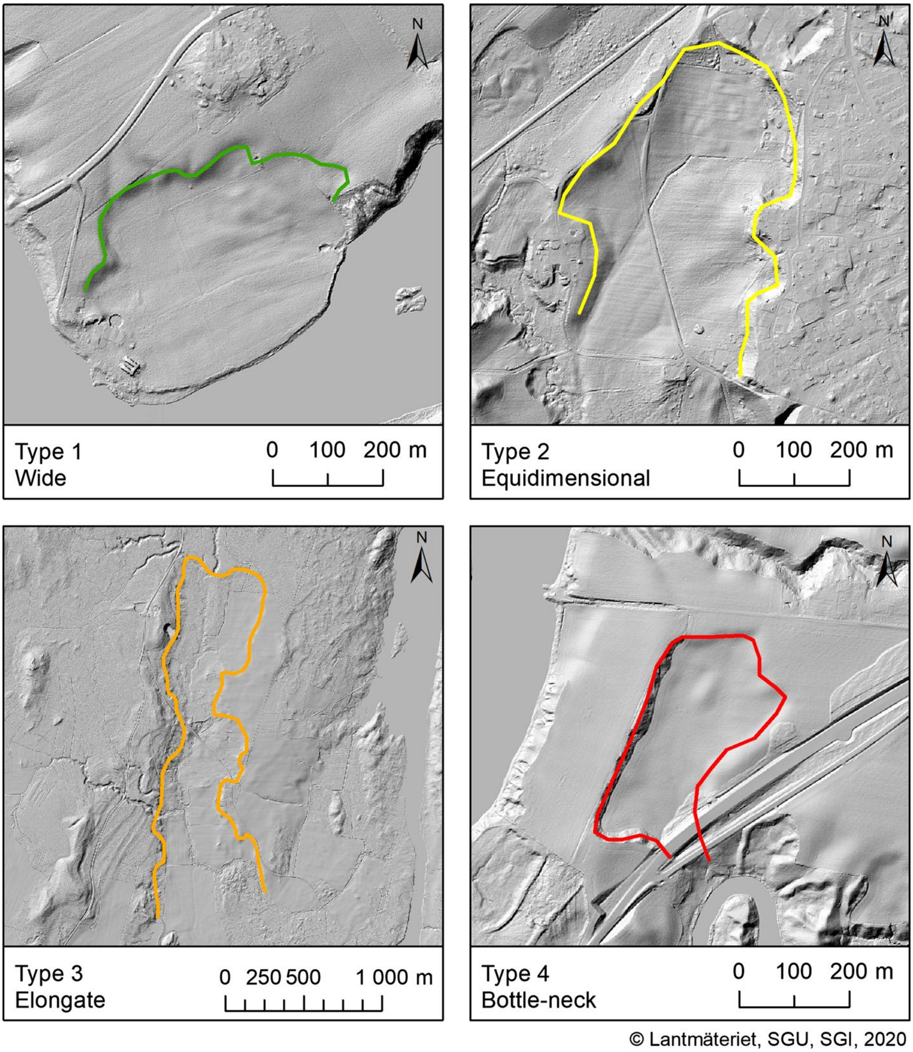

Fig. 6 Four types of morphological classes for division of landslide scars according to a method by Quinn et al. (2011) Type 1 (wide) indicate flake/lateral spread, type 2, (equidimensional) indicate flake or flow and type 3 (elongate), and 4 (bottle-neck) indicate flow (Melchiorre et al. 2014)

an increase in the electrical resistivity of quick clays relative to non-quick clay. Marine non-quick clay generally shows very low resistivity down to around 1 Ωm and a resistivity larger than 3 to 5 Ωm may indicate the presence of quick clay. This contrast makes the electrical and electromagnetic methods attractive for studying and modelling quick clays. Airborne and ground geophysical methods are used for mapping and modelling of quick clays in Sweden (Shan et al. 2016; Bastani et al. 2017; Dahlin et al. 2013; Löfroth et al. 2011a, b) and Norway (Solberg et al. 2012; Pfaffhuber et al. 2017). Here, a summary of the three geophysical methods used in this study is provided.

All sites are covered by the airborne transient electromagnetic (ATEM) measurements. The company SkyTEM Surveys ApS conducted the data acquisitions with a nominal terrain clearance of 30–50 m and an average flight-line spacing of 75 m. The methods and equipment are described by Sørensen and Auken (2004). For data acquisition, the SkyTEM 301 system was used. The system is composed of a transmitter loop (three hundred square meters) that sends transients with a high magnetic moment (100,000 Am^2). The signal induces currents in the ground which in turn creates a secondary magnetic field. The data, namely the secondary field, is recorded during the transmitter off-time at different time gates using a receiving loop. The measured data are then modelled to study the subsurface resistivity along flight-lines using a 1D inversion scheme using spatially constrained inversion (SCI) developed by Viezzoli et al. (2008). The fit to the data was reasonably good with a root means square (RMS) of less than 1.5.

3.5 Late stage: geophysical methods

The electrical resistivity tomography (ERT) method was also employed at all sites. It is a ground-based method that uses four electrodes inserted into the ground. A pair of electrodes inject a direct current (DC) and another pair measures the potential difference. Depending on the array configuration selected, locations of the two pairs are set. Using the measured current, the potential difference and the geometry of the electrode configuration, the apparent resistivity of the ground is calculated. An iterative mathematical approach is then used to convert the measured data into the resistivity of the ground below the measurement points. An automated multi-electrode data acquisition system (Dahlin, 2001) is used that considerably optimized the fieldwork.

Radio magnetotelluric (RMT) is an electromagnetic method that is used at two sites (Slumpån and Strömstad). The signal sources are distant radio transmitters operating in the 15–250 kHz frequency range. At each RMT station three components of the magnetic field and two horizontal components of the electric field are registered at the same time (Bastani et al. 2015; Shan et al. 2016), and the apparent resistivity is calculated at each frequency. The penetration depth of the method can vary between 5 and 500 m and depends on the ratio between the electrical resistivity of the ground and the signal frequency. The EnviroMT system (Bastani et al. 2015) is used for the RMT measurements.

3.6 Late stage: geotechnical methods

To assess the possible occurrence of quick clay, different types of geotechnical methods have been evaluated where the total penetration resistance is registered (Rankka et al. 2004; Lundström et al. 2009). The assessment is made based on the slope of the rod friction curve.

To estimate quick clay from static pressure soundings (Tr) and cone penetration tests (CPTu), the total penetration resistance is measured and complemented by the weight of the rods and, for the CPTu, reduced by the tip resistance. This corresponds to the rod friction (in kN). The rod friction is then compared with a rod friction of 1 kPa/m. The process is done using a simple algorithm in an Excel-based evaluation tool (SGI 2018b). If the increase in rod friction with depth is less than 1 kPa/m, the clay is classified as quick (Möller and Bergdahl 1982; Rankka et al. 2004; Löfroth, 2011a, b). In the Göta River investigation, Tr and CPTu were used to evaluate quick clay at 595 samplings levels in 157 boreholes (more than one level was tested in each borehole). Both methods overestimate the presence of quick clay, but the CPTu is more accurate than the static pressure sounding. The main reason is probably that the tip resistance is measured using the CPTu and it can then be subtracted from the total penetration force, which is not the case with the static pressure sounding (Löfroth et al. 2012). Löfroth (2011a, b) concludes that both methods could be used but that CPTu is the most accurate. Therefore, in this paper, only CPTu results are considered.

As a complement to CPTu measurements, an adapter measuring the resistivity while continuously probing can be added (CPTu-R). This method has previously been tested and evaluated in Sweden by Schälin and Tornborg (2009) and Löfroth et al. (2011a, b). Compared to airborne TEM and ground resistivity measurements, CPTu-R allows a direct measure of the resistivity with high precision adjacent to the probe. Compared to airborne TEM and ground resistivity measurement, CPTu-R is relatively time-consuming and costly for a coverage over large areas.

The field vane test (SGF 1993) is well established and is presently the only in situ method used to measure both the undisturbed and the remoulded undrained shear strength in clay, and thereby also the sensitivity. However, Rankka et al. (2004) concluded that the field vane tests generally underestimate the sensitivity, particularly in quick clays. The field vane test is therefore not recommended as a method to be used to determine the presence of quick clay.

Determination of quick clay is done through measurements of the undrained shear strength by fall cone tests in the undisturbed and remoulded state of the clay. This is done in laboratories on undisturbed samples retrieved by a piston sampler (Larsson 2008; Hov and Holmén 2018).

Previous studies have shown that decreasing salt content reduces the clays liquid limit (w_L) (Rosenqvist 1946; Bjerrum 1954). For Norwegian clays, Bjerrum (1954) found a linear correlation between the liquidity index and the logarithm of the sensitivity of clay. In Sweden, the corresponding simplified relationship between quasi-liquidity index (natural water content/liquid limit, w_N/w_L) and sensitivity has been used (SOU 1962; Larsson and Åhnberg 2003). These studies indicate that the index should be higher than 1.1 for clay to be quick (Larsson 2011). Both the natural water content as well as the liquid limit are determined by routine examination of undisturbed samples in laboratories.

At all sites in this study, CPTu-R together with piston sampling and laboratory tests have been employed. In addition, results from static pressure soundings and laboratory tests from other investigations have been used in the analysis.

4 Results

4.1 Geological, hydrogeological and topographical methods

Based on the geological, hydrogeological and topographical methods for overview assessment of the potential for quick clay, a web mapping service shown in Fig. 7 was developed (SGI and SGU 2019). The service opens in scale 1:1 000 000 showing areas being covered with salt or brackish water. In the next scaling step (1:500 000), the area below the highest coastline and areas with fine-grained soil and potential for quick clay are shown. These criteria form the basis for assessment of the potential for quick clay based on the geological history of the area.

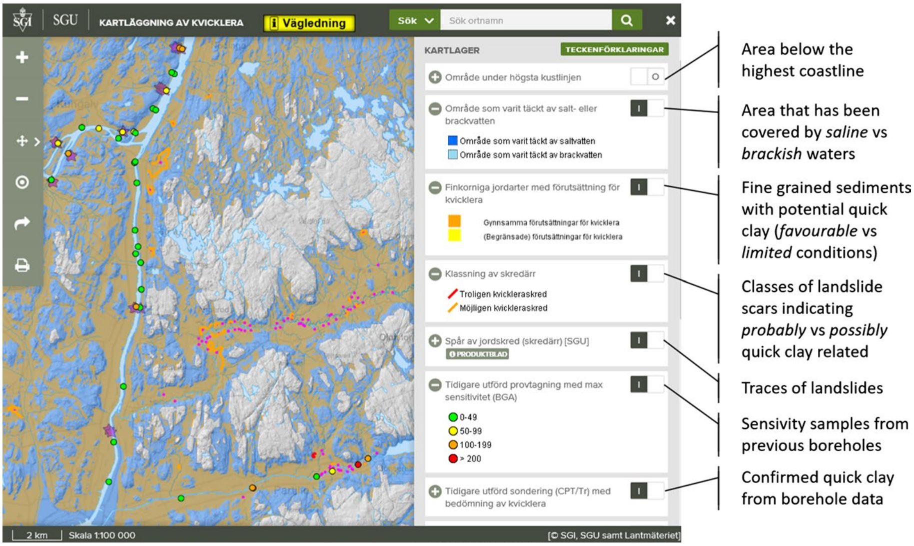

Fig. 7 Example from the web mapping service for mapping of quick clay (https://gis.sgi.se/metodik_kvicklera/). The map covers the whole of Sweden and presents relevant information with increasing detail according to the legend Areas with prerequisites for quick clay is presented with a yellow/orange colour

This assessment can be complemented by assessing local geological and hydrogeological conditions in the investigation area that could indicate quick clay and its spatial distribution. One such local condition is the classification of landslide scars (Melchiorre et al. 2014). A comparison between the classification of landslide scars and areas where quick clay has been detected by sampling and laboratory tests were carried out within the test sites. The comparison shows that combining the classified forms and the inclination of the scars would form a good basis for the assessment of the potential presence of quick clay. For landslide scars forms, see Fig. 6. The following combinations are proposed and included in the web mapping service:

- One class with landslide scars type 4 and inclinations less than 10°—probably quick clay slide
- One class with landslide scars type 1, 2, 3 and inclinations less than 10°—possibly quick clay slide
- Other landslide scars not classified in accordance with above, but shown as landslide scars.

In the web mapping service, the sensitivities of the clay from previous geotechnical investigations are also given. If more than one sample has been analysed with respect to sensitivity from one borehole, only the maximum is presented. A checklist was developed for guidance in the assessment of the spatial distribution of the potential presence of quick clay based on other local prerequisites.

4.2 Geophysical results

Geophysical data were collected from all four sites, but the authors have chosen to present the results from two sites, namely Strömstad and Lödöse. At each site, ground geophysical measurements along with a few profiles have been carried out. The location and direction of the profiles are chosen by considering the variation in the geology as well as the existing geotechnical data. In the following, some of the results from modelling of the airborne data and ground geophysical data are presented and compared with the geological and geotechnical data.

4.2.1 Site: Strömstad

Ground geophysical measurements including the RMT and ERT methods were conducted in the Strömstad area (see Fig. 5a for locations). The RMT data were collected along the four profiles (RMT-1 to RMT-4) with a station spacing of 10 m. The ERT data with the Wenner electrode configuration were only acquired along profile RMT-4. Both datasets were inverted in 2D and the resistivity models were compared with the resistivity models from the 1D inversion of airborne TEM data and with the collected geotechnical data including CPTu-R.

Profile RMT-3 is 620 m long. Four geotechnical soundings (S1 to S4) exist along (or in the vicinity of) the profile and piston sampling has been performed at S1 and S4. The resistivity model from the 1D inversion (SCI) of SkyTEM data in the interval covered by RMT measurements is shown in Fig. 8. For the comparison, the geotechnical interpretations made at the sounding locations are also shown on top of the resistivity model. Note that the depth of investigation (DOI) of the system is shown by a transparent white color on the model (in this model between 270–400 m distance). In the first 100 m of the profile, the resistivity model from SkyTEM shows relatively high resistivity (> 100 Ωm) at depths below 5 m which indicates the presence of the resistive bedrock that outcrops further to the south of the profile (see Fig. 8). Fall cone tests in S2 confirm the presence of quick clay between 3–15 m depth.

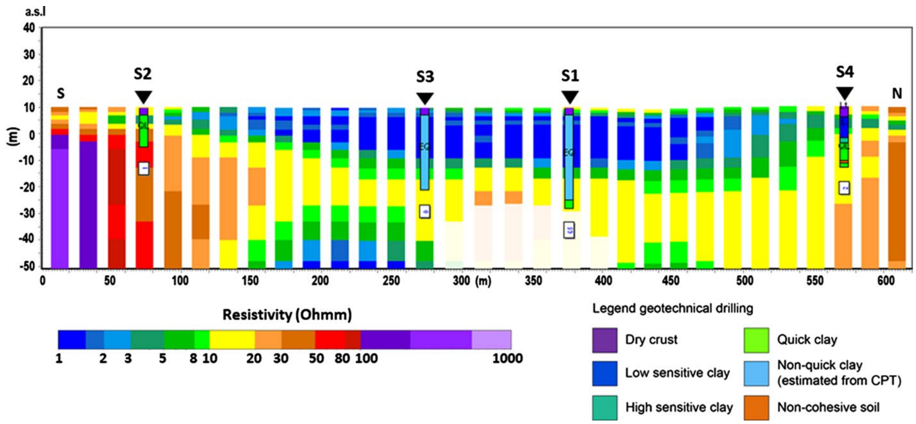

Fig. 8 Comparison between the resistivity model from the SkyTEM data and the geotechnical information from four boreholes located very close to the same flight line

The two CPTu-R soundings at points S1, at about 275 m, (located 65 m west of the profile) and S3, at about 375 m, show clay thicknesses between 30 and 40 m. According to the resistivity model, most of the clay layer generally has very low resistivity (approx. 1–3 Ωm) down to 15—25 m depth (see Fig. 8).

Results from CPTu-R and piston sampling in S4 show a 20 m-thick marine clay followed by a thin sand layer (1 m) and then silt and clay down to about 23 m. Results from fall cone tests verify the presence of high-sensitivity and quick clay between 12–14 m and 14–20 m, respectively. The resistivity model (Fig. 8) shows a value between 5–10 Ωm in the first 10 m and then the resistivity gradually increases with depth to 20 Ωm. The resistivity exceeds 20 Ωm at depth > 35 m. At greater depths (> 20 m), the resistivity model shows no variations that can be related to the variation in the CPTu-R soundings. Similar cases are found in other study areas, which indicate difficulties with the resolution of SkyTEM measurements to identify more resistive layers with a thickness of approximately 2–3 m at depths exceeding 20 m.

Within the framework of the project, CPTu-R measurements were performed with a resistivity probe at all eight boreholes in Strömstad. Two boreholes S3 and S4 have been selected for a detailed comparison between CPTu-R data and resistivity models from the different geophysical methods. The comparison is shown as the variation of measured CPTu-R and modelled resistivities (SkyTEM and RMT) as a function of depth (Fig. 9). The geotechnical interpretations from CPTu and laboratory tests (fall cone) are shown on the right side of each diagram. For borehole S4, the water content, the liquid limit, the sensitivity, and the remoulded shear strength of the clay are shown. In borehole S3, no quick clay is interpreted from the geotechnical data. In this borehole, CPTu-R shows higher resistivity (> 10 Ωm) close to the surface (Fig. 9a). The resistivity drops below 1 Ωm at depth of about 5 m. The RMT model follows the CPTu-R trend with underestimated values at depths below 10 m. Below this depth, the resistivity values seem to be underestimated where the RMT signal does penetrate the low resistivity clay layer. The resistivity model from the SkyTEM shows poor resolution at the surface (depth < 4 m) and correlates very well with the measured CPTu-R down to the depth of 18 m. The SkyTEM model shows a sharp increase in the resistivity below 18 m that is not observed in the CPTu-R data. Deviations from 1D assumption in the inversion process might cause such differences. For example, because of larger footprints of the SkyTEM system at depth, the data might be affected by off-the-profile undulating and more resistive crystalline bedrock. Figure 9b shows the same comparison at the location of borehole S4 along line L3. Low-sensitivity clay occurs between 4–12 m depth in S4, and according to the CPTu-R measurements, it has a resistivity of about 2 Ωm. From 12–21 m depth in the borehole high-sensitivity, clay and quick clay are observed. In this depth range, the measured CPTu-R resistivity changes from 3 up to about 70 Ωm. The non-cohesive soil at 21 m depth gives rise to high resistivities of about 100 Ωm. Resistivity from SkyTEM and RMT in S4 shows little variation below 14 m depth. Although both SkyTEM and RMT models show higher resistivity at depths > 10 m, they do not contain enough information to indicate the presence of quick clay or the presence of non-cohesive soil layers.

4.2.2 Site: Lödöse

Lödöse area is located on the eastern side of the Göta river. The overburden mainly consists of clay and silt with thicknesses that exceed 50 m in many places. The northern part of the area was selected for detailed ground geophysical and geotechnical measurements, in

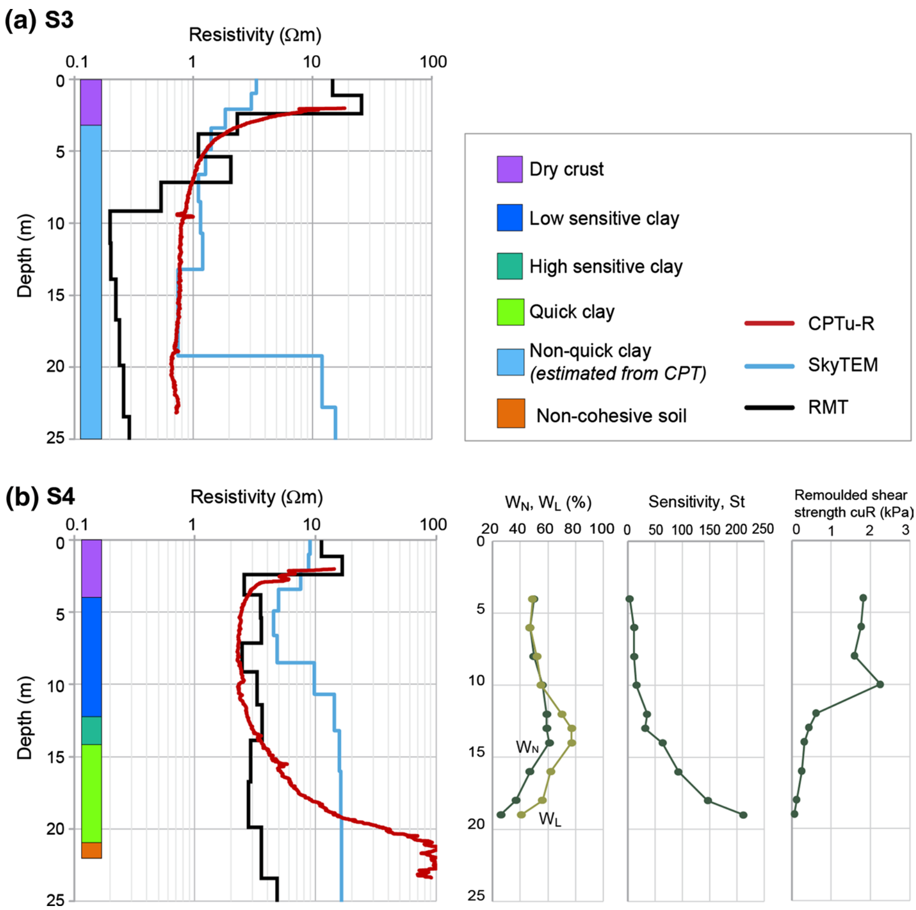

Fig. 9 Comparison between the resistivity from CPTu-R, RMT, and SkyTEM at the location of boreholes in the vicinity of the geophysical profiles (for the location see Fig. 5a). The geotechnical interpretations from CPTu results and laboratory tests are also shown on each diagram. For a more detailed comparison, the water content and the liquid limit of the clay as well as the values of the sensitivity and the remoulded shear strength are shown for one of the boreholes (S4)

addition to the airborne TEM survey (Fig. 5b). In total, six ERT profiles and six geotechnical borings (L1–L6), including cone penetration test with resistivity (CPTu-R) and piston sampling, were performed in the area.

The resistivity map obtained from SkyTEM data at the depth interval 4–8 m shows large variations over the area (Fig. 10). High resistivities (> 100 Ωm) correspond to areas with outcropping bedrock or very thin soil cover. At the location of boreholes L1 to L5, the resistivity varies between 5 to 20 Ωm that may indicate the presence of quick clay. Close to borehole L6 the map shows very low resistivities of around 1 Ωm, indicating that the overburden is dominated by low-sensitivity marine clay. This result is also supported by geotechnical CPTu sounding and piston sampling with laboratory tests where the presence of quick clay was found in borehole L1-L5. In borehole L6, located in the very low resistivity region, no quick clay was found.

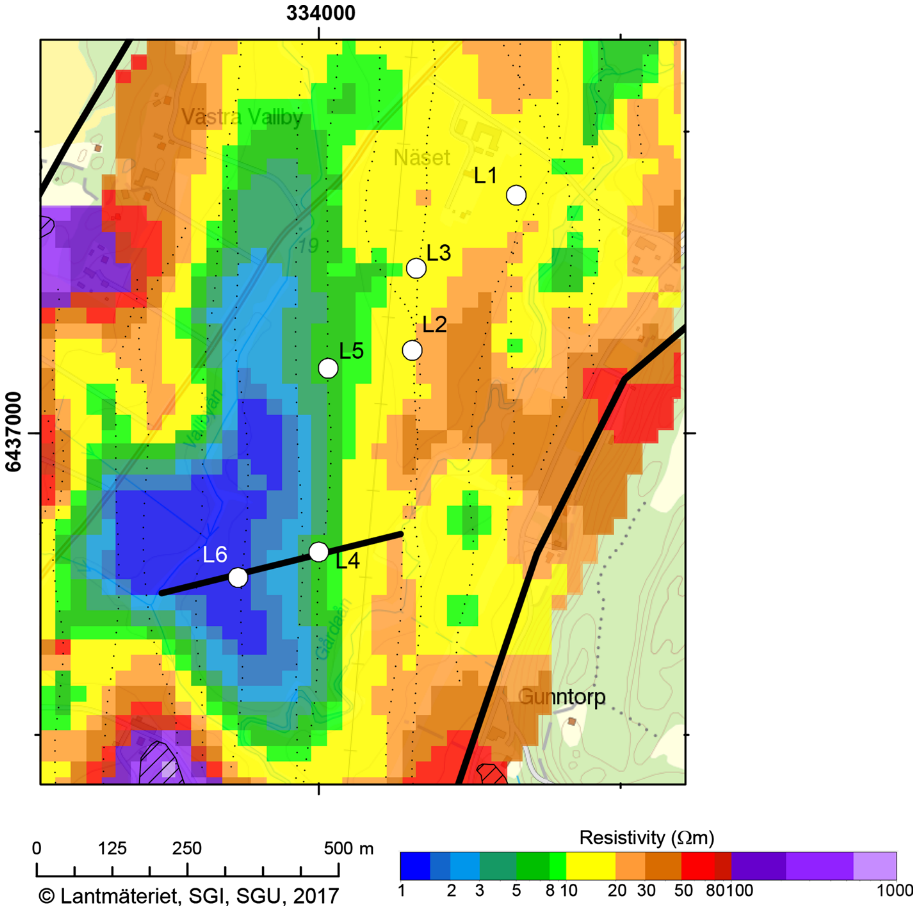

Fig. 10 Resistivity map at depth interval 4 to 8 m obtained from SkyTEM data over part of Lödöse area. The location of the geotechnical borings and profile ERT 6 are shown on the map

The resistivity map derived from airborne data correlates very well with the result from the ground ERT profile (Fig. 11). At the location of borehole L6, the resistivities are generally < 3 Ωm, indicating low-sensitivity, marine clay, while at the location of borehole L4, the resistivities are ranging from 5 to 20 Ωm, indicating the presence of quick clay. The thin layer close to the surface with slightly higher resistivity corresponds to the dry crust and the very high resistivities at the end of the profile corresponds to till and bedrock.

A comparison between CPTu-R and modeled resistivity from SkyTEM and ERT at points L4 and L6 shows very good agreement, especially in the upper part down to 15 to 20 m (Fig. 12).

In Fig. 13, a comparison is shown between all the measured CPTu-R and the modelled resistivities from SkyTEM, ERT and RMT data in Strömstad and Lödöse areas in the form of bar diagrams. The values shown in the diagram are extracted from each resistivity model at the location of the borehole with the CPTu-R measurements. To make the comparison as simple as possible, just the resistivity variations in two classes are presented, namely non-quick clay (NQC) and quick clay (QC). The divisions into the two classes are based

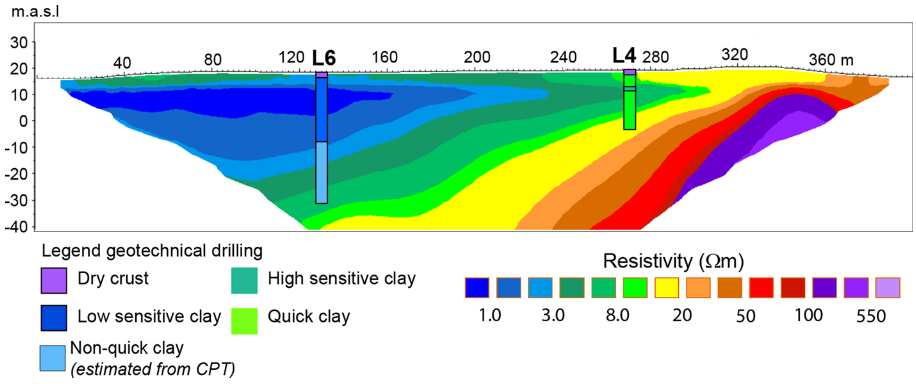

Fig. 11 Resistivity section from ERT profile 6 and the two boreholes L4 and L6 located on the profile

on the interpretations of the geotechnical soundings and samplings. The first and maybe most important point observed in Fig. 13 is that the NQC has lower resistivity than QC as measured by all the methods. For the NQC class, the RMT and ERT data have resistivity estimates closer to the measured CPTu-R data. The SkyTEM resistivities are higher and show an overestimation which might be related to deviation from 1D, coarser resolution (larger cell sizes), and larger footprint of the measurement system. For the QC class, the RMT slightly underestimates and the ERT overestimates its presence. Similar to the NQC results, the SkyTEM has the highest resistivity estimation of the QC.

4.3 Geotechnical results

Investigations from the two sites, Strömstad (borehole S4, Fig. 14) and Lödöse (borehole L4 Fig. 15) are presented as examples of evaluation of quick clay from geotechnical investigations. CPTu (in-situ) and fall cone tests (laboratory) have been used in both boreholes. Also, resistivity measurement using CPTu-R has been used and the data are presented in the geophysics section, Figs. 10 and 13 and in Löfroth et al. (2018) and SGI (2018a).

As can be seen in Fig. 14 and the results from the Strömstad area, the interpretation of CPTu-data is affected by the occurrence of a dry-crust down to 3 m depth. The evaluation tool incorrectly evaluates this as quick clay. The absence of data in the depth interval 0–2 m is because this part has been pre-drilled and that sounding started from 2 m. From about 12 m depth the CPTu data indicate that the clay is quick. From about 14 m depth the analysis with fall cone test confirm the presence of quick clay. At about 20 m depth there is a course-grained layer within the clay. At greater depths, 22–23 m, there is a layer interpreted as quick clay. However, it is very important that this interpretation must be dealt with caution as this most likely is due to the overlying course-grained layer with higher mobilised friction. No sampling or analysis with fall cone test at greater depth than 20 m were conducted during this survey. At 23 m, the probe cannot be driven any further down due to the resistance. Based on the soundings and the geological knowledge of the area, the conclusion is that it is likely that the probe has encountered the upper part of the till.

The interpretation of CPTu in Lödöse is much easier (Fig. 15). The top layer does not affect the interpretation (the pre-drilled part was sufficient) and there is no course-grained layer within the clay. A significant part of the clay layer is interpreted through CPTu data as quick clay and mostly confirmed by the fall cone test where sampling has been made.

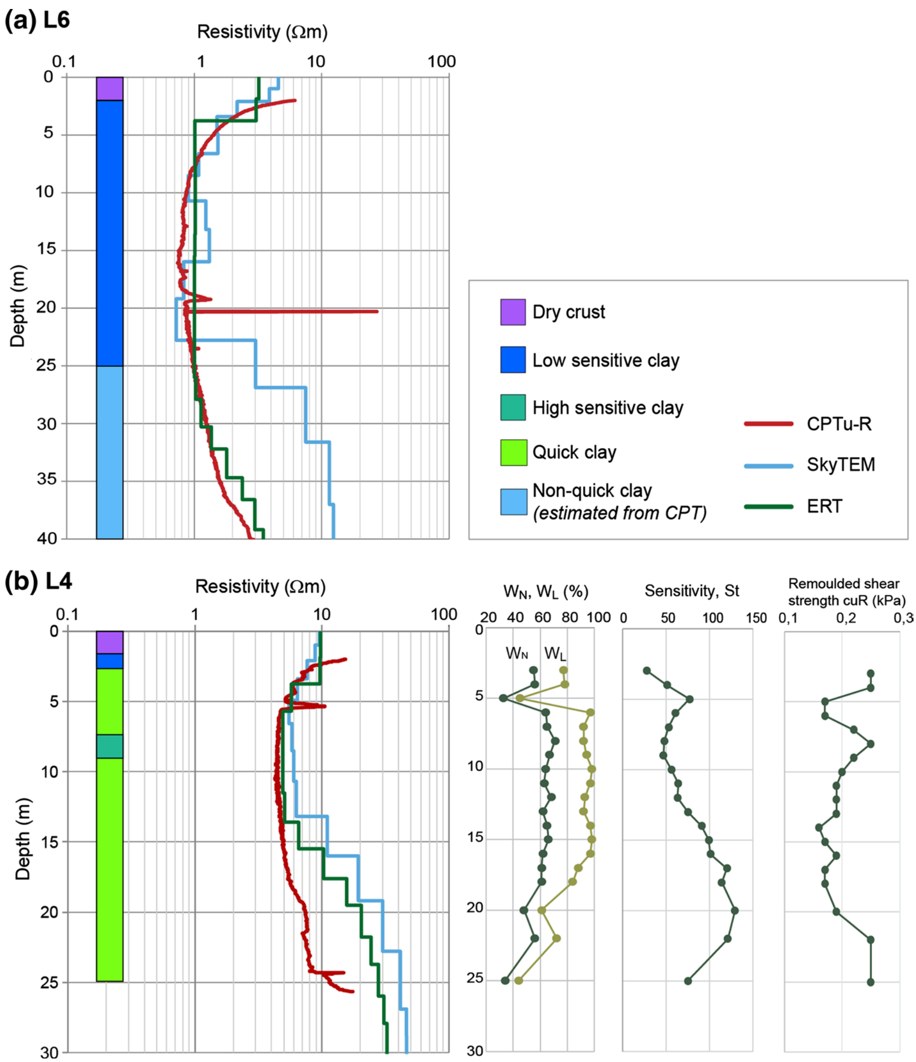

Fig. 12 Comparison between the CPTu-R, ERT, and SkyTEM at the location of boreholes L4 and L6. For a more detailed comparison, the water content and the liquid limit of the clay as well as the values of the sensitivity and the remoulded shear strength are shown for one of the boreholes (L4)

It is evident that an engineering judgement must be advocated, after evaluation of quick clay from CPTu sounding making use of the rod friction with the evaluation tool. The evaluation made by using the tool is commonly misleading in cases where clay is located just under a layer of friction material, for example, directly followed the dry crust. The method is also not advisable to use when the clay is under a thick layer of fill unless pre-drilling and casing have been carried out. When compared, evaluation of quick clay from the rod friction of CPTu has in general corresponded well with determination by fall cone tests from sampling and the investigations have confirmed earlier results (Löfroth 2011a, b).

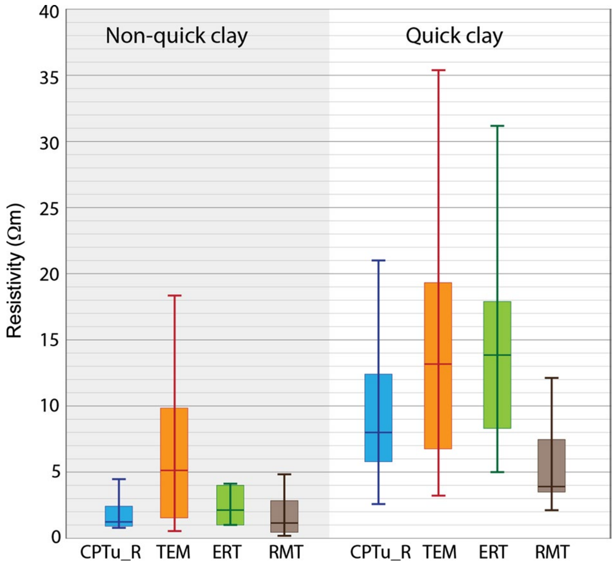

Fig. 13 Box-plot diagram showing the resistivity distribution for CPTu-R data (*blue*), modelled SkyTEM (*orange*), ERT (*green*), and RMT (*brown*). The box has a spread between the first and third quartiles (25% and 75%) and the whiskers show the max and min value (outliers excluded). The middle horizontal line shows the median value. The data are extracted from the resistivity models at the location of each borehole where the CPTu-R data are collected

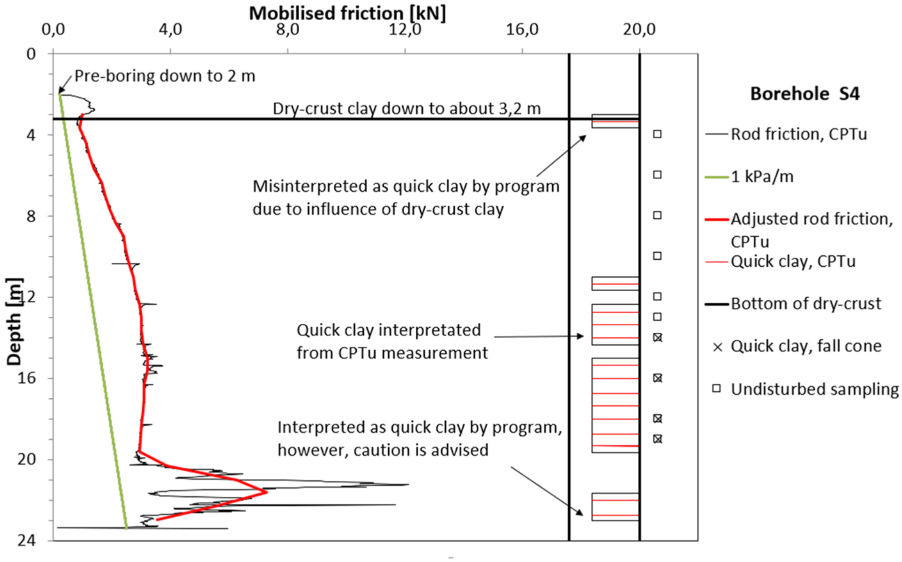

Fig. 14 Example of evaluation of quick clay from CPTu in borehole S4 at the Strömstad test site. Horizontal red bars show where the evaluation tool has interpreted the clay to be quick using the data from the rod friction. As shown in the figure, the uppermost part is affected by the presence of dry crust. Analysis performed with fall cone tests is indicated by squares. The square is marked with an x if the analysis has shown the presence of quick clay. The indication of quick clay at 22–23 m must be dealt with very carefully. No sampling or analysis with fall cone test at greater depth than 20 m were conducted during this survey

The quasi-liquidity index (w_N/w_L) was compared with sensitivity for more than 1100 laboratory samples from 90 sampling points along the northern part of the Göta River, including the Slumpån study areas (SGI 2012; Löfroth et al. 2018). The samples presented

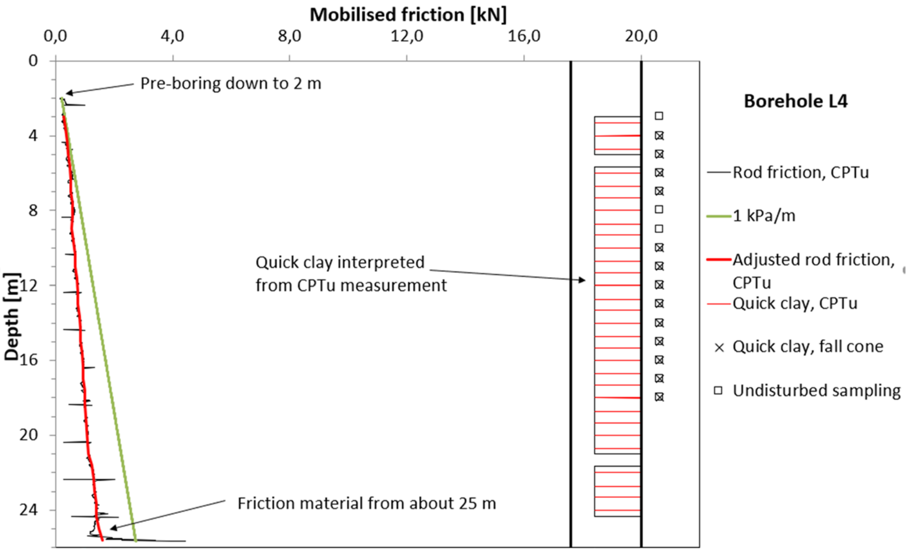

Fig. 15 Example of evaluation of quick clay from CPTu in borehole L4 at the Lödöse test site. Interpretation of rod friction data. Horizontal red bars show where the evaluation tool has interpreted the clay to be quick. According to the CPTu, quick clay is present at 3–24 m. However, according to the cone sample, 8–9 m does not have a sensitivity of 50 or higher though the value is close, 48, respectively 47

in Fig. 16 show a rather large spread, where a sensitivity of 50 gives quasi-liquidity indexes between 1.0 and 1.3. Results from earlier studies showed that the quasi-liquidity index should be above 1.1 for the clay to be quick (Rankka 2004; Larsson 2011). Although the majority of the quasi-liquidity indexes of quick clay from this study are above 1.1, this comparison shows that even a quasi-liquidity index as low as 1.0 could indicate quick clay.

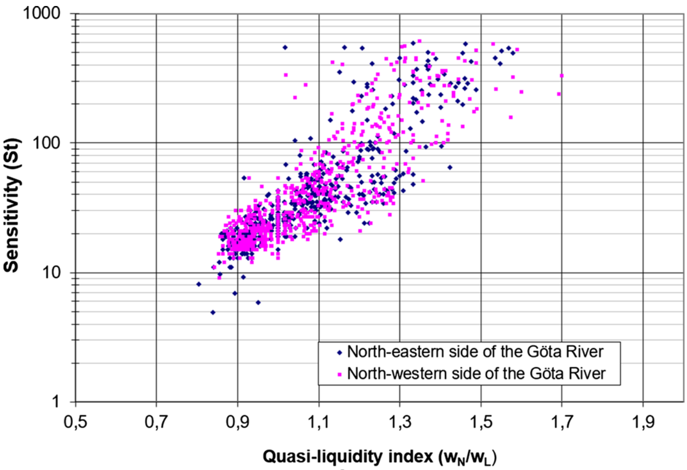

Fig. 16 Relation between quasi-liquidity index (w_N/w_L) and sensitivity for samples from both sides of the Göta River at the Slumpån test site

5 Discussion

The main objective of this work is to present a methodology to gradually reduce the extents of an area for more precise geotechnical investigations in areas prone to quick clay landslides in Sweden (SGI 2018a). While the approach reported by Solberg et al. (2012) focus on ERT and CPTu-R, for the methodology developed in this study several geological, geophysical and geotechnical methods were evaluated. The methodology presented is more like the strategy presented in Sandven et al. (2015, 2017). But, even though in principle the concept is the same using geological, geophysical and geotechnical methods, differences in the geological settings and is commonly used investigation methods between the two countries, dictate the choice of different methods. Our findings regarding the properties of quick clays and consequently mapping criteria are to a great extent in line with those reported by other groups but differ in details. Even if a detailed methodology is not presented, several authors propose the combination of geophysical and geotechnical methods for characterization of quick clay, e.g. Bélanger et al. (2017) and Pfaffhuber et al. (2014, 2017).

Maps presenting the highest coastline and the presence of clays deposited in salt or brackish water were found to be useful as a basis for assessment and selection of the potential area containing quick clay. This is also considered as a prerequisite by Sandven et al. (2017) in Norway. However, in Sweden, this needs to be complemented by a map showing occurrences of clays under the highest coastline deposited in a brackish-marine environment with a potential for quick clay and clays deposited mainly in freshwater with insignificant potential for quick clay (Fig. 1). To facilitate the assessment process in the early stage, a web mapping service was developed in the frame of this project. In addition to showing the areas where clays are deposited in saltwater or brackish water under the highest coastline, the service offers localization and classification of landslide scars and extraction of information about the sensitivity of the clay from earlier geotechnical investigations.

Having found the potential areas for quick clay, the next stage is to carry out airborne geophysical measurements. This was done in this project using SkyTEM as a first step, followed up by other geophysical investigations. These investigations were later of great importance for planning the geotechnical investigation in the project. Baranwal et al. (2017) show the use of frequency-domain airborne EM system and ground geophysical methods to investigate quick clay areas in Norway. The system used has different investigation depth and sensitivity compared to the one used in this study. However, the modelled resistivity from various geophysical methods shows similar trends of variation. It has been observed that the presence of high-sensitive and quick clays results in an increase of the modelled resistivities compared to the areas dominated by low-sensitive marine clays (see Fig. 13). This study has shown that quick clay may occur in areas with resistivities as low as 3 Ωm, lower than the 5 Ωm limit earlier considered as a reasonable assumption in Sweden (Söderblom. 1969; Lundström et al. 2009). Baranwal et al. (2017) report the same trend for the variation of resistivity for the sensitive and quick clays in Norway. However, in the Norwegian case, a 10 Ωm threshold is suggested for a first-order classification of clay as also reported in the study presented by Solberg et al. (2012) and Long et al. (2017). It is important to note that the definition of quick clay slightly differs in Sweden and Norway. Also, that the range of modelled resistivity variation differs, which depends on the method used, the assumptions made in the modelling, and most importantly the difference between the geological/hydrogeological settings in Norway and Sweden that may have a high impact on the bulk resistivity. Further research in this area comparing results from investigations regarding the characteristics of quick clay, in particular, would be interesting.

Our findings show that the resistivity of quick clay modelled from ATEM data is overestimated when compared to the resistivities from CPTu-R data. This accords nicely with those reported by Christensen et al. (2021) and is shown in the diagrams in Fig. 5 of their paper.

The SkyTEM system, used in this study has a broader footprint than both the ground geophysical methods ERT and RMT as well as the CTPu-R and is thus more affected by the structures adjacent to the profiles. Similar conclusions have also been drawn in Solberg et al. (2012) when comparing ground geophysical measurements with CTPu-R. However, the estimated resistivity from SkyTEM correlates often well with those from RMT, ERT and CPTu-R (Figs. 9 and 12). One should always incorporate other existing knowledge such as geological and geotechnical data when using the resistivity models to identify areas with the occurrence of quick clay.

As proposed in this study, Sandven et al. (2015) assess CPTu/CPTu-R as the most reliable sounding method for the detection of quick clay. But, both Solberg et al. (2012) and Sandven et al. (2015) suggested that results from conventional geotechnical soundings such as rotary pressure soundings and total soundings could be used as an indication of quick clay. Detection of quick clay from these methods is mainly based on the shape of the sounding curve, and less on the magnitude of the penetration resistance (Sandven et al. 2016). These methods are not commonly used in Sweden and have consequently not been considered within the scope of this investigation. However, in addition to CPTu, static pressure sounding is suggested for the detection of quick clay in Sweden (Löfroth et al. 2012; SGI 2018a). Although it is less accurate than CPTu, it is a conventional method in geotechnical investigations and is often used to a large extent for the assessment of soil stratigraphy.

The evaluation of quick clay from the rod friction of CPTu has in general corresponded well with determination by fall cone tests. However, an engineering judgement must be advocated after evaluation making use of the evaluation tool. Difficulties might be experienced, for example, in interpretation of the soft clay adjacent to dry crust and just under an intermediate coarser layer within the clay. Determination of quick clay in Sweden is done in laboratories through fall cone tests on undisturbed and remoulded clay specimens. This study, as well as Sandven et al. (2015) acknowledge this method as the only reliable method for the determination of quick clay. Thus, results from site investigations should also in the future be verified in this manner as was done in this project. This is implemented as the last step in the flowcharts. However, determination of the quasi-liquidity index could be used as a complement to fall cone tests for the assessment of quick clay.

6 Conclusions

- This paper presents a methodology for mapping quick clay under Swedish conditions with methods that are commonly available at a local level. The methodology is structured in steps with different levels of detail and presented in two flowcharts. Depending on the stage of planning, different types of surveys are recommended.
- Based on the methods for overview assessment of the potential for quick clay a web mapping service (https://gis.sgi.se/metodik_kvicklera/) was developed and is available as open access (SGI and SGU 2019). A checklist was developed and is included for guidance in the assessment of the spatial distribution of the potential presence of quick clay based on other local prerequisites (SGI 2018a).

- The resistivity models from different geophysical methods show slightly different values for similar geological features including areas with quick clays. This is partly because of the different levels of precision of the methods used and partly because of the modelling assumptions. However, the general trend of resistivity variations is similar, meaning that quick clay has a generally higher resistivity than the surrounding glaciomarine clays (see Fig. 13). Therefore, the use of airborne electromagnetic surveys is recommended as a cost-effective tool to identify potential areas and plan for more detailed ground investigations.
- A resistivity of 5 Ωm has previously been accepted for the Swedish conditions as a lower limit value for the presence of quick clay. However, this study has shown that quick clay may occur in areas with even lower resistivities (as low as 3 Ωm). It is therefore advisable to subsequently confirm the limit value for each area as the investigation becomes more detailed.
- The method developed by Christensen et al. (2021) seems promising and could be tested on the datasets collected in this study to evaluate its applicability for mapping the quick clay in Sweden which can be a complement/a new step to our proposed methodology.
- The ATEM survey in reasonably large areas (> 10 km^2) is a cost-effective and non-invasive tool to utilize to map potential areas with quick clays at the early stage of any infrastructure project. The resistivity models can be used for planning more detailed geotechnical and ground geophysical measurements at the later stages. In an iterative manner, the ATEM models and ground geophysical data together with geotechnical data can be later used.
- Evaluation of quick clay using CPTu has corresponded well with determination by fall cone test from sampling. The method is less applicable when used in soil that is layered and consists of alternating clay and silt. Also, the method is not advisable to use without predrilling when the clay is under a thick layer of fill or coarse material.
- Quasi-liquidity index could be used as a complement to laboratory investigations for evaluation of quick clay by fall cone test, for example when the determination of the undisturbed undrained shear strength is uncertain due to difficulties in acquiring an adequate sample. Although earlier studies have shown that the quasi-liquidity index should be above 1.1 for the clay to be quick (Rankka, 2004, Larsson, 2011) data from this study shows that even a quasi-liquidity index as low as 1.0 could indicate quick clay.
- Determination of quick clay done with fall cone test in laboratories on undisturbed samples retrieved by piston sampler is still thought to be the most accurate method and should be used to verify the presence of high-sensitive and quick clay.

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Declarations

Conflicts of interest The authors declare that they have no conflict of interest.

Consent to participate All authors have approved.

Consent for publication The authors' affiliations have been approved.

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