Predicting Spatial and Stratigraphic Quick-clay Distribution in SW Sweden

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Predicting Spatial and Stratigraphic Quick-clay Distribution in SW Sweden

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Abstract

Clay sediments are associated with a wide variety of engineering problems, of which landslides, together with settlement, are the most investigated due to the large associated costs. Quick-clay deposits, which if disturbed can transform into a liquid, pose a serious threat to society in southwestern Sweden and have been involved in several large landslides, sometimes with fatal consequences. Even though the theories that explain quick-clay formation are well advanced, no modeling that combine geologic information and reasoning with hard geotechnical data to predict its distribution has previously been done.

The stepwise multi-criteria evaluation technique suggested here involves identification of quick-clay preconditions from the literature. Then to derive criteria priorities, an expert group consisting mostly of geologists and geotechnical engineers carried out pairwise comparisons using matrices from which weights were calculated. The same group also participated in the development of the utility functions used to standardize the criteria to allow direct criteria comparisons. To populate the model, all criteria were quantified using empirical geotechnical data, existing geological documentation and/or environmental proxy data. The model results were later cross-checked at selected sites with geophysical methods. Finally, a rather large geotechnical data set was divided and used to add a depth dimension to the model results and to test the predictive powers of 2D and 3D models.

Quick-clay type settings were separately defined to facilitate clear communication of quick-clay predictions to non-specialists and to provide a structure for comparisons to the depositionary and post-depositionary conditions in well-studied east-Canadian and Norwegian quick-clay areas. These settings were derived from trends observed in geotechnical, geologic, geophysical and modeling records.

Results of the predictive modeling were subsequently applied to landslide hazard zonation in SW Sweden. However, the framework could, with slight regional adaptation, also be applied in other areas (e.g. eastern Canada and coastal mid-Norway) or even to other issues, wherever groundwater fluxes and ground conditions are of interest (e.g. in contaminant transport, geological process studies and groundwater resource exploration).

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Popular science summary

Quick clay is initially stable but may after disturbances lose nearly all of its shear strength (i.e. sediment particle's resistance to move relative to each other) and thanks to its high water content transform into a liquid. The remoulded shear strength is low and less than one fiftieth of the undisturbed strength (i.e. the "sensitivity" is 50). The characteristic bottleneck-shaped landslide scars in Sweden remind us of the occurrence, behavior and consequences of quick clay. The presence of these highly sensitive clays does not degrade the initial stability but is strongly decisive for the final size and damage of landslides. In southwestern Sweden, major quick-clay landslides have repeatedly destroyed infrastructure, property and caused fatalities, from the major landslide at Intagan in 1648 continuing until today (e.g. 2006 in the Småröd area, Bohuslän). Although many landslides during the last 100 years have been at least partly triggered by man it is important to recognize that these events are linked to chemical and physical changes in the clays that have occurred over thousands of years. These changes in mechanical properties depend on local and regional geological conditions.

Quick-clay developments, with few exceptions, occur in clay originally deposited in former marine environments next to the continental ice sheets. Subsequently, these sediments were lifted over sea level and exposed to groundwater leaching and other post-depositional processes affecting the sediment and its porewater. The distribution of cations, whose positive charge originally kept the negatively charged clay particles from repelling each other, is hereby removed. Many of the basic conditions that contribute to producing quick clays exist in southwestern Sweden and no significant difference between the quick and the non-quick clay deposits can be seen in grain-size distribution, mineralogy or sediment age in this area. It is mainly the depositional environment and post-depositional processes (mainly leaching) that explain local differences in clay strength. The quick-clay forming processes occur at different rates depending on the stratigraphic architecture, surrounding geology and geomorphology and groundwater conditions. The important changes in porewater chemistry are most effective where groundwater flow in sandy or gravelly sediments occur close to the clay.

The conditions described above were parameterized to form the basis of the model designed to predict the conditions that can change the mechanical properties of the clay, allowing quick clay to develop in parts of the landscape. By using mainly geomorphological and geological factors, it was possible to build a computer model that can help predict the conditions for quick-clay formation over large areas. To facilitate this, a group containing geologic, geotechnical and chemical expertise weighted all of the contributing criteria relative to each other. The next step, which was also done in the expert group, was to standardize the effects of each criterion so that they could be compared with each other and added together. Data and information regarding all involved criteria were combined to produce maps and 3D models showing the expected leaching probability at each site, called the "quick-clay susceptibility index" (QCSI). Finally, the predicted results were tested against existing geotechnical measurement results, mainly from road and railway feasibility investigations for and areas of known landslide problems.

Just over 80 % of the study area consists of exposed bedrock or coarse glacial sediments (sand and till which only rarely have clays beneath). The model suggests that leaching conditions that affect the remaining areas (approximately 20 %), where clay is present, vary, but that about 4% of SW Sweden is likely to contain quick clay at some depth below the ground surface. If the quick clay was formed very deep there is no threat since normal landslides only reach down to about 35 m at most. Other quick-clay areas are located far from river and stream banks (where many slides start), but these could still be hazardous if the slopes are steepened or overloaded. Generally the preconditions for quick-clay developments are best fulfilled in central Bohuslän and along the Göta älv River valley (including many of its tributaries). This is reflected both in high QCSI values from the model, geotechnically documented highly sensitive clays and in a landslide scar geomorphology typical of quick clays.

Quick-clay predictions can often not replace other more traditionally used geotechnical field and laboratory measurements but can help anticipate clay strength in areas without measurements, suggesting where the need for more information is the greatest. Although the model predicts areas with very weak clay strength (quick clay) and areas with quite high clay strength reasonably well, it does not predict the clay with intermediate clay strength (sensitivity values of 30-50), which may nevertheless be of geotechnical concern. This may be because most marine clay deposits originally had sensitivity values close to this intermediate strength, and these occur throughout SW Sweden, even in areas where some clay has been altered to be quick.

Populärvetenskaplig sammanfattning

Kvicklera är ursprungligen stabil men kan, tack vare sitt höga vatteninnehåll, till följd av störningar förlora nästan all sin skjuvhållfasthet (d.v.s. lerpartiklarnas motstånd mot att röra sig gentemot varandra) och således omvandlas från ett fast till ett flytande tillstånd. Skjuvhållfastheten är i omrört tillstånd, per definition, låg och understiger en femtiodel av den ursprungliga (eg. ”sensitiviteten” är 50). De karaktäristiska flaskformade skredärren i Västsverige påminner oss om förekomsten, beteendet och konsekvenserna av kvicklera. Dessa känsliga leror försämrar inte den initiala områdesstabiliteten men är starkt bestämmande för den slutliga utbredningen och skadeverkningarna hos jordskred. Flera stora skred där kvicklera bidragit till konsekvenserna har, vid upprepade tillfällen åtminstone sedan det allvarliga skredet vid Intagan 1648 och ända fram till idag (exempelvis i Smårödsområdet, 2006), drabbat Västsverige. Trots att många skred under de sista 100 åren har orsakats delvis av människan är det viktigt att notera att dessa händelser också är kopplade till tusentals år av kemiska och fysikaliska förändringar i leran. Dessa förändringar har, beroende på regionala och lokala geologiska förutsättningar, resulterat i skiftande mekaniska leregenskaper.

Bildning av kvicklera sker, med få undantag, i lera som ursprungligen avsatts i marina miljöer i anslutning till inlandsisen. Härefter har dessa sediment, med landhöjning, lyfts ovan havsvattenytan och blivit utsatta för grundvattenlakning och andra processer som påverkar sedimentet och dess porvatten. Fördelningen av positiva katjoner vars laddning ursprungligen hindrade de negativt laddade lerpartiklarna från att stöta ifrån varandra blir på så sätt borttagna. Många grundförutsättningar som bidrar till utveckling av kvicklera är väl tillgodosedda i Västsverige men inga påtagliga skillnader finns mellan kvicka och icke-kvicka leror vad gäller kornstorleksfördelning, mineralogi eller sedimentens ålder. Istället är det främst skillnader i avsättningsmiljön och de efter avsättningen aktiva processerna som förklarar skillnaderna i leregenskaper. Kvicklerebildningen går med olika hastighet beroende på jordlagerföljdens uppbyggnad (stratigrafisk arkitektur), omgivande geologi och landskapsform och grundvattenförhållanden. De viktiga förändringarna i porvattenkemi sker främst där grundvatten kan strömma i sandiga eller grusiga sediment i nära anslutning till leran.

De ovan beskrivna förhållandena utgör basen till den datormodell som designats för att förutsäga hur möjligheter för kvicklera att bildas varierar i landskapet. Genom att främst använda geomorfologiska och geologiska kriterier har det varit möjligt att snabbt prognostisera kvicklereförutsättningar över stora områden. För att möjliggöra detta arbete har en expertgrupp innehållande geologisk, geoteknisk och kemisk kompetens viktat alla inblandade kriterier relativt varandra. Härefter, också med hjälp av expertgruppen, har de olika kriterierna blivit standardiserade för att deras respektive effekter ska bli direkt jämförbara och för att dessa ska kunna läggas ihop. Data och information gällande alla kriterier kombinerades sedan till kartor och 3D-modeller som visar förväntade kvicklereförutsättningar. Detta skedde genom användandet av ett så kallat kvickleresusceptibilitetsindex, QCSI. Slutligen testades resultaten mot befintliga geotekniska mätresultat som tagits fram främst i samband med infrastrukturbyggnation och vid stora släntstabilitetsutredningar.

Drygt 80 % av området består av ”berg i dagen” eller grova glaciala sediment som endast i undantagsfall överlagrar lera. I resterande omkring 20% (där lera kan finnas) förutsäger modellen att lakningsförhållanden varierar men att ungefär 4 % av totalytan har kvicklera i något djupinterval i jordlagerföljden. Om kvickleran har bildats på större djup finns inget större hot då normala skred inte inbegriper material på nivåer djupare än ca 35 m. Andra kvickleror som kan ha bildats på större avstånd ifrån älvar eller åar (där många skred sätts igång) kan bli farliga först om slänterna blir förbrantade eller överbelastade. Generellt sett är förutsättningarna för kvicklera bäst representerade i centrala Bohuslän och i Göta älvdalen (inklusive dess biflödens dalgångar). Detta reflekteras i höga QCSI-värden från modellen, höga sensitivitetsvärden i de geotekniska undersökningsresultaten, hög elektrisk resistivitet (eller dålig elektrisk ledningsförmåga) i geofysiska mätningar och i skredärrens form.

Modellerade kvicklereförutsägelser kan oftast inte ersätta mer traditionellt använda geotekniska fält- och laboratoriemetoder men kan hjälpa till med att uppskatta lerans egenskaper och föreslå var behoven för nya fältundersökningar är som störst. Även om modellen relativt träffsäkert förutsäger områden med kvicklera och områden med jämförelsevis hög skjuvhållfasthet har den svårare att rättvist representera lerområden med känslighet nära det normala (sensitivitet mellan 30-50) som trots detta ibland kan vara av geoteknisk vikt. En anledningen till dessa prognostiska brister kan vara att leravsättningarna ursprungligen enbart hade liknande värden och att dessa förekommer i hela Västsverige, även i områden där leran ställvis omvandlats till kvick.

Preface

This dissertation consists of a background description (Part I) and five attached papers (Part 2) listed below.

I. Persson M. A. and Stevens R. L. (2012). Quick-clay formation and groundwater leaching trends in southwestern Sweden. In: Eberhardt, E., Froese, C., Turner A. K., & Leroueil S. (Eds.). *Landslides and Engineered Slopes–Protecting Society through improved understanding* (pp. 615-620). London: CRC Press. Taylor and Francis group.

Persson planned the layouts of the Kåhög and Bellevue investigations, participated in the fieldwork here and at the Hjärtum and Agnesberg localities, inverted all raw resistivity data and interpreted or re-interpreted modeling results. Persson produced all figures and text in consultation with Stevens who also improved the language and participated in discussions during all stages of the work. Many people not in the author list (but acknowledged in the paper) contributed with raw resistivity data, planning, discussion or fieldwork.

II. Persson M. A., Stevens R. L. & Lemoine, Å. (2014). Spatial quick-clay predictions using multi-criteria evaluation in SW Sweden. *Landslides 11*, 263–279.

Persson constructed and ran the model and produced all figures. The writing process was done jointly by Persson and Stevens. Lemoine was involved in technical discussions. A project reference group including Persson and Stevens jointly developed model weights and utility functions.

III. Persson M. A. (2014). Three-dimensional quick-clay modeling of the Gothenburg region, Sweden. In: Landslides in L'Heureux, J.-S.; Locat, A.; Leroueil, S.; Demers, D.; Locat, J. (Eds.): *Landslides in Sensitive Clays - From Geosciences to Risk Management* (pp. 39–50, Advances in Natural and Technological Hazards Research, Vol. 36). Dordrecht: Springer Science+Buisness Media

Persson compiled, digitized and interpreted the geotechnical data received from various existing sources and constructed and used the model framework. Stevens improved on the language and paper structure and discussed the content.

IV. Persson, M. A. and Stevens, R. L. (Manuscript, planned submission to Engineering Geology) Landslide retrogression potential assessment using quick-clay prediction models – an example from the Slumpån Stream-Göta älv River confluence area, SW Sweden.

Persson and Stevens cooperatively wrote the text and discussed most aspects of the contents. Persson constructed the model component that is a key feature of the paper and produced figures with inputs from Stevens who also corrected the language.

V. Persson, M. A., Stevens, R. L., Engdahl, M. (Manuscript) Comparison and classification of quick-clay settings in Sweden, Norway and Canada.

Stevens proposed the paper idea and did the initial planning. Persson did the bulk of the literature review and produced all figures and jointly with Stevens produced all text. Engdahl will provide regional geologic knowledge. Additional unspecified co-authors will be invited to contribute with complimentary geologic and geotechnical expertise and review the final manuscript before submission.

Relevant publications not in dissertation

Persson M. A. & Stevens R. L. (2012) *Predictive modeling of quick-clay distribution in SW Sweden* (Report C93, Final report delivered to the Swedish Civil Contingencies Agency, Karlstad). Department of Earth Sciences. University of Gothenburg

Persson, M. A. & Stevens, R. L. (2012) *Kvickleremodellering - Förutsägelser och tillämpning.* Swedish Civil Contingencies Agency popular science report.

Persson, M. A. (2012) Var finns kvickleran? *Geologiskt forum 19(74)*, 26-28

Persson, M. A. (in prep.). *Prognoskarta över förutsättningar för kvicklera med bifogad beskrivning över kartans användning* (Tentative title). Quick-clay prediction map with attached user manual for the Swedish Transport Administration (Preliminary delivery May 30, 2014)

Project outreach activities

Project related course elements on Applied Geology and Applied Geophysics courses held at the University of Gothenburg 2008-2014.

29th Nordic Geological Winter Meeting, Oslo, January 11-13, 2010:

1. Parameterization in Quick Clay Modeling–Introducing Stratigraphic Detail (Conference abstract by Persson, M. A. and Stevens, R. L, presented by Persson)
2. Quick clay comparisons: Sweden, Norway & Canada (Conference abstract by Stevens R. L., Persson M. A., Engdahl, M., Andersson-Sköld Y., Lundström, K., Hansen, L. & Torrance J. K., presented by Stevens).

QUICK Project meeting at the Geological Survey of Norway, Trondheim, October 19-20, 2010.

Quick-clay symposium in connection with QUICK research project closure for invited SW Swedish engineering geologists and geotechnical engineers, Gothenburg, September 26, 2011.

Swedish Civil Contingencies Agency meeting: Mötesplats samhällssäkerhet, Stockholm, November 16, 2011.

Swedish Civil Contingencies Agency quick-clay seminar, December 1, 2011.

11th International and 2nd North American Symposium on Landslides and Engineered slopes, Banff, June 3-8, 2012. Presentation of Paper I.

1st international workshop on landslides in sensitive clays, Université Laval, Québec city, October 28-30, 2013. Presentation of Paper III.

Contents

Part 1: Summary

1. Introduction and objectives

The total annual costs of landslides in Sweden (including quick-clay landslides) has been estimated to be roughly 100–200 million Swedish kronor (SEK) or 15–30 million US dollars (re-calculated from Cato, 1984 to account for inflation). Among landslides, the potentially largest and consequently most hazardous are the quick-clay landslides. The total societal cost of the Småröd, 2006 landslide alone has been estimated at approximately 500 million SEK (MSB, 2009).

Quick clay is a type of clayey sediment that can, upon disturbance, rapidly turn from a solid to a liquid (Reusch, 1901). Salt leaching, or more accurately cation leaching, was originally proposed by Rosenqvist (e.g. 1946; 1953, 1955) to be responsible for quick-clay formation and still is generally accepted as the most important way to achieve quick properties. These theories were later confirmed and complemented e.g. by Talme et al. (1966), Talme (1968), Andersson-Sköld et al (2005).

Geohazard zoning utilizing multi-criteria evaluation tools in GIS has been a large interest area for at least 20 years (e.g. Ayalew et al., 2005; Komac, 2006; Yoshimatsu and Abe, 2006; Yalcin et al., 2011). However, only comparably few scientific modeling studies have been done to spatially evaluate landslide likelihood in Swedish, Norwegian and Canadian sensitive-clay settings (Erener et al., 2007; LESSLOSS, 2007; Quinn, 2008, 2009, 2010, 2011). Moreover, even if quick-clay developments has been studied using field and laboratory methods for at least 70 years no predictive spatial modeling of quick-clay preconditions and constraints has ever been undertaken. Nevertheless, there are rather obvious benefits of cross-utilizing information from a wide variety of sources (i.e. geotechnical, stratigraphic, geologic, geographic and hydrogeological datasets, maps, information and conceptual reasoning and expert judgment). Data to facilitate such activities is also increasingly more accessible (e.g. through databases that is now emerging; cf. INSPIRE, 2007; Fortin et al., 2008; Rydell and Öberg, 2013).

This dissertation is aimed at the combination of geological and geotechnical knowledge in the development of new tools and procedures that can be used in quick-clay prediction and give decision support in different stages of stability mapping. The necessary methodological developments summarized below were accomplished stepwise, with improvement feedback between the main components (Figure 1).

1. A spatial database where stratigraphy and shear strength properties were interpreted from preexisting geotechnical survey results.
2. A MCE (Multi-Criteria Evaluation) model that can predict clay shear strength properties (i.e. sensitivity and remoulded shear strength) by calculating a 2D or 3D quick-clay susceptibility index (Paper II and III).
3. A framework for using geographical, geological and geotechnical information sources (i.e.the results from step 2.) in modeling of landslide propagation assessment (Paper IV).
4. Electrical resistivity tomography (ERT) results at selected sites that can be used to interpret and explain the stratigraphy and its effectiveness in creating groundwater and leaching pathways assumed to be important for quick-clay formation (mainly Paper I and V).
5. Type settings for quick-clay developments have been defined based on trends observed in the application of components 1–4 (above). These settings are designed to give perspective to the original modeling assumptions and to help increase the interpretability of model results. (Paper V).

In addition to the feedback mechanisms within the modeling activities themselves (Figure 1), the use of multiple information types (geotechnical, geological, geophysical and geographical) provides valuable control on the conceptual assumptions from each information field. Spatial and stratigraphic modeling allows testing against inconsistencies with empirical data at any site. Com-

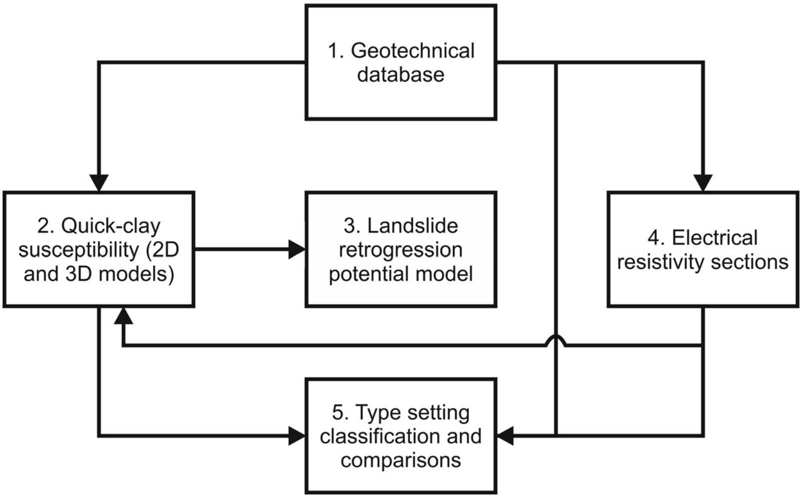


Figure 1. General methodological layout of the project where the main component connections are indicated by arrows.

parison of Swedish quick-clays to similar deposits in Norway and Canada (within component 5) is also beneficial since the focus of research differs between countries and the regional conditions and processes demonstrate the possible range of variations more completely.

2. Background

The geologic origins, depositional conditions and post-depositional changes are the basis for interpreting and modeling quick-clay characteristics, as is presented in papers I–V. The present section aims at providing background information for appreciating this approach, and also some concepts that have been produced within the project but that have not been made available before.

The formal definitions of quick clay vary between countries but usually involve a high sensitivity ratio (Eqn. 1), low remoulded shear strength or some other indicator of the liquid remoulded flow properties. The sensitivity scale first suggested by Skempton (1952) has undergone several revisions and adaptions to regional conditions. In Sweden a sensitivity (St) of >50 and additionally an undrained, remoulded shear strength (S_{ur}) of <0.4 KPa (Karlsson and Hansbo, 1989) are used for most purposes. The sensitive clay nomenclature used in Sweden is summarized in Table 1.

$$St = \frac{S_u}{S_r} \tag{1}$$

Where:

St = Sensitivity

S_u = Undrained undisturbed shear strength

S_{ur} = Remoulded shear strength

Sensitivity	Denotation
<8	Low sensitive
8–30	Medium sensitive
30–50	High sensitive
>50	Quick clay (if S_{ur} is <0.4kPa)
>200	Extreme quick clay

Table 1. Swedish sensitive-clay nomenclature (after Karlsson and Hansbo, 1989, with a later, less formal addition by Löfroth, 2011, in grey).

2.1. Sedimentary environments in SW Sweden

The sedimentary sequences of SW Sweden, known from geologic (e.g. Hillefors, 1969; Cato et al., 1982; Stevens et al., 1984; Stevens, 1985; Stevens, 1986; Stevens et al., 1991), geophysical (e.g. Turesson, 2005, Klingberg et al., 2006; Karlsson, 2010; Malehmir et al., 2013) and geotechnical field and laboratory studies (e.g. SGI, 2012a-c) reflect the environmental changes that have occurred, locally and even globally, over the past 15,000–20,000 years (Figure 2). Following the climatic shifts that resulted in deglaciation, uplift has exposed the sediments from former glacial, glaciomarine, open marine and near-shore environments to atmospheric and groundwater contact. The sedimentary series is briefly summarized below.

The coarse-grained and highly permeable till and glaciofluvial deposits that formed beneath the ice or in close proximity to the retreating ice margin (Figure 2 & 3) are hydrogeologically in strong contrast (i.e. considerably more permeable) to the much finer clayey sediments deposited simultaneously in glaciomarine settings only a short distance from the icefront. The thickness of coarse-grained sediments may in places reach 50 m or more, while at other localities they are missing or have very limited thickness. Till and glaciofluvial distribution is largely controlled by the distance to geographic standstill positions of the icefront, the regional glacial flow and bedrock morphology (resulting e.g. in stoss side deposits) and by sub-glacial meltwater drainage patterns.

The overlying glaciomarine clay (Figure 3) varies in thickness from zero to over a hundred meters. Its overall character is related to its source (which has varied with time). First, the glacial meltwaters carried abundant fine-grained sediments, typically allowing 0.01–0.1 m/yr deposition in biologically low-productive environments along the Swedish west coast. Glaciomarine varves (cf. Stevens, 1985) and associated silt and sand lamination formed in the oldest (i.e. deepest) clay due to seasonal ice melting. Since they have only poor contact with coarse-grained deposits and are often thin, the groundwater transport through these laminations can be expected to be low. As climate got warmer the production of meltwater increased, as did the distance to the icefront. Sand and coarse-silt supply to the marine sediments was now limited by the transport capacity of the meltwater while fine-grained material was still abundant. Silt and sand layers could still form by wave erosion and reworking of the earlier coarse deposits exposed in the isostatically rising, hilly terrain. These layers within the middle and upper part of the stratigraphy have thicknesses from zero to several meters and are often effective carriers of groundwater. Eventually the Scandinavian ice sheet was too far away and diminished in size to provide significant sediment. The still on-going land uplift (1-2 mm/yr; Ågren & Svensson, 2007) allowed reworking to be the dominant sediment source for new deposition, as the marine environments became shallower, until lifted above sea level.

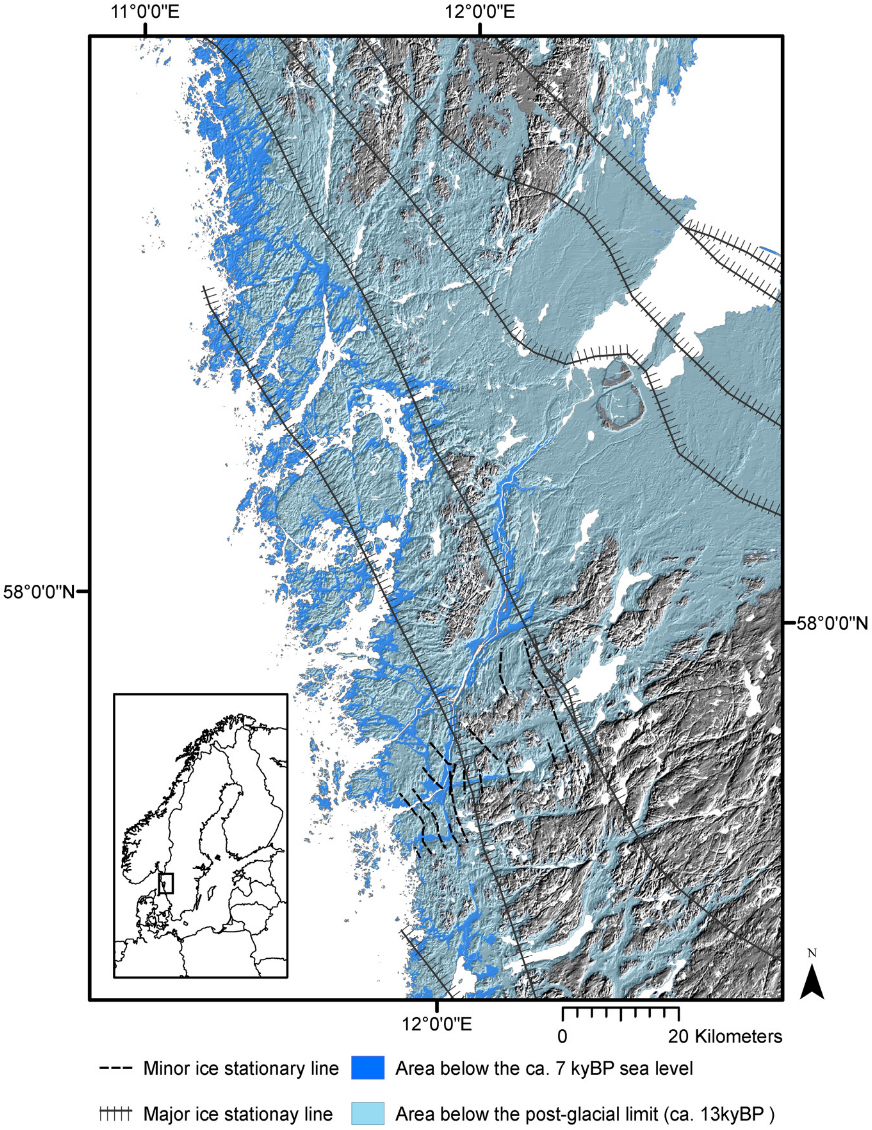
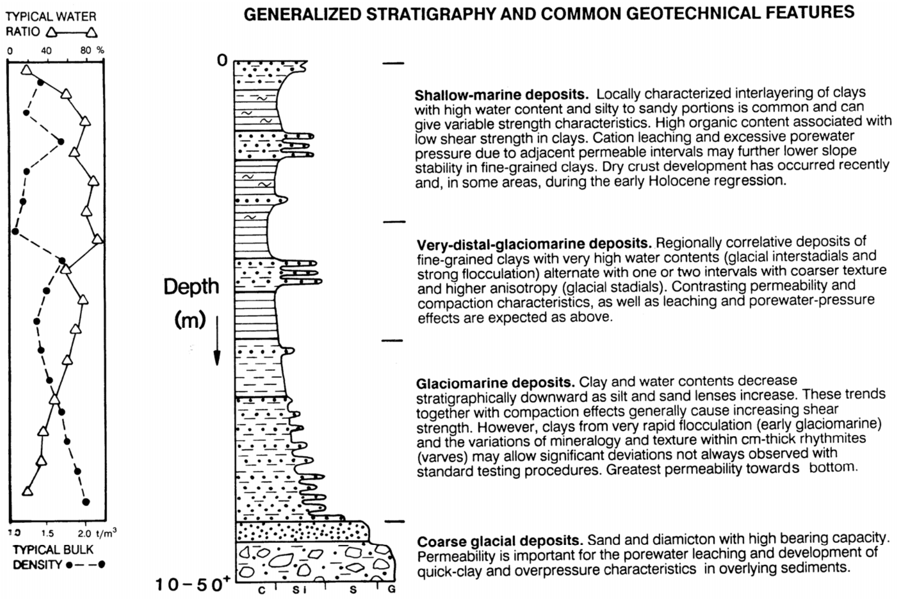


Figure 2. Paleogeographic map indicating areas below the 7 kyBP and the 13 kyBP sea levels and mapped icefront positions (compiled by using data from Björsjö, 1949; Stevens, 1986; Lundqvist and Wolfarth, 2001; Påsse, 1996; Påsse and Andersson 2005 on a hillshade background derived from NLSS, 2010).



Shallow-marine deposits. Locally characterized interlayering of clays with high water content and silty to sandy portions is common and can give variable strength characteristics. High organic content associated with low shear strength in clays. Cation leaching and excessive porewater pressure due to adjacent permeable intervals may further lower slope stability in fine-grained clays. Dry crust development has occurred recently and, in some areas, during the early Holocene regression.

Very-distal-glaciomarine deposits. Regionally correlative deposits of fine-grained clays with very high water contents (glacial interstadials and strong flocculation) alternate with one or two intervals with coarser texture and higher anisotropy (glacial stadials). Contrasting permeability and compaction characteristics, as well as leaching and porewater-pressure effects are expected as above.

Glaciomarine deposits. Clay and water contents decrease stratigraphically downward as silt and sand lenses increase. These trends together with compaction effects generally cause increasing shear strength. However, clays from very rapid flocculation (early glaciomarine) and the variations of mineralogy and texture within cm-thick rhythmites (varves) may allow significant deviations not always observed with standard testing procedures. Greatest permeability towards bottom.

Coarse glacial deposits. Sand and diamicton with high bearing capacity. Permeability is important for the porewater leaching and development of quick-clay and overpressure characteristics in overlying sediments.

Figure 3. Generalized stratigraphic sequence for SW Swedish valleys (Stevens et al., 1991).

2.2. Clay properties

Clayey sediment in SW Sweden is partially derived from the grinding and crushing of rock and partly by the erosion and reworking of earlier sediments, before its subsequent deposition in marine water (cf. section 2.1 above). Physical, chemical and mineralogical properties all interact to produce the resulting geotechnical behavior.

2.2.1. Physicochemical properties

Engineering classifications often requires only 15% clay-sized material to define clay, whereas the rest may be silt or sand. The clay particles, if originally settled in a marine environment, are usually in flocs with card-house structure. Contrary to ordinary card-houses the building elements are of unequal size and can be arranged edge-to-face, face-to-face or edge-to-edge. Clay particles are small (by most definitions <2 μm or <4 μm). The clay minerals occur abundantly in this fraction and are plate shaped (edge to face ratio of 1:100–1:1000). These carry negative surface charges due to isomorphous substitution (i.e. replacement of atoms in the crystal lattice by other similarly sized atoms without changing the crystal structure). In illitic clays, this occurs mostly by substituting Al^{3+} for Si^{4+}, giving the negative surface charges. To satisfy these charges cations are attracted and held to the exchange sites by electrostatic forces. The distances within which the clay particles may attract cations are explained by the diffuse double layer theory that were suggested by Derjaguin and Landau (1941), extended by Verwey and Overbeek (1948) and reviewed by van Olphen, 1977).

In a diagenetic or groundwater influenced environment the cations can be leached or exchanged, but the extent varies between species. A lyotropic series, such as the one suggested by Troeh and Thompson (2005; $Al^{3+}>Mg^{2+}>Ca^{2+}>K^{+}=NH_4^{+}>Na^{+}$), illustrates the adsorption strength for various cations and thus how easy they are to exchange (depending on cation valence, their relative concentrations and their hydrated size; e.g. Carroll, 1959; Torrance, 2009). A similar series (i.e. $Ca^{2+}>Mg^{2+}>>K^{+}>Na^{+}$), for the same reasons, indicates the relative influence of different cations on flocculation processes (Rengasamy and Sumner, 1998).

The organic content of SW Swedish Holocene clays is generally <5%, often decreasing with increasing age of the deposits (i.e. depths). The glaciomarine clays deposited during the late-Pleistocene deglaciation contain <1% organic matter. The $CaCO_3$ contents usually exhibit a trend opposite to the organic contents (i.e. increasing with depth). Also, areas near exposed sedimentary rocks (e.g. the Västgötabergen plateau mountains) generally have higher carbonate contents in till aquifer groundwater.

2.2.2. Mineralogical composition

Quick clays are mostly associated with low-active (Ac<1; Eqn. 2) glaciomarine or marine silty-clayey deposits. The activity of Swedish inorganic clays commonly ranges from 0.4 to 1.1 while regionally found quick-clays are 0.2-0.4 (Karlsson, 1981). This composition enables flocculation and hence a collapsible metastable microstructure (card-house structure).

$$Activity = \frac{Plasticity\ index}{\%\ of\ material{<}2\mu m} \qquad (2)$$

A clay sediment's mineralogy impacts the permeability, pore number and flow path tortuosity, which in turn affects the rates of several physical and chemical processes (cf. sections 2.3.2 and 2.3.3). Clay sediments are normally comprised of both primary minerals from eroded bedrock (e.g. silicates) and clay minerals (phyllosilicates) derived from both weathering and erosion of bedrock and former sediments. In the clay fraction of Swedish Quaternary clays, clay mica (often referred to as illite) is most abundant (e.g. Brusewitz, 1982; Stevens et al., 1987). Other major mineralogical constituents, in decreasing proportions, are quartz, feldspars and chlorite. Apart from soil horizons, mixed-layer vermiculite-biotite and vermiculite are the only swelling clay minerals which commonly occur, but at low concentrations. Swelling clay minerals negatively correlate with clay sensitivity and only small amounts of these are needed to exclude quick-clay developments (cf. Torrance, 2014). Other minerals (e.g. hornblende, epidote and garnet) occur, although much less frequently.

2.2.3. Leaching and cation redistribution

A general or selective removal of cations from the originally marine porewater expands the diffuse double layer which causes an increase in inter-particle repulsive forces which. In turn this lowers the remoulded shear strength, increases the sensitivity, and results in a liquid limit lower than the natural water contents (W_N). Other Atterberg limits and related index properties (including the liquid limit (W_L), the plasticity index and the related sediment activity; cf. Eqn. 2; Løken, 1970; Larsson, 2008) are also shifted. By leaching the samples with two to three times the pore volume Bjerrum and Rosenqvist (1956) achieved quick behavior on non-quick clay samples sedimented under marine conditions in the lab. The cations, which in the original stage help balance the negative clay particle surface charges, are continuously detached by two separate processes: advective leaching (due to groundwater movement) and cation diffusion (when concentration gradients preexist or have developed). Both can depress the diffuse double layer and result in the domination of the repulsive negative particle charges over the electrostatic and van der Waals forces attraction. The simple, so-called advection–diffusion relationship (Eqn. 3) can be used to illustrate cation transport in quick-clay development, where the first term represents the effect of diffusion on particle exchange, the second advection, and the third adsorption. The detailed effect of these processes for sediment and porewater geochemistry over time is, however, also dependent on the interdiffusion of multiple ions and the equilibrium coefficients for cation exchange relative to the cations and minerals involved (Lerman, 1979).

$$\frac{\partial c}{dt} = D_L \frac{\partial^2 c}{\partial x^2} - v \frac{\partial \mathrm{c}}{\partial \mathrm{tx}} - \frac{\rho}{\eta \rho_w} \frac{\partial c^*}{\partial \mathrm{t}} \qquad (3)$$

Where
c = concentration of cation in question,
t = time
D_L = cation dependent diffusion coefficient
v = advective velocity
x = spatial coordinate
ρ = sediment bulk density
ρ_w = density of water
η = sediment porosity
c^* = concentration adsorbed on sediment particles.

As is inferred by Eqn. 3, diffusion of cations occurs when concentration gradients exist. At least two separate diffusion fronts usually develop in valley stratigraphic sequences. First, an upward diffusion occurs in response to the low-saline, surface infiltration into the partly fractured deposits of the dry crust. Second, diffusion either toward relatively fresh groundwater in the lower till aquifer or in inter-layered sand layers may occur if these are present.

Advective leaching occurs mainly in response to pressure differences in the three principal stratigraphic units. Artesian flow into the clay can originate from groundwater in the lower till or glaciofluvium aquifer or from permeable sandy layers interlayered in the clay sequence (cf. Berntson, 1983). If these coarser, conductive units are laterally drained then the underpressure will induce advection in the opposite direction, toward the conductive units and may also introduce an increased horizontal groundwater flow component. This situation will also aid the downward percolation from surface infiltration. Clay permeability affects the advective velocity, and is commonly $<10^{-8}$ m/s in the SW Swedish glaciomarine and marine clays, as opposed to 10^{-6}–10^{-8} m/s or greater in sandy till aquifers or 10^{-6}–10^{-1} m/s in glaciofluvial aquifers and permeable sand layers (Larsson, 2008). The water-conducting coarse glacial units are recharged either by direct surficial contact or via groundwater transport in fractured bedrock. For clay samples with equal clay content, a slower sedimentation rate will result in an initially more open microstructure and higher permeability (Bjerrum and Rosenqvist, 1956). Lower loading pressure and the greater bonding strengths favored by slower sedimentation will further help maintain the open microstructure. Permeability of sodium-illite and silt mixtures prepared to resemble the Champlain sea clay, which are similar to the SW Swedish clays, were shown to be affected by clay content, sedimentation procedure (initial structure), hydraulic gradients and electrolyte concentrations (Quirk and Schofield, 1955; Hardcastle and Mitchell, 1974).

A combination of the features listed above affects leachability of the cation species, their varying diffusion constants and their relative flocculative powers that are obviously important when considering the evolvement of geotechnical behavior through time. In agreement with this, it has been suggested (e.g. by Talme, 1968; Andersson-Sköld et al., 2005) that not only the total porewater salinity but also the ratios between cations affect the quick properties. In short, clays of suitable origin that have not become quick regardless of leaching tend to have relatively more divalent cations in the porewater than their quick-clay counterparts. The ratio $Na^+/(K^+ + Ca^{2+} + Mg^{2+})$ is used to illustrate that at high relative Na^+ concentrations, sensitivity tends to be higher. However, the correlation between this ratio and sensitivity does not apply when the total salinity is too low to maintain floc stability (Andersson-Sköld et al., 2005).

Although cation leaching is considered an important or even dominant process affecting the shear strength properties of quick clays (Brand and Brenner, 1981; Torrance, 2014), at least three other processes can be locally important. First, according to Söderblom (1959) naturally occurring organic or inorganic substances act as dispersants that raise the sensitivity by decreasing the remoulded shear strength. Second, cementation that may affect sensitivity and clay behavior has been mostly studied in Canadian settings (e.g. by Torrance, 1986, 1990 and Boone and Lutenegger, 1997). The analogous conditions and effects in Sweden involving silicates, crystalline or amorphous iron and aluminum oxides or carbonate presence are largely unknown. Third, depending on its form negatively charged organic matter may compete in the clay-water-electrolyte system for cations by complex binding (Söderblom, 1969; Pusch, 1973) or act as a dispersant (Söderblom, 1974).

2.2.4. Distribution of quick clay in Sweden

The extent of quick-clay deposits is mostly known from geotechnical investigations that have been undertaken prior to infrastructure and other construction projects, following landslide events and during regional stability investigations that have taken place in the last 100 years and, to a lesser extent, from scientific studies. It is, in this perspective, worth noting that the knowledge of clay character decreases with depth below the ground surface, distance from major linear infrastructure and away from streams and rivers.

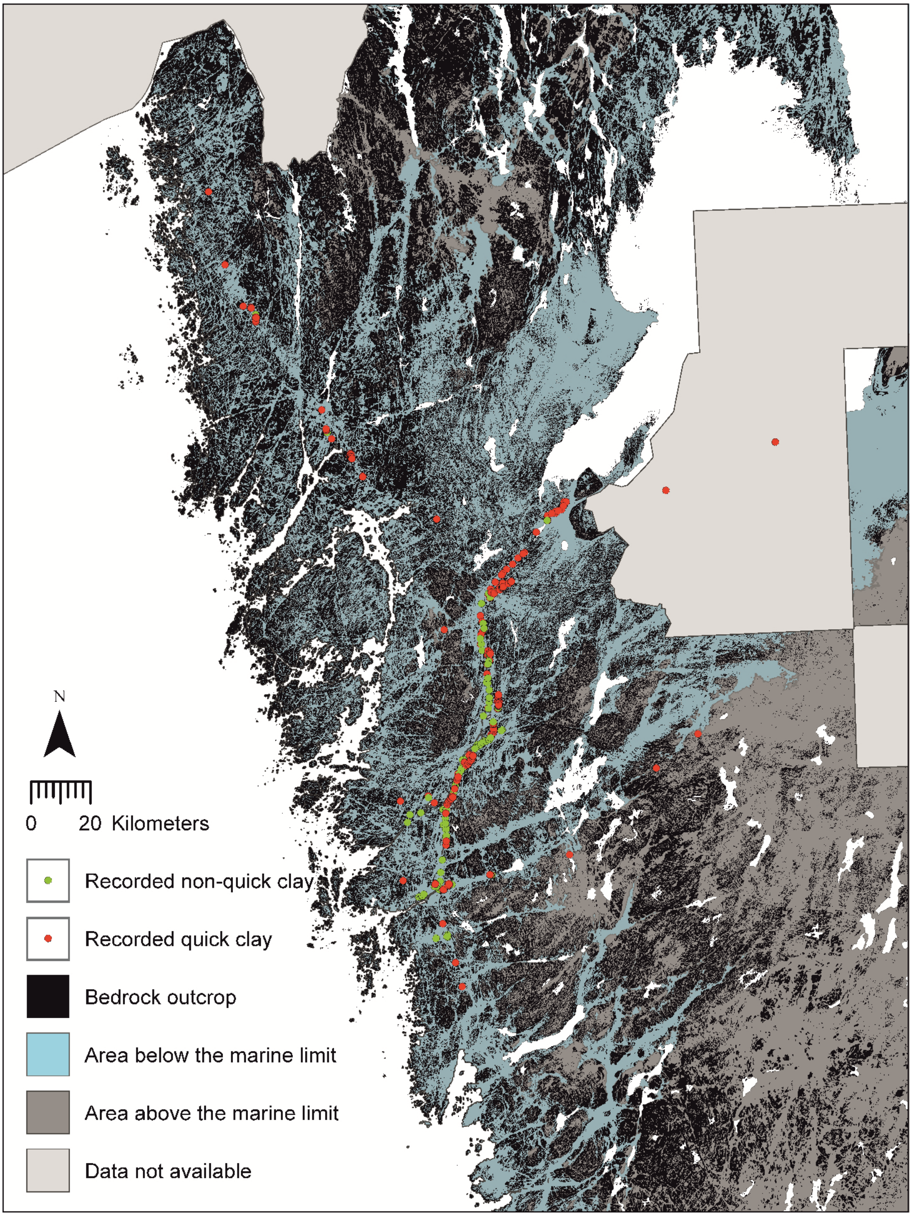


Figure 4. Confirmed quick-clay deposits from infrastructure and slope stability projects, especially along the Göta älv valley (SOU, 1962; Talme et al., 1966, SGI, 2012a and Swedish Transport Administration VV references given in section 3.1.7).

The distribution of known Swedish quick clays is heavily clustered in areas below the marine limit on or near the west coast, although some smaller and less frequent deposits have been recorded on the east coast of Sweden. These latter deposits (cf. Talme et al., 1966) have largely brackish-freshwater origins and will not be further addressed in this work.

To constrain the distribution of the SW Swedish quick-clay deposits, areas below the shoreline that prevailed ca. 7,000 years before present (see Figure 2) could be emphasized, since the Holocene marine clays deposited long after the glacial retreat are a common quick-clay stratum (SOU, 1962). Nevertheless, the clay sediments within the rather large areas below the marine limit differ in their exposure to quick-clay formation processes. Therefore, to achieve greater predictive power, additional stratigraphic and geographic criteria (presented in papers II and III) need to be used.

The most studied and best known quick-clay deposits are located in certain areas along the Göta älv River and its tributaries (e.g. SJ, 1922; Talme et al., 1966; VV, 2008b; SGI, 2012a), the Lidan River valley (e.g. Odenstad, 1951) and large and small stream and river valleys of the Bohuslän province (e.g. VV, 2002, 2005a-b, 2006a-g and 2007a-b). Usually only part of the stratigraphy has experienced sufficiently favorable conditions for quick-clay formation. Talme et al. (1966) compiled approximate thicknesses of stratigraphic intervals with quick clay from various 1950s and 1960s landslide studies in SW Sweden and concluded that the thickness of the quick interval varied between 3 and 20 m, which is only a part of the total thickness at these sites. It has been proposed by Talme (1968) that the Holocene marine clays (sometimes misleadingly referred to as post-glacial clays) are more prone to becoming quick than the earlier glaciomarine clay (sometimes simply called glacial clay). Permeable sand layers within this part of the stratigraphy also favor quick-clay development. The SOU (1962) investigations of the Göta älv River valley conclude that the location of clay deposits in relation to the groundwater recipient (commonly a stream or river) dictates the clay volume leaching effectiveness, that the rate of leaching is affected by the proximity to coarse-grained sediments and that the cation removal processes is nearly always complete close to valley margins and where clay thicknesses are limited.

2.3. Landslides in sensitive clay areas

Although quick clays do not affect the initial stability conditions the size and consequences of a landslide are. At least 2% of the banks along the Göta älv River have been affected by landslides (Hågeryd et al. 2007). Typically, quick-clay landslides (Figure 5) are large flowslides in which a varying portion of the involved masses has liquefied. With limited flow (due to less complete remoulding or higher S_{ur}), horst and graben structures also occur, but the classic example of a quick-clay landslide with extensive liquefaction is the so-called bottlenecked landslide where narrow outflow channels have evacuated the debris from a larger volume inside the zone of depletion. These can occur even with very low slope gradients. Although the slide debris must be able to flow when remoulded, the areal extent of quick-clay landslides is not solely dependent on clay properties (e.g. St; Mitchell and Markell, 1974; Larsson et al., 2008; L'Heureux, 2012; Thakur and Degago, 2012) but also the stability of the initial landslide backscarp and the ability of slide debris to get remoulded, (cf. Tavenas et al. (1983). Landslide propagation is also dependent on the accommodation space in the flow-out area, irregularities in the underlying bedrock surface and stratigraphic variations in strength related to leaching or consolidation. To exemplify, Bohuslän landslides are often small, not because of lack of quick clay, but since they are often restricted by outcropping bedrock and associated coarse sediments of higher stability. Landslide propagation may be either retrogressive (i.e. start close to stream or river and progress uphill) or progressive (i.e. start at higher slope elevations and progress forward) depending on local conditions. The former are most common in connection with natural stream erosion and over-steepening, whereas progressive slides are common with overloading in connection with construction or other human activities (cf. Bernander, 2011; Locat et al., 2011).

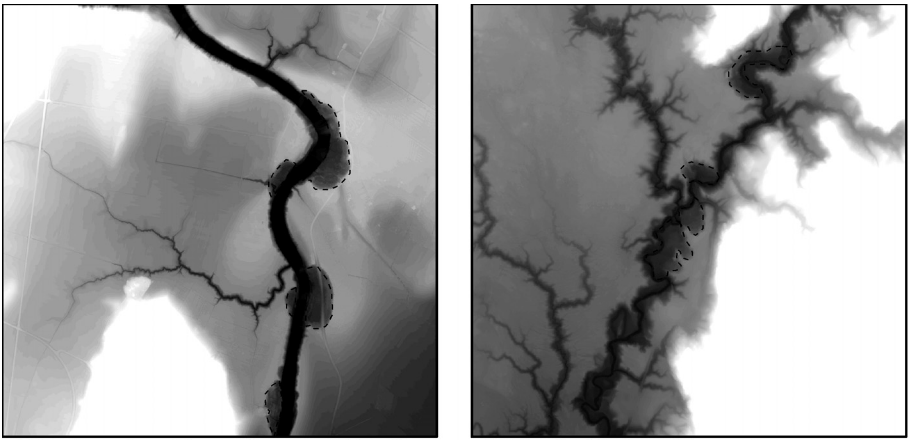
Some of Sweden's most severe landslides are documented in Table 2 together with Canadian and Norwegian examples. The morphology of selected landslide-prone areas is demonstrated in Figure 5 where Figure 5d shows parts of the Göta älv River valley that will be discussed later (section 4.3). Apart from the direct effects in the landslide area, upstream and downstream areas along rivers can be secondarily affected. Increased water turbidity, contaminant resuspension, flooding may occur either initially or after dam drainage (Göransson et al., 2009).

Table 2. Selected examples of large SW Swedish (above horizontal divide) and international landslides.

Landslide	Zone of depletion area (m^2)	Consequences	Cause
Jordfall ca. 1150[1], Bohus	370,000	Probably dammed The Göta älv River and rearranged the river course	Natural
Intagan 1658[2], Åkerström	270,000	Damming of the Göta älv River, 85 fatalities	Natural
Surte 1950[3]	240,000	Damming of the Göta älv River disturbed traffic.31 houses destroyed. 450 families homeless.1 life lost, 2 persons severely injured	Low natural stability and passing train
Göta 1957[4]	370,000	3 lives lost and at least 3 injured. Substantial property damage (e.g. several industrial structures destroyed).	Erosion and possibly sulphite liquor infiltration from adjacent factory.
Tuve 1977[5]	270,000	9 fatalities, 60 injured and 436 temporarily homeless. Road and 65 houses damaged. Total cost of landslide estimated at 140 million kronor (which roughly correspond to 580 million kronor today; MSB, 2009).	Steep bedrock inclination under clay, heavy precipitation, artesian conditions, traffic vibration and increased load.
Sköttorp 1946[6]	34,500	Lidan stream dammed. Material damage to a mill	Heavy rain and snow melting
Småröd 2006[7]	85,000	Demolished road, rail, cars and other property. Societal costs estimated at 500 million kronor.	Overloading by stored filling material.
St Vianney 1971[8], Québec , Canada	324,000	31 lives, 40 homes	Natural
Notre-Dame-de-la-Salette, 1908[9], Québec, Canada	40,000	33 lives, 12 homes	Natural. Failure plane on porous horizon
Gauldalen 1345[10], Norway	Uncertain	An estimated 500 lives lost many in subsequent landslide dam drainage. Some churches and 48 farms destroyed.	Natural
Verdal 1893[11], Norway	4 000,000	116 people perished, 105 farms destroyed. 3.2km^2 lake formed.	
Rissa[12],Norway	330,000	1 person died and 7 farms and 5 single family homes were destroyed or permanently evacuated.	Shore-proximal slope redesign during barn construction

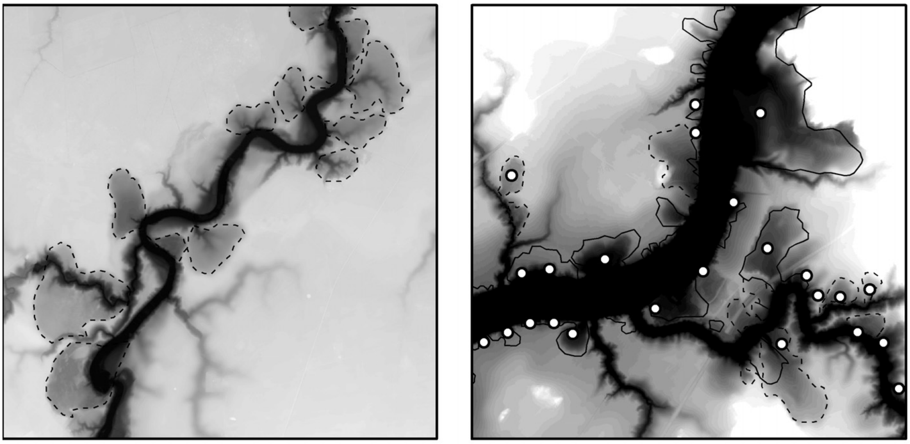
Swedish examples: [1]SOU (1962), Hultén et al. (2006); [2]Järnefors (1957); [3]Jakobson (1952) and Caldenius and Lundström (1955); [4]Odenstad, 1958; [5]Cato (1981); [6]Odenstad (1951); [7]Hartlén et al. (2007).

International examples: [8]Tavenas et al. (1971); [9]Ells (1908); [10]Rokoengen (2001); [11]Bjørlykke (1893) and Reusch (1901); [12]Gregersen (1981).



a) The Norsälven River valley near Edsvalla

b) The Örekilsälven River valley near Ed



c) The Lidan Stream valley near Järpås

d) The Slumpån stream - Göta älv River confuence

Figure 5. Landslide scars shown on a DEM backdrop (NLSS, 2012) where the grey tone has been modified to amplify the landslide scar imprint.

2.4. Quick-clay mapping and management

Of the choices available for quick-clay mapping (Table 3), the most traditional and also the most widely applied method includes core sampling and laboratory testing on the undisturbed and remoulded shear strengths using the Swedish fall-cone apparatus and then calculating the sensitivity.

Geotechnical field methods for estimating sensitivity include the rotary field vane, frequently utilized in Norway, and total penetration resistance derived from static pressure soundings and cone penetration tests (Löfroth, 2011 and references therein).

Additionally, electrical resistivity tomography (ERT) in two or more dimensions is increasingly popular (cf. Solberg et al., 2008; Lundström et al., 2009) and used to separate leached from unaffected clay deposits and to interpret stratigraphy. Resistivity methods are however limited by the influence of vertical fractures and buried objects, overlapping resistivity values (e.g. potential quick clay, floodplain deposits and varved glaciomarine clay can all have identical resistivity values) and the fact that low porewater salinity does not always correspond to quick clay. Resistivity probes (CPT-r) have also been tested in several studies (e.g. Schälin & Tornborg, 2009) and yield results consistent with the more common 2D ERT. To increase the spatial coverage, that is inevitably small in land-based surveying, initial testing of helicopter-borne electromagnetic methods has been done in Norway (Pfaffhuber, 2014), but with relatively low subsurface survey resolution and with the same problems as conventional 2D ERT. Other electromagnetic methods, (e.g. radiomagnetotelluric and controlled-source audiomagnetotelluric methods: Kalscheuer et al., 2013) have similar problems in resolving stratigraphic detail and distinguishing the strength characteristics when factors other than leaching have been important. Most, if not all, geophysical methods should be constrained or calibrated using information from geotechnical measurements.

Table 3. Relative strengths (pale gray) and limitations (black) of alternative quick-clay mapping tools. These methods have different and complementary purposes and cannot be strictly compared (modified from Persson and Stevens 2012).

	Quick-clay identification and mapping methods			
	Fall-cone determination of shear strength	**CPT and static pressure sounding**	**ERT for porewater salinity and *St* assessment**	**MCE to predict quick-clay probability (e.g. QCSI)**
Confidence in method	Established and used for quick-clay definitions	Established	Growing	Improving
Method robustness	Sound empirical relationships.	Assumptions needed	Relies on complimentary data	Improving. Some subjective components
Quick-clay mapping capability	Disturbance during transport and storage	Very high sensitivity values underestimated.	Relies on complimentary data	Decreases in areas with low data density.
Spatial coverage	Largely 1D	Largely 1D	Commonly 200–400 m 2D profiles	1–3D
Stratigraphical resolution	High, Potentially very accurate	High, Potentially very accurate	Thin units (<5m) are excluded	Depending on model inputs
Running costs	Very expensive	Expensive	Potentially costly	Very inexpensive.
Survey time expenditure	Time consuming	Time consuming	Time consuming	Dependent on operator's experience
Survey site damage	Disturbance due to coring and drill rig treads. Areas may needs to be cleared	Disturbance due to coring and drill rig treads. Areas may needs to be cleared	Little damage on vegetated surfaces	None
Method's agility	Machines might be unsuitable if stability is poor	Machines might be unsuitable if stability is poor	Difficult in densely forested terrain	No restrictions
Additional information received	Stratigraphy	Stratigraphy. Pore pressure can be measured	Indicates groundwater and leaching pathways	Interpretations of groundwater regime and stratigraphy

In Sweden, the evaluation of slope stability is initially based on a delineation of areas where stability may be problematic (cf. MSB, 2010). This is done largely by first considering surficial sediment type and slope geometry. The hazard class where landslide retrogression is expected is defined based on a 1/10 slope gradient (i.e. 5.71°). In subsequent steps geotechnical soundings are carried out to provide input data for safety-factor calculations (cf. Skredkommisionen, 1995). Following this, stability zones are expanded to include quick-clay areas if these have been documented from field and laboratory testing.

A risk assessment includes, in addition to the probability of slope failure, consideration of consequences of landslides. A recent example is reported as part of the Göta älv River valley survey project (SGI, 2012a), and dealt with the possible negative impacts on buildings, roads, railroads, river shipping, water and wastewater systems, natural environments, cultural heritage sites, power supply systems, trade and industry monetary loss (Andersson-Sköld, 2011). Generally, if the quick-clay hazard is too large and the consequences of landslide occurrence is too high, ground reinforcements (such as decreasing slope steepness, installation of lime-cement columns, erosion control and slope-support filling), removal of contaminated masses or property evacuation is recommended.

Increasingly faster and affordable computers have advanced computational-intense modeling from one to four or more dimensions in the past 60 years, whilst 90 % of the total global data was generated over the past two years (Moore, 1965; Dragland, 2013). Several fields (e.g. military, finance and resource prospecting) have been driving data production and the evolvement of modeling procedures that takes advantage of these technical developments.

3. Methodology

This dissertation is chiefly concerned with predictive modeling of quick-clay formation. The other objectives given in the introduction (Figure 1) are supporting, developing or applying the model results. The following modeling section (section 3.1) describes the modeling procedures to an extent that in combination with papers I–V will allow an experienced GIS user with access to suitable datasets to repeat, manipulate or revise the model without little additional instructions. The subsequent section 3.2 illustrates electrical resistivity tomography which was used both to examine modeling results and to formulate the five quick-clay type settings of section 3.3 where the combination of geophysical, geotechnical and geological evidence is used. Last, in section 3.4, it is demonstrated how the model results can be used in a landslide hazard zonation context.

3.1. The QCSI model

In all essence, the suggested modeling follows the analytical hierarchical process to sequentially assess the effects of multiple contributory preconditions on, in this case, clay leaching to predict quick-clay properties. Broad reviews and further details on other thematically related MCE methods are given by Keeney & Raiffa (1993) and Malczewski (1999).

3.1.1. 2D quick-clay susceptibility modeling

The modeling steps used to meet the problem formulation, *Which areas best fulfill the requirements for leaching of glaciomarine and marine clays and are thus susceptible to quick-clay formation?,* were (as illustrated in Figure 6, papers II and III and further explained in coming sections):

1. formulation of the model objective,
2. identification and hierarchical structuring of conditioning criteria,
3. criteria weights assignation,
4. criteria ranges standardization using utility functions to generate single criterion utility maps,
5. aggregation of criteria utility maps and criteria weights into one resulting quick-clay susceptibility map corresponding to the model objective and
6. model result evaluation and presentation.

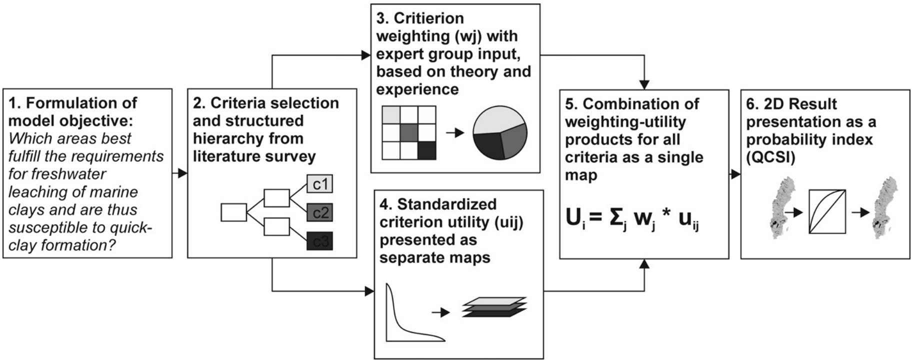


Figure 6. Workflow of 2D QCSI modeling (reprinted from Paper II).

3.1.2. Criteria identification

A large number of criteria known from the literature (and reviewed e.g. by Quigley, 1980; Brand and Brenner, 1981; Torrance, 1983 and 2014; Rankka et al. 2004) to be involved in quick-clay formation were considered and used in Papers II and III (cf. section 3.1.4). Later, in paper IV, an additional criterion (i.e. proximity to >2nd order streams) was added to better reflect a previously unaccounted pathway for leaching related to near-horizontal groundwater flow near streams (cf. Lefebvre, 1996). In the present work, stream order was assigned by giving main rivers an order of 1 and tributaries given successively higher order.

Criteria that do not vary significantly in southwestern Sweden or are not possible to predict from our data and information basis were excluded from further modeling although some of them might still be locally important (Table 4). This source of error is recognized and, in part, defined by relations presented in section 4.6. Criteria are, after selection and exclusion (Table 4), parameterized, ordered into a hierarchy and weighted (Table 5 and Figure 7) to facilitate further modeling.

Table 4. Excluded model criteria alternatives.

Environmental factors	Physical character of clay
• Accumulated Holocene precipitation (Paper V)[2, 3] • Peaks in underlying bedrock (Rankka et al. 2004)[2]	• Clay grain size distribution[1, 2] • Clay permeability[1, 2] • Clay microstructure (cf. Pusch 1970)[1, 2]
Mineralogical factors	**Chemical composition of clay**
• Contents of or proximity to carbonate rich sediments and rocks[1] • Clay mineralogy (cf. Brusewitz, 1982)[2] • Degree of Ca-feldspar weathering[2] • Amount of swelling clay minerals[1, 2] • Ratio of clay minerals to primary minerals[1, 2]	• Organic and inorganic dispersants (Söderblom 1974a & b)[2] • Porewater cation ratios (e.g. Sodium adsorption ratio, cation exchange capacity, porewater Mg^{2+} contents relative to other cations or ratios cf. Talme et al., 1966 or Andersson-Sköld et al., 2005)[2] • Cementation (e.g. Bentley & Smalley, 1978; Bentley, 1980; Torrance, 1990; Torrance 1995; Boone and Lutenegger, 1997; Berry and Torrance, 1998; Torrance, 2012)[1, 2, 3]

[1]Criterion have no significant variance within the study area, [2]Data insufficient for modeling and [3]The criterion impact on quick-clay developments in SW Sweden not fully investigated (modified from Persson and Stevens, 2012).

3.1.3. Weighting procedure

Pair-wise comparison matrices (Paper II) were set up following the AHP (Analytical hierarchical process) methodology suggested by Saaty (e.g. 1977, 1980, 2008) for each hierarchical level (Figure 7). An ordinal scale (Table 5) was used by a group of 7 Swedish quick-clay experts (5 geologists, 1 geotechnical engineer and 1 chemist) to describe the relative importance of pairwise compared criteria. Hereafter, the expert group and additional specialists confirmed the calculated weights. The criteria weights (Figure 7) with respect to the previously formulated problem were derived by multiplying the matrix with itself repeatedly until consistency in eigenvalues were reached and then dividing each row sum by the sum of all rows. The full mathematical derivations are given by Saaty (1977). Calculations were done using Logical Decisions® v 6.1 for Windows. The expert group and additional specialists were also given the chance to suggest modifications to the set of weights that was finally used.

Table 5. The rating scale used in AHP weighting (modified after Saaty 1977 & 2008).

Relative importance	Definition	Explanation
1	Equally important	Two criteria contribute equally to the objective in section 3.1.1
3	Moderately more important	Experience and judgment slightly favor one criteria over another
5	Strongly more important	Experience and judgment strongly favor one criteria over another
7	Very strongly more important	One criteria is favored very strongly over another; its dominance demonstrated in practice
9	Extremely more important	The evidence favoring one criteria is overwhelming
Reciprocals of above	The members of each pairwise comparisons have reciprocal values	By definition
Rationals	Ratios arising from the scale	If consistency were to be forced by obtaining *n* numerical values to span the matrix

Consistency ratios (C.R.) were calculated (Eqn. 4) to assure consistency in the weighting process. Consistency indexes (C.I.) were first calculated for the weighting matrix and a random matrix (Eqn. 5).

$$C.R = C.I \text{ of matrix} / C.I \text{ of “random matrix”}, \quad (4)$$

where

$$C.I. = (\lambda max - n) / (n - 1) \quad (5)$$

in which

λmax = Principal Eigenvalues (i.e. the product of the matrix and the unadjusted weight vectors) and

n = number of rows or columns in the weighting matrix

All weighting matrices within this study had C.R <0.1, satisfying conditions recommended by Saaty (1977).

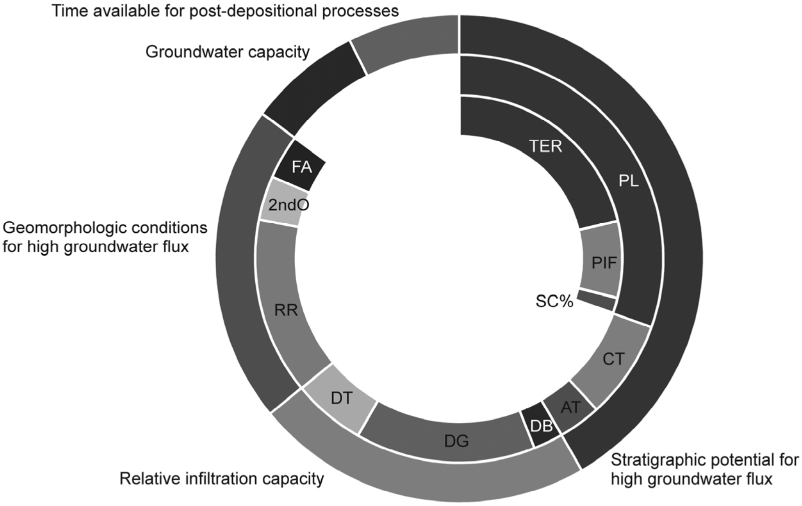


Figure 7. Criteria weights, modified from Papers II and IV, symbolized by the angular extent of each field. The outer ring represents criteria groups and the inner rings give single criteria and sub-criteria weightings where PL = permeable layering, CT = Clay thickness, AT = Aquifer thickness, DB = Distance to bedrock outcrop, DG = Distance to glaciofluvial outcrop, DT = Distance to sandy till outcrop, RR = Relative relief, 2ndO = Proximity to 2nd order streams, FA = flow accumulation, GC = Groundwater capacity, TA = Time available for post-depositional processes, TER = Topographic exposure to rework, PIF = Proximity to icefronts, SC% = Areal % of surficial coarse material.

3.1.4. Criteria quantification and standardization

Empirical data were preferred over theoretically derived data. However, when criteria data were sparse or missing, proxy data and conceptual information were also considered.

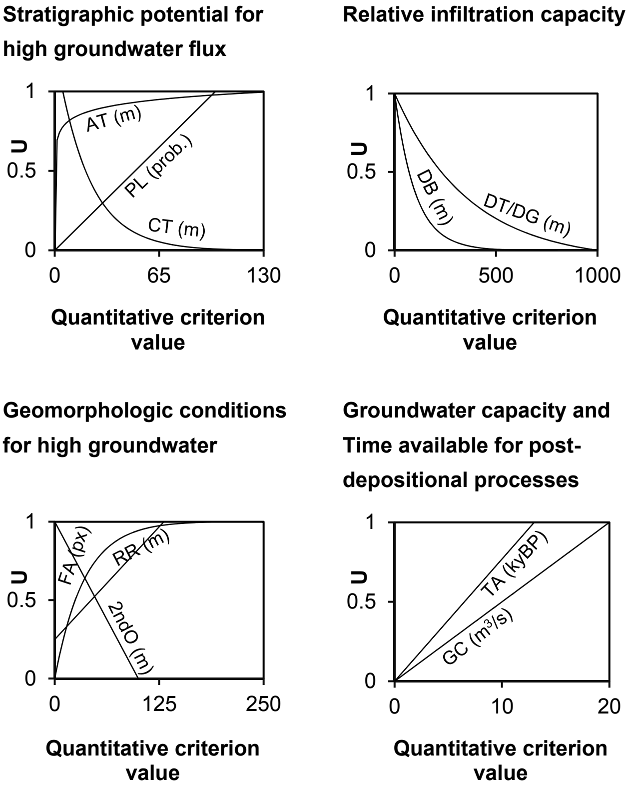


Figure 8. Utility functions used for standardizing criteria. TA = Time available for post-depositional processes, WC = Groundwater capacity. The other abbreviations are given in the caption to Figure 7.

The observed (or model derived) criteria data (Table 6–Table 11) were used to construct separate maps of each criterion's utility (i.e. the effect on quick-clay formation). To be directly comparable, single criterion utility functions (Figure 8) were used to standardize all originally dissimilar criteria quantities into a common 0–1 utility range. Here 0 was *no fulfillment* and 1 was *optimal fulfillment* of individual model criteria (i.e. quick-clay prerequisites). For some criteria with naturally occurring geographic trends, two functions were applied to specific intervals to account for their spatial dependency. The criteria maps are shown in Figure 9.

Table 6. Quantification of criteria in the *Stratigraphic potential for high groundwater flux* group.

Criterion	Data and processing
Clay thickness	Stratigraphic values from documented localities (SGU, 2012c; Klingberg et al., 2006) were used for ordinary cokriging interpolation of clay thickness (Figure 9a) using co-variate proxy information (i.e. proximity to bedrock outcrops).
Aquifer thickness	Localities where the thicknesses of non-differentiated till or glaciofluvium (Figure 9b) are known (SGU, 2012c; Klingberg et al., 2006) were interpolated with ordinary cokriging and using the assumed covariates of stoss-sides and proximity to icefront positions. Glaciofluvial deposits were not possible to distinguish from till deposits but were here given a common permeability. First, lee and stoss-side deposits were assigned to areas where the slope aspect deviation is less than 15° from the optimum orientation parallel with the prevailing glacial striae directions and the bedrock slope is more than 7°. The prevailing ice direction was interpreted from glacial striae observations (SGU, 2012e). Proximal and distal distances to icefront positions were separately calculated as a second sub-criterion. The two proxies for aquifer thickness were subsequently combined using weighting factors.
Permeable layer probability	To predict the likelihood of permeable layers (Figure 9c) within the clay, areas were defined where coarse-grained surface deposits (extracted from SGU, 2012a, b) are exposed and likely vulnerable to reworking during shoreline regression, and where the mid-Holocene (ca. 7 kyBP) stagnation in relative land uplift was significant (cf. Påsse & Andersson, 2005). Further, areas close to icefront positions were considered extra susceptible for sand-layer formation. Such areas were modeled using a non-symmetrical utility function to account for differences in the sedimentary environments on the ice-proximal and the ice-distal sides, respectively.

Table 7. Quantification of criteria in the *Geomorphologic conditions promoting high groundwater flux* group.

Criterion	Data and processing
Flow accumulation	Flow accumulation (i.e. the accumulated number of DEM raster cells upstream from any grid cell of interest; Figure 9d) was calculated from NLSS (2010) using standard hydrologic tools within the GIS. The result reported is each raster cell's available catchment. Rivers and streams were excluded to get mainly the flow oriented transverse to surface waterways. The available groundwater flow is assumed to follow the topography and flow accumulation was used to quantify this.
Relative relief	A migratory, circular search window (r = 300m) was used to calculate the relative relief (Figure 9e) within each ca. 0.28 km^2 circle from the DEM (LMV, 2010).
Proximity to >2nd order stream	Hack's stream order was calculated from a stream network dataset (SMHI, 2012) and its utility is presented in Figure 9f.

Table 8. Quantification of criteria in the *Relative infiltration capacity* group.

Criterion	Data and processing
Distance to sandy till outcrop	The Euclidian distance (i.e. straight-line distance) from mapped, surficial sandy till units (SGU 2012a, b) was calculated and is exemplified in Figure 9g.
Distance to glaciofluvial outcrop	The Euclidian distance (i.e. straight-line distance) from mapped, glaciofluvial units (SGU 2012a, b) was calculated and is exemplified in Figure 9h.
Distance to bedrock outcrop	The spatial extents of infiltration-prone deposits are often small enough to be excluded even from the 1:50,000 maps of surficial deposits (SGU, 2012a). The distance to bedrock outcrops (SGU, 2012a, b; Figure 9i) was therefore used as a proxy for these. A handling similar to the two criteria above was used although the effective distances used to define utility functions were shorter (cf. Figure 8).

Table 9. Quantification of criteria in the *Groundwater capacity* group.

Criterion	Data and processing
Water capacity in the lower aquifer	The groundwater capacities (Figure 9j) of rock and sediment were interpolated from ca. 72,000 well log records (SGU, 2012d) using ordinary kriging. No distinction was possible to make between bedrock and glacial deposit aquifer capacity. Only wells positioned with accurately <100 m were used.

Table 10. Quantification of criteria in the *Time available for post-depositional processes* group.

Criterion	Data and processing
Time available	The time that a land area has been located above the present sea level was used as a proxy for the time available for post-depositional, quick-clay forming processes (Figure 9k). The number of years was calculated using empirical equations simulating shoreline fluctuations caused by eustacy and isostacy in the late Pleistocene and Holocene (Påsse, 1996; Påsse & Andersson, 2005). Ordinary kriging interpolation of each necessary term (except elevation; NLSS, 2010) preceded the full calculations covering the whole area, and resulted in time above-sea-level maps.

Table 11. *Boolean constraints*

Criterion	Data and processing
Absence of marine sedimentary settings	Areas above the marine limit (cf. Figure 9l) were not considered since leaching in glaciomarine and marine fine sediments is the primary cause for quick-clay formation in the area (cf. Larsson, 2010). The marine limit was interpolated from the literature records (references listed in Påsse, 1996) and a DEM (NLSS, 2010).
Bedrock outcrops and non-susceptible sediments	Areas covered by coarse glacial sediments were excluded (cf Figure 9m). Clay deposits may occur, in rare cases, beneath coarse glacial sediments in connection with ice re-advances during glacial stadials, but these occurrences are believed to be of minor importance. Note that sandy layers within the Holocene clay deposits develop much later and are not part of this constraint.

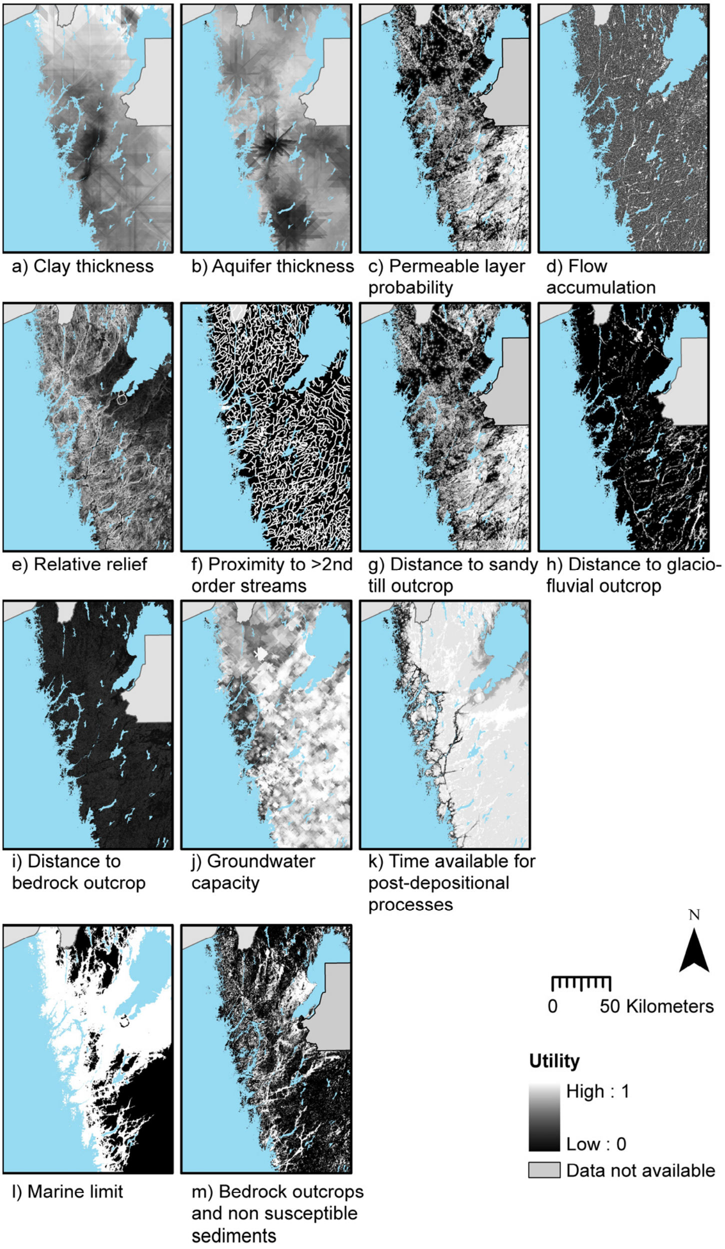


Figure 9. Spatial distribution of criteria utilities (a–k) where data were not available for Norwegian territory or in areas unmapped with respect to surficial deposits The areal extent of high-utility areas of map k) is exaggerated. Boolean constraints are shown in l and m.

3.1.5. Combining model components

All criteria weights and site-specific utilities were combined using Eqn. 6 in ArcMap (ESRI, 2011) to obtain the overall utility, U_i, expressed in a unit-less likelihood ranging from 0 (lowest) to 1 (highest).

$$U_i = \sum(w_j u_{ij} \cdot \prod c_j) \tag{6}$$

Where w_j is the weight constant for the i^{th} criterion (relative to the problem formulation and illustrating the single criterion's relative importance) and u_{ij} is the normalized criterion score, utility, for the same criterion on the j^{th} dimension (e.g. the degree to which the criterion is fulfilled at a specific site represented by a raster grid cell), while c_j corresponds to the Boolean constraints in Table 11. U_i is calculated for every pixel in the resulting raster map and is hereafter referred to as quick-clay susceptibility index (QCSI).

3.1.6. Adding the depth dimension

After the initial QCSI modeling (Paper II) the model framework was expanded to include also the third dimension (i.e. depth). This was exemplified in the Gothenburg region (Paper III) and in the Göta älv River-Slumpån Stream confluence area as part of Paper IV.

A very simplified stratigraphy with only clay, inter-layered silt or sand (assumed when permeable layer utility >0.5; cf. Paper II), and coarse grained glacial drift (assumed when aquifer thickness utility >0.73) together with geologic history gave four stratigraphic scenarios: 1) Clay directly resting on bedrock, 2) Clay with glacial drift below, 3) Clay with inter-layered silt or sand at 15 m and 4) Clay with inter-layered silt or sand at 15 m and underlying glacial drift. The sensitivity trends in each scenario were interpreted from the geotechnical data (specified in section 3.1.7) and adapted for use as scale factor functions (Paper III) that gave depth and scenario specific scale factors (SF_d) which in turn allowed for the transformation of QCSI into depth specific $QCSI_d$ and predicted sensitivity (St_p; Eqns. 7 & 8). The functions were compressed depth-wise when clay thicknesses were small. A sensitivity of 5 was assigned to the ground surface to account for near-surface processes lowering the sensitivity. St_{QCSI} is the maximum site-specific sensitivity interpreted from the QCSI-model results and the *geomean + 1σ function* of Figure 15.

$$QCSI_d = QCSI \cdot SF_d \quad (7)$$

$$St_p = St_{QCSI} \cdot SF_d \quad (8)$$

In the Gothenburg example of Paper III, St_p was calculated to populate point sets (horizontal point separation 50 m) constructed for each 5 m depth interval down to 80 m. In the Göta älv River–Slumpån Stream confluence example (Paper IV) depth-specific 2D layers with a pixel size of 2×2 m and a separation of 5 m. The lowest level studied here was 20 m which cover the depth of most landslide scars locally. All calculations combining QCSI, QCSI-sensitivity relations and scale factor functions were done using ESRI® ArcMap™ 10 (ArcInfo licence) while model results were presented in 3D using ESRI® ArcScene™ 10.

3.1.7. Result validation and verification

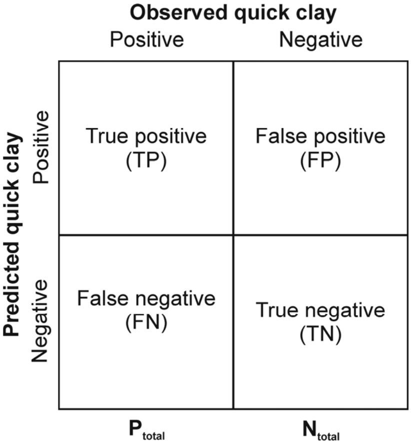
The model outcomes were compared to archive results from fall cone analyzes made on core samples taken from varying depths by standardized Swedish piston corers (ST II type). Rather than to core and sound new sites within the project, extensive work was put into digitalizing and synthesizing geotechnical information from existing documentation. Most sensitivity analyzes (including remoulded shear strength data) used in model testing were commissioned by the Swedish Transport Administration, including its predecessors, and executed by consultant companies, mainly preceding construction work on roads E45 and E6 and the adjacent Norge–Vänerbanan railroads (SJ, 1989; VV, 1997, 2002, 2004, 2005 a & b, 2006 a–g, 2007 a–d, 2008 a–d, 2010); BV, 2002, 2008). Additional sensitivity data from investigations in the Göta älv River valley (SGI, 2012b, c) and in the city of Gothenburg (Gatubolaget, 2008) were used although to less extent. The archive data from the sources specified above were chosen as they cover both the valley central and valley marginal settings and thus coincide with different sedimentary settings where the conditions for the development of quick clay vary (cf. section 4.5).

To test the model's predictions against known sensitivity values the samples were classed and plotted separately. For the 2D case, only the maximum sensitivity recorded (St 13 to 707) in each of the 392 studied sediment cores (altogether >2,800 sub-samples) was used for comparison.

In 3D model applications, locally available comparison data (e.g. BV, 2008 & SGI, 2012b, c) for 1–5m depths interval were used. The Göta älv River–

Slumpån Stream confluence area was studied more carefully as part of paper IV by using geotechnical documentation spanning over the last 50 years and ERT profiling. Seismic reflection records (Malehmir et al., 2012; Klingberg et al., 2006) complemented the picture of the ground conditions, as did utilization of geophysical methods, as described below (sections 3.2 and 4.5) and in paper I.

Receiver operating characteristics (ROC) were originally developed to test the performance of models for military applications and later adopted for medical and a wide range of other research purposes (see Fawcett 2006, for review and methodology). A ROC curve describes the relation between the two key characteristics: sensitivity and specificity for possible cutoff values (Figure 10 and Eqns. 9 and 10). Sensitivity, in a ROC context (ROC-sensitivity hereafter), is sometimes referred to as true positive rate or hit percent, while specificity is also known as true negative rate. In ROC curve construction specificity is commonly represented as false positive rate (i.e. 1-Specificity). Further, the area under the ROC curve is often used to indicate model success rate and to compare between competing models. Here, ROC analysis was used to test the QCSI model's ability to discriminate between clay with sensitivity values over or below 50 given geotechnically described samples (see section 3.1.7) and the entire QCSI range as potential thresholds. Specificity and ROC-sensitivity correspond to correctly classified, non-quick clays and quick clays, respectively. The SPSS Statistics 20 software (IBM, 2011) was used for calculating the sensitivity, specificity and related statistics.



		Observed quick clay	
		Positive	Negative
Predicted quick clay	Positive	True positive (TP)	False positive (FP)
	Negative	False negative (FN)	True negative (TN)
		P_{total}	N_{total}

Figure 10. Confusion matrix defining the four possible states used for the ROC prediction (modified from Persson and Stevens 2012).

$$\text{ROC-Sensitivity} = \frac{{}^{n}FN}{{}^{n}TN + {}^{n}FN} \tag{9}$$

$$\text{Specificity} = \frac{{}^{n}TN}{{}^{n}TN + {}^{n}FP} \tag{10}$$

Finally, the distribution of QCSI relative to the sizes and geometries of known quick-clay deposits (e.g. from SOU, 1962) and landslide scars (SGI, 2011) indicating quick-clay presence were then less formally compared.

3.2. Electrical resistivity tomography

Continuous electrical resistivity sections were measured using ABEM SAS 4000 and ABEM LS Terrameter instruments and multi-electrode Gradient, Wenner and Dipole array protocols (Paper I), typically resulting in approximately 200 data points per 100 m of measured section. The electrode spacing was varied between two and five meters. Induced polarization (IP) was measured as a complement at one locality. Inversion of measured resistivity and IP pseudo-sections were done mainly using the robust L1 norm in Res2dInv 3.59 (Loke, 2010) for sharp geological contacts and smooth modeling for salinity variations in clay porewater. Some complementary refraction seismic surveying was done using ABEM Terraloc Mk6 and Mk6 v.2 multi-geophone acquisition systems. Locally available geotechnical information (specified in paper I) was used for model validation, calibration and to support the interpretations of geophysical data.

3.3. Type-setting classification

Accessible information on stratigraphy, quick-clay susceptibility, leaching trends, shear strength variations and hydrogeology from modeling, geophysical surveying, literature and geotechnical records were used to define quick-clay type settings. These illustrate the conditions and processes under which quick clay form without the technical complexity of the MCE modeling. Also other variations in geotechnical character that can relate to geological and geomorphological circumstances were addressed within the framework of type settings.

The type settings were also used to compare the Swedish quick-clay occurrences with similar deposits in the St. Lawrence lowlands in Canada, mid-Norway and southern Norway (Paper V).

3.4. Landslide retrogression potential

To effectively take advantage of the components described in sections 3.1–3.3, a partly new slope stability classification scheme was suggested (Figure 11; Paper IV) and demonstrated in the Göta älv River–Slumpån Stream confluence, where previous investigations (e.g. SGI, 2012c) have produced good documentation. This scheme combined the current mapping strategies used by sub-

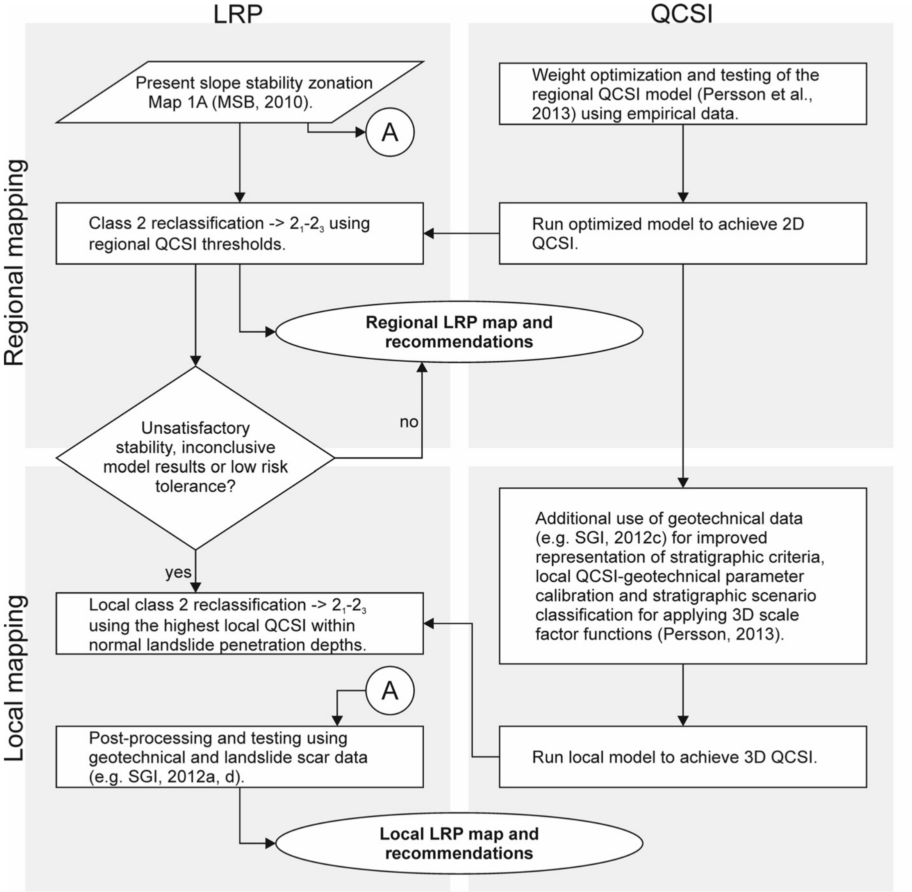


Figure 11. Swedish stability mapping strategy (MSB, 2010) with proposed model-driven refinements.

contractors under the Swedish Civil Contingencies Agency and the 2D and 3D versions of the QCSI model from this work. By looking for areas that are of low initial stability (MSB class 1; MSB, 2010) and overlapping high QCSI values, the MSB class 2 was redefined and sub-divided to include the varying potential of areas to be involved in secondary landslide developments.

4. Results

The results from papers I–V and an earlier, research project report (Persson and Stevens, 2012) are briefly summarized. The interested reader is referred to the full papers and the report for additional details.

4.1. Quantity and position of quick deposits

The importance of stratigraphy for quick-clay formation is clear, especially if the details of individual sites are considered. The effect of permeable layers within the clay sequence has an exceptionally high, modeled weight (38%), reflecting its strong impact on the clay shear strength properties. This impact decreases with distance from such layers, but can often be distinguished in geotechnical soundings up to 10 m from the stratigraphic contact. Other criteria of strong impact are *Relative relief* (13%) and *Distance to glaciofluvial deposits* (12%). The two criteria of the least importance of those modeled are *Distance to bedrock* (1.9%) and *Aquifer thickness* (4.2%).

The majority of the investigated land area (81 %; Figure 12) is characterized by bedrock, sediment unlikely to cover clay, or situated above the marine limit, and therefore lacking quick-clay susceptibility. Of the remaining 19% of the land area very high QCSI (>0.40) prevail for ca. 5%. These conditions occur predominantly in the central Bohuslän province and in the Göta älv River valley and parts of its tributary valleys as well as in parts of the Värmland and Skaraborg provinces, chiefly in areas below the ca. 7 ka shoreline. QCSI and quick-clay deposits are limited to the south, east and north by the shortage of late-Pleistocene and Holocene marine sequences. Also, in the Dalbo and Vara areas, west and south of Lake Vänern, respectively, the low relief is associated with low leaching effects.

The 3D model results (Figure 13) show that in certain, favorable stratigraphic intervals the sensitivity values are frequently over ten times or more of the original background sensitivity of normal clay in the Gothenburg area (i.e. *St* =

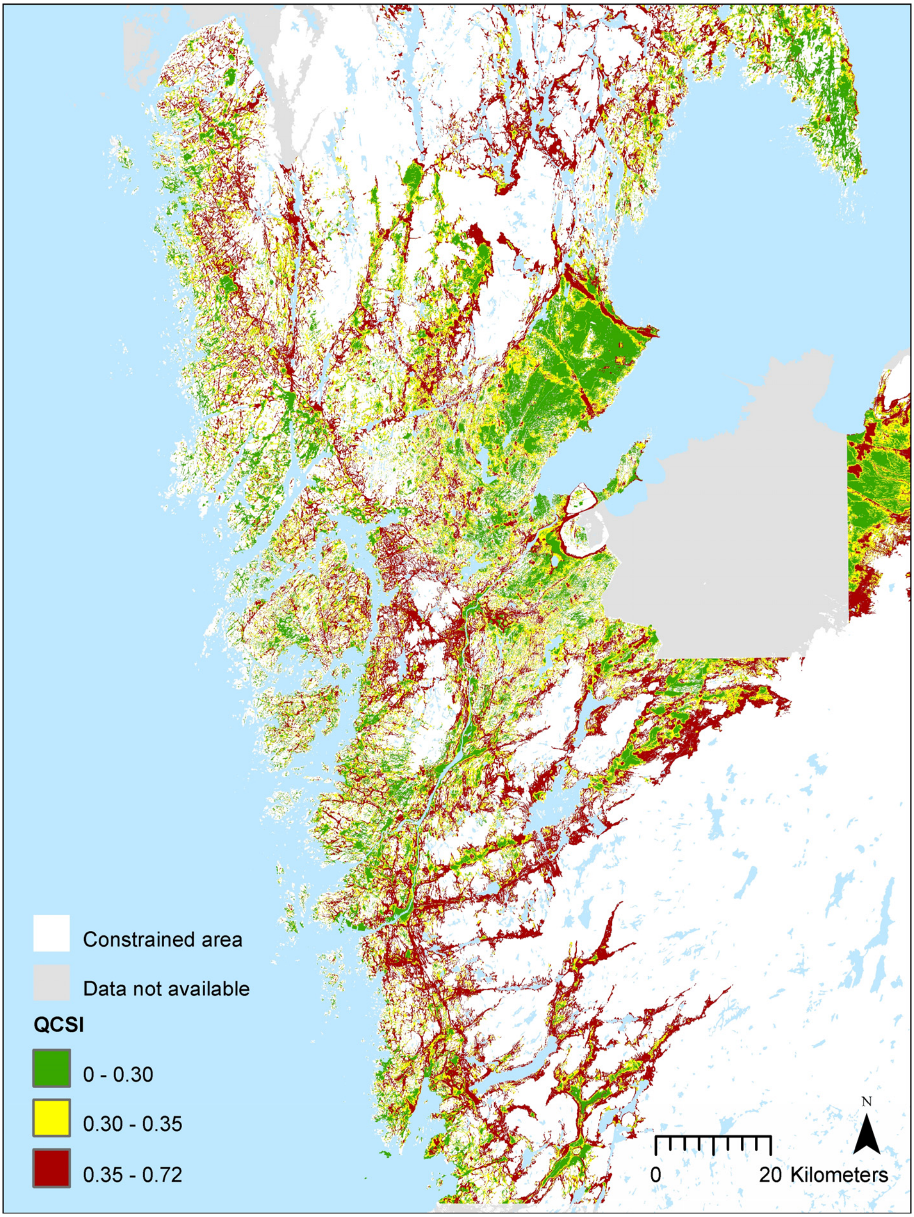


Figure 12. Regional map of QCSI values presented for demonstrative purposes. At this map scale, practical use should not be attempted.

15–25). Areas with clay directly resting on bedrock are characterized by only small deviations from the background sensitivity and are only rarely quick. The thickness of the affected volume is greatest where clays overly glacial drift, while the highest sensitivity values are reached next to sand inter-layers. In the latter situation, the sensitivity maxima tend to be below the layer. In this position the vertical component of pressure gradients related to the layer and overpressure effects from the drift aquifer beneath potentially interacts to amplify leaching influences.

Using the modeled spatial and stratigraphic distribution of QCSI and transformation to corresponding sensitivity values using a simple equation (Figure 15) for the ~8.5 km^3 of clay sediment represented in the Gothenburg area, approximately 70% of the geographic points in clay areas that have a sensitivity of over 50 somewhere at depth. If the sample distribution of Figure 12 and Figure 17 is considered then the proportion corresponds to ca. 50% which still is, for reasons given in section 5, an overestimation. If instead the function based on geometric mean of samples in Figure 15 is used, a more moderate 28% of points are predicted to be quick. In either case, the upper 5–15 m depth interval is suggested by the model to contain a majority of all quick data points.

A similar 3D QCSI framework, although with a larger amount of empirical inputs was utilized also in the Göta älv River–Slumpån Stream confluence area. The frequency of high very high mid-valley sensitivity values (sometimes >600) is explained by a locally occurring clay interlayer likely composed of fine sand.

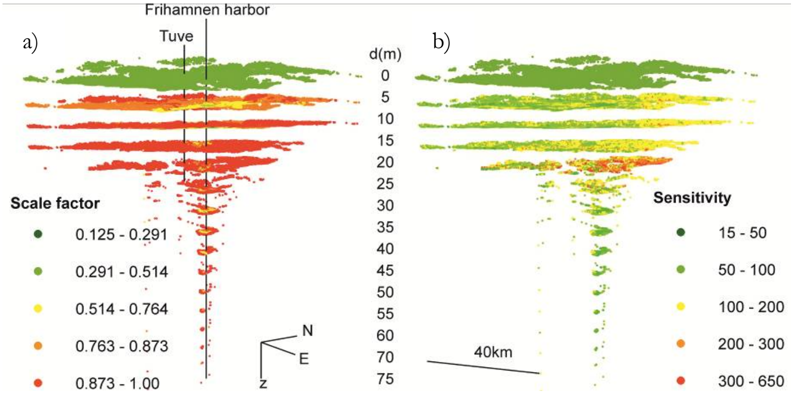


Figure 13. Layered maps of scale factors and sensitivity predictions derived from QCSI$_d$ (modified from paper III). The topography of each layer is represented (only slightly visible) on the vertical scale for orientation. The spacing between layers is exaggerated. The spectator view is toward the northeast. Maps are presented only for demonstrative purposes. At this map scale, practical use should not be attempted. A separate more detailed example is given in Figure 14.

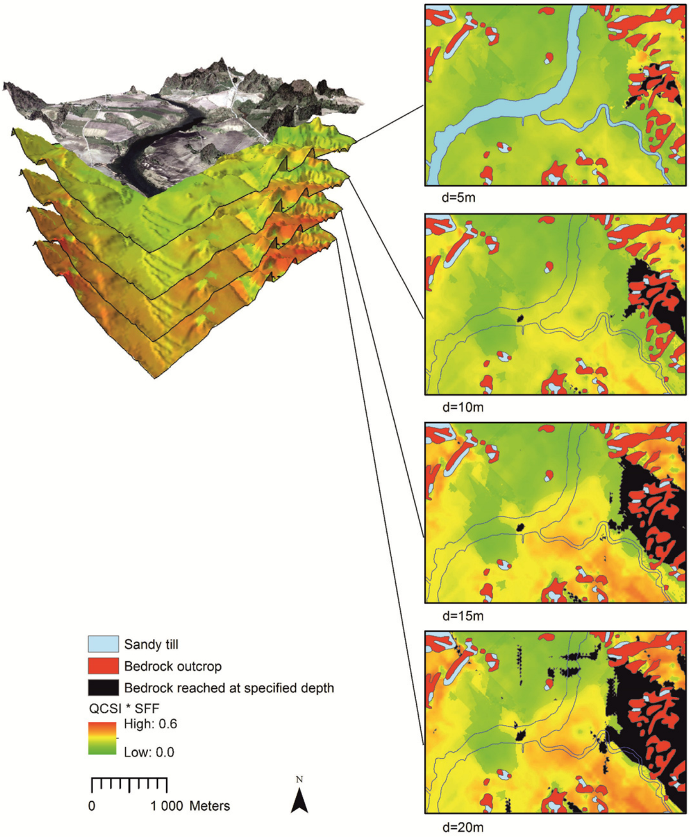


Figure 14. A area (the Göta älv River-Slumpån confluence area) selected to illustrate detail of predicted 3D quick-clay extent that would not be visible on the scale of Figure 13. Practical use should only be attempted by experienced users with insight into the nature of the model (including its strengths and weaknesses).

Also the northeastern parts of the study area have been exposed to extensive leaching with correspondingly high sensitivity values although here related to groundwater movement in and near the sub-clay aquifer.

4.2. Model reliability

Model testing was focused largely on validating QCSI relative to geotechnical data. Model performance is summarily presented here while more discussion is given in section 5 and in Papers II, III and IV. The additional result comparisons between QCSI and ERT are presented separately in section 4.4 (below).

All known quick-clay areas except for those in the central valley setting at Slumpån are closer than 400 m to areas of very high QCSI (>0.5). Areas of generally high QCSI (Figure 12; Paper II) are consistent with documented quick-clay areas in Småröd (survey references listed in section 3.1.7), at Hogstorp (Andersson-Sköld et al., 2005), in the Vesten–Intagan stretch along the Göta älv River immediately north of the Slumpån confluence (SOU, 1962; SGI, 2012a), at Utby west of the same confluence (Söderblom, 1969; 1974) in the Göta–Lilla Edet area east of the Göta älv River (Söderblom, 1969; 1974 and survey references listed in 3.1.7.), Ellesbo on the western side of the Göta älv River (Söderblom, 1969; 1974), in the Surte–Agnesberg area (SOU, 1962; Andersson-Sköld et al., 2005), in quick-clay areas documented in conjunction with landslide events along the Göta älv River valley (SGI, 2011) and inside and surrounding the Tuve landslide area (Cato, 1981).

Empirical information and modeling results are less in agreement in the low-QCSI–high sensitivity areas in mid-valley locations of the Göta älv River–

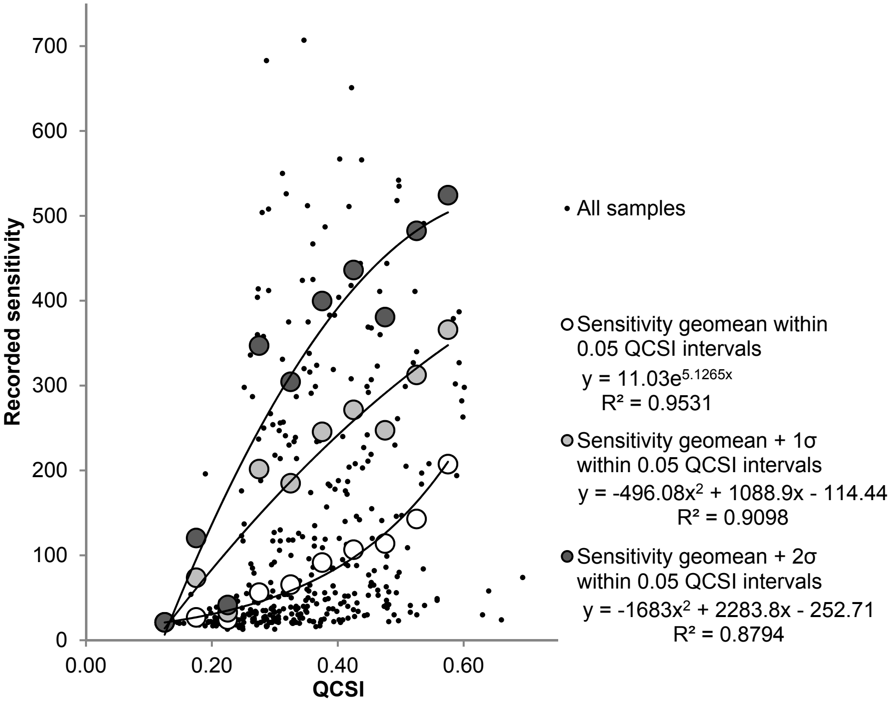


Figure 15. Distribution of sensitivity results from laboratory fall-cone test records vs. QCSI. The correlation coefficients values (R^2) using both individual sensitivity observations and geometric means of sensitivity values within 0.05 QCSI intervals are indicated (reprinted from Paper III).

Slumpån Stream confluence. This is likely due to underestimated importance of a local permeable layer, further discussed in Paper IV. In the Lödöse area, poor agreement may be due to dispersants in the soil (Söderblom, 1969). Model revision with additional data is the ideal approach to such issues, as is illustrated for the Slumpån example (section 4.3).

In detailed comparisons to geotechnical core sample data it is clear that medium sensitive samples are concentrated toward the lower QCSI range (<0.20) while quick samples are at the other end of the scale (>0.30). High-sensitive samples (which by SW Swedish standards are quite modest) are the most common and plots over the entire QCSI interval.

The stratigraphic scenarios used for the 3D modeling (Figure 16; Paper III)

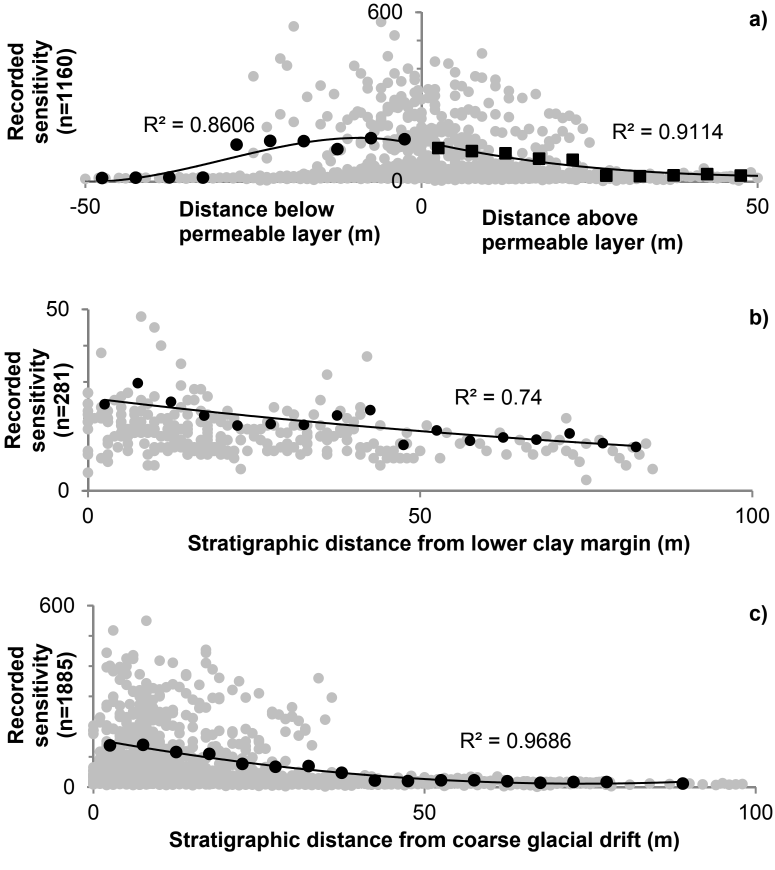


Figure 16. Sensitivity distribution trends for stratigraphic scenarios from geotechnical records. Grey points = all comparison data, black points = geometric mean + 1σ for 5 m depth intervals. Simplified from Paper III, where line equations values are given. Note that the vertical scale *(St)* is different in b).

show a similar scattered distribution of the unclassed sensitivity data and a much better correlation for the QCSI-classed population.

Based on the geographic distribution of individual QCSI classes (Figure 12) and their class-wise distribution of sensitivity (Figure 17), it is predicted that ca. 3000 km^2 of southwestern Sweden contain quick-clay deposits at some depth interval. Low-sensitive samples (*St* <8) have only exceptionally been documented and have never been the predominant sensitivity class in any of the cores studied. Approximately half of the sample population qualifies as quick clay.

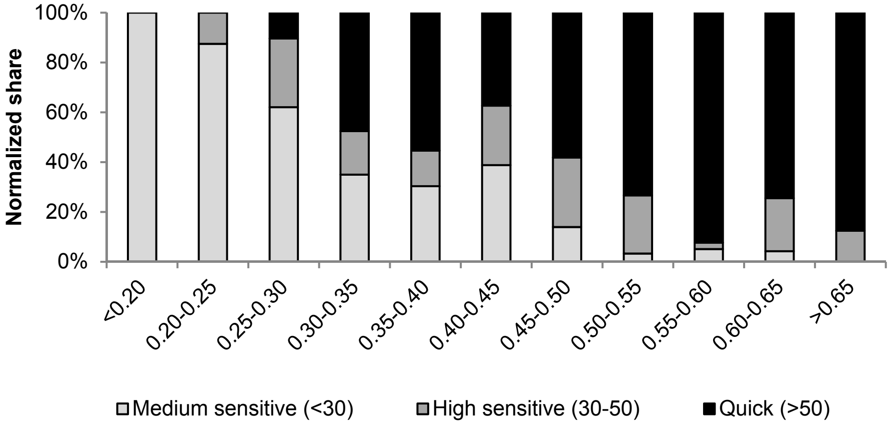


Figure 17. Normalized distribution of observed sample sensitivity class per QCSI class (modified from Paper III).

The QCSI$_\text{d}$ relationships with some geotechnical parameters (i.e. *St*, S_{ur}, W_L and quasi-liquidity index) are shown in Figure 18. Common for all these comparisons is that there is a rather large scatter of data that will diminish if QCSI values are classed (e.g. in 0.05 intervals) with subsequent geometric mean calculations for each class. The correspondence between QCSI and parameters are best for *St* (R^2>0.96)

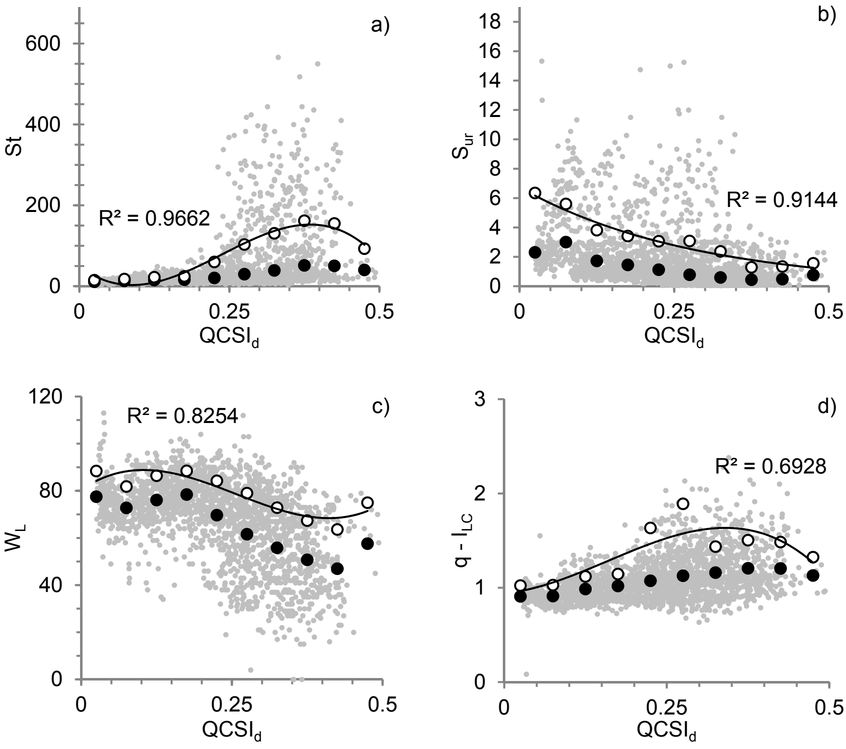


Figure 18. Regionally derived QCSI$_d$ compared to a) sensitivity *(St)*, b) remoulded undrained shear strength *(S_{ur})*, c) liquid limit *(W_L)* and d) quasi-liquidity index, all of which have earlier been linked to landslide retrogression developments. R^2 values are for the geometric mean + 1σ populations. Data references are given in section 3.1.7.

The area under the ROC curve for the full model is close to 0.73, which together with the asymptotic significance suggests a model that performs considerably better than guessing. Using the Swedish quick-clay definition, ~75 %

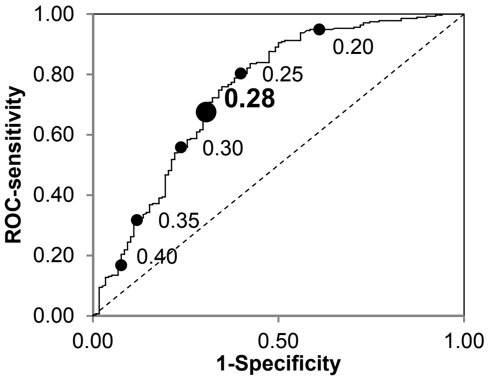


Figure 19. Receiver operating characteristics for the 2D QCSI model. Numbered black dots indicate QCSI thresholds. The bold dot serves as an example within the text.

correctly classified quick samples are reached at a 0.28 QCSI cut-off (Figure 14). At the same QCSI threshold ~63 % of the non-quick samples are correctly classified. Notches in the ROC curve is inherited from that each line segment is produced by two, by QCSI, nearby samples of varying sensitivity.

4.3. Landslide retrogression potential

Large parts of the Göta älv River–Slumpån Stream confluence area are susceptible to landslides (cf. Figure 5d) and quick-clay occurrences have been documented, e.g. by SGI (2012b, c) and the Swedish Road Administration (VV, 2007d & 2008b). Landslide scars are focused to the lower reach of the Slumpån Stream. Several of these (where the largest is ca. 300,000 m^2) have a bottle-necked morphology typical of quick-clay flow slides with a highly remoulded sediment with very low residual strength. The local QCSI$_d$ modeling (Figure 14) and stability evaluation together imply that the potential for landslides to propagate is high. Even with poor overall stability, the worst initial conditions are along the lowermost Slumpån Stream banks, while landslide retrogression is mostly expected in the orange areas denoted 2^1 (cf. Figure 20).

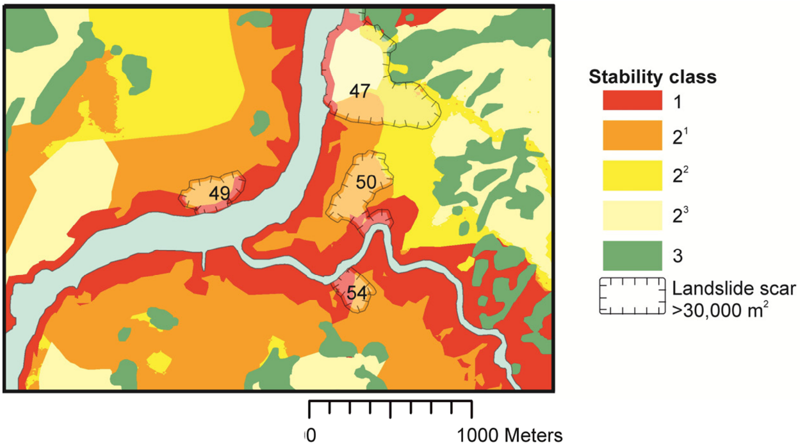
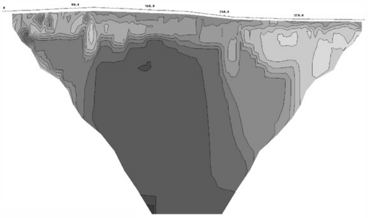
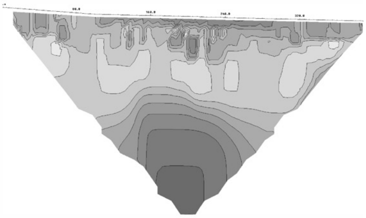


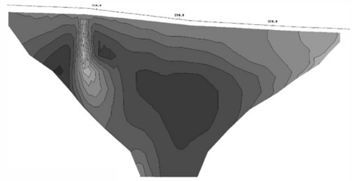
Figure 20. Landslide hazard map over the Göta älv River–Slumpån Stream confluence area derived by combining the current mapping praxis (MSB, 2010) with the QCSI results (Figure 17) so that the original stability class 2 (i.e. areas that could be secondary affected by landslide propagation) is expanded to include 2^1, 2^2 and 2^3, all with varying possibilities for landslide propagation. Class 1 = areas where initial landslides can occur; class 3 = solid ground, mainly bedrock or till outcrops.

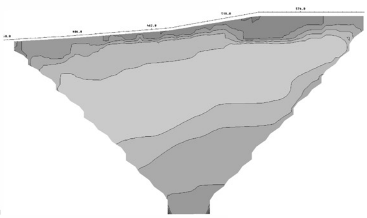
4.4. Resistivity of some SW Swedish sites

Seven electrical resistivity sections (five from Paper I and two unpublished) that illustrate different characteristics (e.g. stratigraphy and leaching effectiveness) of the sedimentary type settings (Paper IV) are shown in Figure 21. In all of the studied sites there is an upper, <7 m leached zone where clay resistivity is relatively high (ρ~10–100 Ωm). It is also evident that in thick sequences (>40 m), there is a central zone with resistivity very close to that of seawater (ρ~1


Bellevue, Gothenburg, 400x70m


Kåhögs gård, Partille, 400x70m


Hjärtum, Lilla Edet, 400x70m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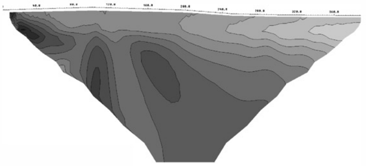
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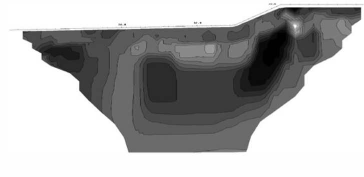
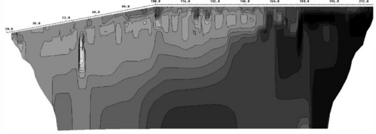

Earth Science Centre, Gothenburg, 80x12m


Lindome church, Mölndal, 200x13m

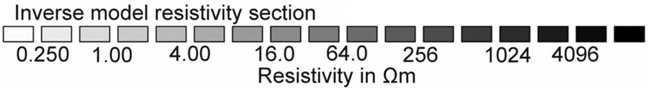


Figure 21. Resistivity sections. Dimensions are given in the format: Section length x Maximum depth penetration. Note the vertical exaggeration.

Ωm). All locations have a lower zone, often approximately 10 m from the till or bedrock aquifer and up, where resistivity values are comparable to the upper zone. Although the permeable interlayers are too thin (often <0.1 m thick) to be resolved by resistivity measurements the leached zones related to them are visible as high-resistivity areas in the resistivity sections. These often stretch from 10 m above to 10 m below the permeable layers. These conditions occur in the Torpa and Kåhög sections where QCSI values are low (<0.25). Quick-clay formation by leaching in these two sections is considered unlikely to have occurred. This is further supported by geotechnical documentation (VV, 2008b; BV, 2002). Quick clay has, on the other hand, developed close to the resistivity sections in conjunction with coarse glacial sediments and related permeable layers within and below the clay deposits. The Hjärtum, Agnesberg and Bellevue sections have higher resistivity, for the most part coinciding with values common for quick clays (cf. Lundström et al., 2009). The QCSI values here follow the general resistivity trends and are mainly over 0.30. Both the Agnesberg and the Lindome sections imply extensive leaching near the icefront deposits and then successively higher porewater salinity with increasing distance.

4.5. Quick-clay type settings

A classification of type settings for quick-clay development is based upon their varying hydrogeological and leaching character (Figure 22). It is favorable for this classification that the common range of stratigraphic conditions and the number of processes involved are conceptually limited (Figure 23). The first three settings (*Areas with significant coarse-grained glacial drift deposits, Wave exposed areas* and *Valley-marginal sites and narrow valley settings*; sections 4.5.1–4.5.3) are characterized by effective groundwater pathways (cf. Lefebvre, 1996) and leaching. For this reason, the clay sensitivity values often significantly deviate from that of unaffected clay (*St*~20), where *St* >100 and, in extreme cases, *St* >600 are observed. The high sensitivity values are largely due to very low remoulded shear strength, occasionally below the feasible detection limit of ~0.06kPa.

The fourth type setting (*Central valleys and lowlands*; section 4.5.4) has low to moderate potential for quick-clay formation. Medium and high sensitivity values can be expected in most of the stratigraphy, while quick and low sensitive clay are more exceptional.

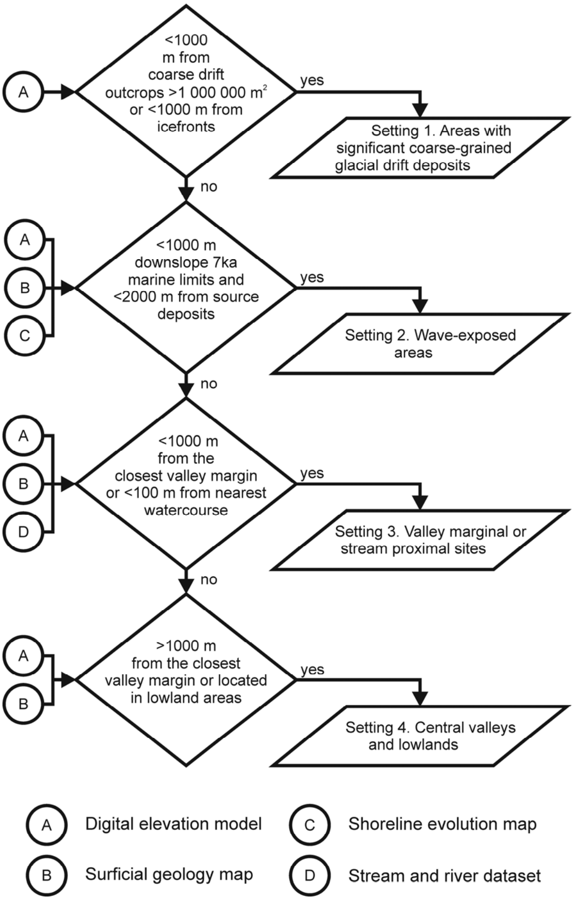


Figure 22. GIS workflow and geographic thresholds for classification of quick-clay type settings (reprinted from Paper V).

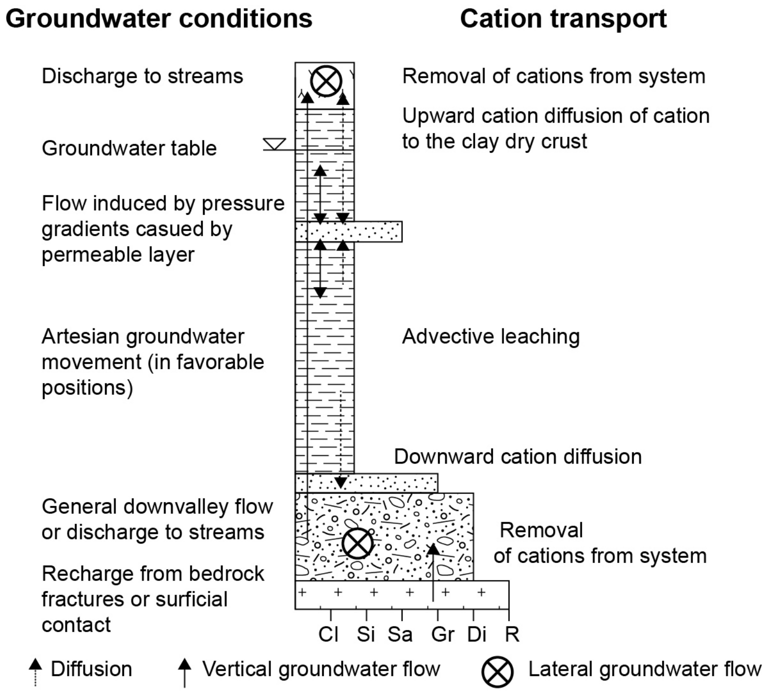


Figure 23. Hydrogeologic features and processes that vary between the type settings described above (modified from paper V).

4.5.1. Areas with significant coarse-grained glacial drift deposits

Several quick-clay prerequisites are well represented in the two principal sub-types of this setting: glacial stoss-side valley positions and icefront positions.

In the icefront case, both the ice-distal and ice-proximal sides of moraines are often associated with relatively thick drift deposits (alternating sandy till and glaciofluvium). The drift can be in direct contact with surficial and buried water sources. Infiltration occurs in the coarse sediments, which usually have at least five orders of magnitude higher permeability than the homogenous clay upward in the stratigraphy. Effective groundwater pathways associated with the lower drift aquifer favor high groundwater fluxes and extensive advective leaching of the originally marine porewater in adjacent clay deposits. Quick-clay deposits related to this setting are often landslide prone, especially where moraines and the related sensitive deposits are intersected by river and stream erosion and where initial slumps may set off retrogressive landslides. The icefront sub-type is exemplified by the Agnesberg area, which is ice-distal to the Gothenburg Moraine, just south of the Angered Bridge. The local stratigraphy and a high relief assure groundwater flow through the underlying aquifer and artesian conditions that affect the overlying clay. With distance from the former icefront clay sensitivity gradually decreases from *St* >200, reaching a non-quick, medium to high sensitive background value (*St* ~25), ca. 700–1000 m south. Further technical details of the area are given by SOU (1962), Larsson et al. (1994), BV (2008), Schälin & Tornborg (2009) and SGI (2012b, c).

Stoss-side deposits occur where glacial movement impinged on topographic obstructions, causing basal melting and release of debris carried by the ice. Drumlin formation in SW Sweden is often due to stoss-side deposition (Hillefors, 1969; Davidsson, 2005). These deposits may facilitate infiltration and provide the groundwater pathways beneficial for quick-clay development in a manner similar to the ice-front sub-type. Leaching is most effective in the clay directly overlying and, to some extent, confining coarse drift aquifers. Landslides involving quick clay in these areas are generally rare but may occur where local erosion is active or where redesign of slopes has occurred (cf. SHK, 2009). Quick clay is documented in individual geotechnical sections of this type of setting. The stoss-side setting is exemplified by the area between the Hjärtum village and the Göta älv River. The village itself is built on the Hjärtum drumlin, where sandy till is abundant (Hillefors, 1969; SGU, 2012a). The effective groundwater movement, typical of the type setting, resulted in extensive leaching of porewater cations and low electrical resistivity in the clay deposits. The stratigraphy, stability conditions and landslide history of the area are known from geological, geotechnical and geophysical fieldwork (Frödin, 1919; Klingberg et al., 2006; and Karlsson, 2011; Löfroth et al., 2011; SGI, 2012a-c).

4.5.2. Wave-exposed areas

At many sites, the local topography allowed extensive wave re-working of coarse deposits (e.g. till) on nearby slopes during the emergence. Re-deposition of silty-sandy material at lower elevations within or on top of the clay sequence was especially favored during virtually stagnant or slow regressive shore-level episodes, primarily at about 7 ka. This sea level corresponds to topographic levels ca. 20 m a.s.l. in the Gothenburg region and increasing northward to ca.

50 m in Strömstad near the Swedish–Norwegian border). There is a general increase of wave exposure northwards in the study area, although some areas further south have also been significantly affected. Effective groundwater flow will later be partly dependent on the possible connectivity of the interbedded layers with other permeable deposits or with the stream bank. Groundwater flow in permeable layers facilitates the removal and exchange of cations necessary for quick-clay formation. The landslide susceptibility of this setting is high since the hydraulic pressures within the permeable layers also promote landslide activity. Stream proximity further increases the risk for unstable slopes and mass wasting processes.

An example of this type setting is found at the Göta älv River-Slumpån Stream confluence. Infiltration occurs in the sandy till, exposed mainly in higher-lying areas (Hillefors, 1969; SGU, 2012a) and near minor ice-front positions mapped by Fredén (1984). In this area, inter-clay, permeable silt and sand layers allow groundwater transport. Local brittle deformation zones may further increase the groundwater fluxes of the area (SGU, 2010). The extent of quick deposits is commonly limited to clay volumes within a 10 m stratigraphic distance from the permeable materials. The stratigraphy and geotechnical character have been dissected by Klingberg et al. (2006), VV (2008b) and Malehmir et al. (2013). Landslide scars are locally very common (Frödin, 1919; Järnefors, 1958 Viberg, 1982).

4.5.3. Valley-marginal sites and narrow valley settings

Several hydrogeological and sedimentological characteristics of this type setting promote quick-clay formation. First, the generally limited clay thicknesses can allow the stream erosion to reach coarse glacial sediments and increase drainage to groundwater pathways. Second, both leaching and cation diffusion will be more effective in relatively thinner clay sequences. Third, high local relief results in high-pressure gradients and can induce artesian flow. Fourth, the valley geomorphology favors icefront and stoss-side sedimentation as well as glacial meltwater-channels, so that conductive coarse deposits are common. The setting can coincide with type 1 setting, but this type setting help detect icefront or stoss-side deposits not identified on geological maps. Fifth, groundwater flow is focused where valleys converge and can be expected to accelerate leaching. The entire clay sequence may be affected by quick-clay development. There is generally a high likelihood for quick-clay deposits to occur and for these to be involved in initial slumping because quick clays here are often located at shallow depths and relatively close to streams.

The Bellevue area, located north of the Säveån stream in eastern Gothenburg, exemplifies this type setting. A small hill (Officerskullen) with bedrock exposure is located centrally in the area, where the Säveån valley is relatively narrow. Clay deposits, which are up to 50 m in thickness, overlie ca. 30 m of glacial drift material. This great thickness is, in SW Sweden, almost always associated with icefront and stoss-side accumulations. Officerskullen and a neighboring bedrock hill focus groundwater flow along pathways that are in contact with the clay. Quick clay has predominantly developed here on the western and northern sides of the Officerskullen. Further details on sedimentary conditions are given by Stevens (1986) and Karlsson (2010). Geotechnical surveying has been done preceding recent construction (Gatubolaget 2008).

4.5.4. Central valleys and lowlands

This low-relief type setting differs from all the others in that it aims at defining areas with lower than normal quick-clay susceptibility. Several paleogeographic, geomorphologic and geochemical conditions may impede quick-clay development. Quick clay forms less efficiently here because both continuous permeable deposits and high hydraulic gradients are less common. Leaching by downward infiltration of freshwater (as reported from eastern Canada by Torrance, 1988) might be the dominating leaching pathway in places but is interpreted to had only minor impacts on sensitivity values and the remoulded shear strengths of samples used for our comparisons. Sensitivity values are commonly below 30. The highest sensitivity values typically occur at depth, overlying drift deposits, or near the surface, immediately below the dry-crust. Undisturbed shear strength increases with depth from ca. 10 kPa near the surface to over 100 kPa at great depths (>60 m). The remoulded shear strength ranges from near 0 to about 10 kPa. The landslide susceptibility is very low for the most part. Locally (e.g. south to southwest of the Västgöta plateau mountains), carbonate rich sediments may occur and impact on both the extent of flocculation and the sediment water geochemistry, consequently affecting the sensitivity ratio.

Low relief characterizes the main part of the area south of Kåhögs farm, ca. 10 km east of Gothenburg in the central Säveån stream valley. Medium sensitive clay predominates and quick-clay deposits are limited to areas very close to glacial drift outcrops (SJ, 1989; BV, 2002). A resistivity section from the valley center indicates resistivity close to that of sea water (Persson & Stevens, in press). Previous landslides and occasional quick-clay deposits are known from the areas east and south of Kåhög (SJ, 1922; SGI, 2011).

5. Discussion

The dynamic nature of quick-clay formation is a spatiotemporal problem, where leaching and other processes as well as time need to be considered. Quick clay forms from clays with a low or medium sensitivity at varying rates. Factors influencing the rate of formation include the anisotropic nature of stratigraphy (i.e. groundwater regimes and leaching pathways) and the varying degrees of post-depositional processes altering the absolute and relative cation contents. A background sensitivity of 20 is assumed to reflect clays unaffected by leaching. The geotechnical comparison data used in Papers II and III is based on this value, and is comparable to that observed in samples from southern Norway (Bjerrum, 1954). The criteria weights (Figure 7) give a general picture of the importance of the individual criteria. Although initially based upon expert judgment, their subjective character is limited by comparison with empirical data from geotechnical soundings and by the refinements to achieve consistency in the overall model results.

Due to the high variability in sensitivity over short vertical and lateral distances and the resolution and accuracy of the current 2D model it is not surprising that there is a very low correlation when considering the entire geotechnical comparison dataset ($R^2 \approx 0.2$). Consistent with separate observations made by Talme et al., 1966), at least one order of magnitude change in sensitivity can be expected between adjacent cores separated by <100 m in the same stratigraphic unit or <10 m stratigraphically. However, the regional 2D QCSI model intends to predict the most representative sensitivity values for the conditions at a particular site. If model results are correlated using the average sensitivity for all sites within 0.05 QCSI intervals (sites with relatively similar conditions), then the correlation coefficient is very strong ($R^2 \approx 0.9$).

Table 12. Characteristics of model QCSI classes (modified from Persson & Stevens, 2012).

QCSI range	Description	Typical *St*	Typical S_{ur} (kPa)	Area (of total land area)	[1]True positive rate	[1]False positive rate
0.0	No potential for quick-clay formation. Area consists of bare bedrock, sandy till or other unsusceptible sediment.	-	-	81%	1.0	1.0
<0.20	No to very low potential for leaching and quick-clay formation. Porewater salinity is still often marine or near-marine.	10–30	>0.8	<1%	0.99	0.78
0.20–0.25	Low potential for effective leaching and quick-clay formation. Marginal quick deposits may occur.	15–30	0.8	2%	0.87	0.48
0.25–0.30	Intermediate to high degree of leaching expected. Quick clay exists in parts of the area.	30–50	0.5	6%	0.62	0.30
0.30–0.35	High probability for leaching clay to quick behavior.	30–100	0.25	6%	0.34	0.15
>0.35	Very high degree of leaching and other post-depositional processes related to groundwater flow.	15–200	0.12	5%	0.01	0.00

[1] If upper end of the QCSI class is used as ROC cut-off (cf. section 3.1.7).

QCSI model results and the application of these in the LRP mapping have importance as a methodological development and for initial ground characterization. Although the model successfully discriminates between clays of varying sensitivity in a regional context, site-specific interpretations are relevance only if the modeling framework and its limitations are kept in focus. A number of uncertainties need to be considered, for instance:

1) Clay disturbance during sampling, transport and storage generally lower the in-situ sensitivity to values later determined in the laboratory (e.g. Lessard and Mitchell, 1985; Bjerrum and Lo, 1963 and Söderblom, 1969). Similarly, unrecognized clay disturbances in the field related to landslides that have transported and remoulded the most sensitive clays may explain several of the high-QCSI areas where geotechnically documentation indicates low sensitivity

values more typical of non-leached clay deposits (e.g. in known landslide localities in Småröd and in parts of the Göta älv River valley).

2) Non-continuous sampling is common practice, resulting in sensitivity analyzes only at selected levels (i.e. every 1–5 m). Some critical levels, such as depths directly overlying permeable strata may be missed.

3) Clay leaching may be counteracted by the secondary supply of bivalent cations (e.g. Mg^{2+}), for instance from vadose zone processes, fossil dissolution or weathering of Ca-feldspars or other crystalline rock components. This can maintain or even improve the original clay shear strength characteristics. These or similar processes have been reported from the Ottawa valley (Canada; Torrance, 1979), Drammen and Buvika (Norway; Moum et al., 1971; 1972; Solberg pers. comm. 2010) and modeled using SW Swedish input data by Suer et al. 2014. However, the rates and means of the processes that impede or reverse quick clay are generally less understood than the ones forming quick clays.

4) The omission of certain criteria in modeling has been unavoidable (cf. Table 4). Local conditions naturally deviate to some degree from the general assumptions in the regional modeling. Both sources of error can motivate further effort for data improvement and revision of the criteria involved.

5) AHP procedures have been criticized for rank reversal problems (e.g. Belton & Gear, 1982) and for subjective derivation of weights. The method benefits, which I consider outweighs the drawbacks, are often summarized by its transparent structure (allowing model refinement), the opportunities to use most any kind of data or information (including empirical observations, expert judgment and belief) and the user's ability to adapt the model to different purposes.

Future model revision and improvement will need to consider these and other uncertainties, but the natural geographic and stratigraphic variability of sensitivity values suggests that modeled results need to be connected to the goals and conditions of that modeling, and not over-interpreted. Refinements could also involve the balance of advection and diffusion within different hydrogeological scenarios, leading to a better specification of rates and predicted leaching effects.

The 3D modeling includes basically the same strengths and weaknesses as its 2D counterpart. Incorporation of empirical information seems like the best improvement for the highly variable settings. This will require increased digitalization and distribution of existing and new datasets, preferably including 3D coordinates (cf. Rydell & Öberg, 2013).

In selecting a suitable QCSI threshold for practical applications it is important to recognize that this cutoff value is a trade-off between correctly classified quick clays and areas wrongfully designated as quick clay. A low threshold is appropriately chosen if the risk tolerance in a specific project is low (e.g. high-consequence decisions). ROC analysis can be used as the judgment basis, ideally within a local modeling context (cf. Persson and Stevens, 2012). The sensitivity estimates presented in this work (Figure 13) were derived using the regression line equation for the geometric mean + 1σ, considering the low tolerance for incorrect decisions regarding quick-clay occurrences.

The most obvious practical application of model results is toward improving the current Swedish method (MSB, 2010) for slope stability zoning. This is achieved by increasing the quick-clay considerations at an early stage. This is most often the stage when large areas need to be evaluated cost-efficiently, which is a main strength of the QCSI model. In preparation of the geotechnical database used in Papers I–V, it was observed that a high sensitivity is largely caused by low remoulded shear strength in SW Swedish clays, as has been noted previously and elsewhere (e.g. Bjerrum, 1954). Sensitivity, remoulded shear strength and liquid limit have in common that they are all affected by leaching and can, thus, be predicted by using QCSI methods. All of these parameters have also been correlated to the sizes of landslides (Mitchell and Markell, 1974; Larsson et al., 2008; L'Heureux, 2012). Recently, the participants of the *1st International Workshop on Landslides in Sensitive Clays* (2013) favored either a remoulded shear strength of 0.5–1 kPa or a high liquidity index for defining sensitive clays. In Sweden, the plastic limit required for quantification of the liquidity index is only rarely measured. The Swedish Geotechnical Institute has developed a simplified, quasi-liquidity index (quasi-$I_{LC} = W_N/W_L$; cf. Åhnberg et al., 2013) that correlates both to liquidity index and to QCSI. Several other parameters more directly related to the clay's ability to flow or the energy needed to achieve a fully remoulded state (e.g. rapidity and quickness) have been proposed (Söderblom, 1983; Thakur and Degago, 2012). Such parameters could, especially if a sufficient quantity of empirical data is developed, also be included in future LRP mapping.

QCSI and LRP model results can be particularly appropriate in cases where new soundings and analyzes are too demanding because of time, cost or safety aspects (e.g. in initial land-use planning, forested areas, acute safety assessment in landslide area evacuation or with an imminent landslide risk). Also, a structured approach to cross-borehole interpolation can motivate using the model results even where geotechnical data coverage is good. In any application, communication of the methodological limitations is necessary to assure proper use.

When applied, modeling will likely increase the number and size of areas allocated for further, more advanced studies (cf. Skredkommisionen, 1995) especially when a large safety margin is desired (i.e. where society's risk tolerance is low). Costs associated to this increase can be partially balanced by a decreased need for sounding and coring. The overall landslide threat will be better specified because several criteria involved in quick-clay developments also impact on the initial slope stability. In particular, the modeled parameter permeable clay interlayering is very often associated with friction reduction and landslide initiation.

Modeling similar to QCSI could be applied to tackle also other geotechnical problems where different stratigraphic structure is important (e.g. settlement or bank erosion). Water resource and environmental issues often focus on groundwater movement and contaminant spreading in clay, permeable layers, sandy till or glaciofluvial aquifers. Since stratigraphic modeling is seldom attempted in highly variable glacial terrains, such as in SW Sweden, this stochastic, multi-criteria approach may provide new perspectives on basic geologic concepts, testing them against large, spatial datasets.

6. Conclusions

Southwest Swedish quick and non-quick clay deposits are more similar than they are different, both during and after deposition. The basic quick-clay prerequisites (e.g. sedimentation and subsequent leaching of low-active glaciomarine and marine clays) are found over the entire region, but the degree and means of cation leaching vary with local geological and environmental conditions.

Quick-clay formation has usually been most effective where clay overlies coarse glacial sediments or where clay sequences are interrupted by continuous silt or sand layers, both situations allow for advective groundwater flow within or adjacent to the clay. In fact, the single most important criterion dictating stratigraphic and lateral quick-clay distribution within SW Sweden, especially in relatively shallow, vulnerable positions, is the presence of permeable layers.

The use of stratigraphic knowledge in a semi-quantitative way to specify leaching vulnerability is the most novel aspect of this modeling. The benefits from using modeling in quick-clay work also include: 1) that the model surveying can be done over study areas from local to regional scale, 2) the stability of sensitive areas is not further aggravated by machinery, 3) both qualitative information and observational data are taken advantage of, 4) new insights into conceptual assumptions are possible through model testing, and 5) model transparency facilitates incorporation of new data or process components.

The largely conceptual 2D model is successful at predicting the average sensitivity or remoulded shear strength trends within the study area. The complementary relationships between geotechnical investigations, geophysical resistivity measurements and the QCSI model suggest that the results from these separate methods should be used to strengthen their individual and mutual interpretations and the data input requirements of each method.

The current model is a step towards incorporating 3D quick-clay predictions in hazard-mapping applications. The results, which are based on a simplified stratigraphic model, cannot replace traditional mapping methods. In practice, information that enables result interpretation and avoids misunderstandings should be clearly given and attached to maps. There is, nevertheless, a complementary relationship between modeling and empirical documentation that underscores the need for both and the possibilities for combined assessments with an increasingly holistic (3D) character. The model has been constructed for and tested in southwest Swedish settings but is applicable in other geologically similar areas, and elsewhere with modification.

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8. References

Andersson–Sköld, Y., Torrance, J. K., Lind, B., Odén, K., Stevens, R. L., & Rankka, K. (2005). Quick clay–a case study of chemical perspective in southwest Sweden. *Engineering Geology 82*, 107–118.

Andersson –Sköld, Y. (2011). *Metodik för inventering och värdering av konsekvenser till följd av skred i Göta älvdalen* (GÄU interim report 12). Linköping: Swedish Geotechnical Institute.

Ayalew, L., Yamagishi, H., Marui, H., & Kanno, T. (2005). Landslides in Sado Island of Japan: Part II. GIS-based susceptibility mapping with comparisons of results from two methods and verifications. *Engineering Geology 81*, 432-445.

Belton. V., & Gear, T. (1983). On a short-coming of Saaty's method of analytic hierarchies. *Omega 11*, 228–230.

Bernander, S. (2011). *Progressive Landslides in Long Natural Slopes - Formation, Potential Extension and Configuration of Finished Slides in Strain-Softening Soils* (Doctoral dissertation). Department of Civil, Environmental and Natural Resources Engineering. Luleå University of Technology.

Berntson, J. (1983). *Portrycksvariationer i leror i Göteborgsregionen* (Licentiate thesis). Gothenburg: Institutionen för geoteknik med grundläggning, Chalmers.

Berry, R.W., & Torrance J.K. (1998). Mineralogy, grain-size distribution and geotechnical behavior of Champlain clay core samples, Québec. *The Canadian Mineralogist 36*, 1625–1636.

Bjerrum, L. (1954). Geotechnical properties of Norwegian marine clays. *Géotechnique 2*, 49–69.

Bjerrum, L., & Rosenqvist, I., Th., (1956). Some experiments with artificially sedimented clays. *Geotechnique 6*, 124–136.

Bjerrum, L., & Lo, K.Y. (1963). Effect of aging on the shear-strength properties of a normally consolidated clay. *Géotechnique 13*:147–157.

Bjørlykke, K.O. (1893). Skredet i Værdalen (pp. 105–112). *Det Norske Geografiske Selskabs Årbog IV 1892–1893.*

Björsjö, N. (1949). *Israndstudier i södra Bohuslän* (C 504). Stockholm: Geological Survey of Sweden.

Brand, E.W., & Brenner, R.P. (1981) *Soft clay engineering* (Developments in Geotechnical engineering 20). Amsterdam: Elsevier.

Brusewitz, A.-M. (1982). Clay minerals and chemistry. In: Olausson, E. (Ed.). *The Pleistocene/Holocene boundary in southwestern Sweden* (C 794; pp. 73–82). Uppsala: Geological Survey of Sweden.

BV. (2002). *Västra stambanan Göteborg – Torp, Partille – Jonsered section.* [Geotechnical survey data]. Swedish Rail Administration.

BV. (2008). *Kil – Göteborg (Agnesberg - Marieholm) section.* [Geotechnical survey data]. Swedish Rail Administration.

Caldenius, C., & Lundström, R. (1955). *The Landslide at Surte on the Göta River* (Report No 27). Stockholm: Geological Survey of Sweden.

Carroll, D. (1959). Ion exchange in clays and other minerals. *Geological Society of America Bulletin 70,* 749-779.

Cato, I. (1981). Kemiska och fysikaliska undersökningar In: *Tuveskredet – geologi* (report 11b, pp. 85-108). Linköping: Swedish Geotechnical Institute.

Cato, I., Fredén, & C., Olausson, E. (1982). Summary of the investigation. In: Olausson (Ed.). *The Pleistocene/Holocene boundary in south-western Sweden* (C 794 pp. 253–268). Uppsala: Geological Survey of Sweden.

Cato, I. (1984). *Survey of potential landslide risk zones in south western Sweden. Striae 19,* 19–24.

Derjaguin, B. V., & Landau, L. D. (1941). Theory of the stability of strongly charged lyophobic sols and of the adhesion of strongly charged particles in solution of electrolytes. *Acta Physicochimica URSS 14,* 633–662.

Dragland, Å. (2013). Big Data, for better or worse: 90% of world's data generated over last two years. *Science Daily* (May 22, 2013). Retrieved from www.sciencedaily.com/releases/2013/05/130522085217.htm

Ells, R. W. (1908). *Report on the landslide at Notre-Dame-de-la-Salette – Lièvre River, Québec.* Ottawa: Canada Department of mines–Geological survey branch.

Erener, A., Lacasse, S., & Kaynia, A. M. (2007). Landslide hazard mapping by using GIS in the Lilla Edet province of Sweden. In: *Proceedings of the 28th Asian conference on remote sensing, 12-16 November 2007,* Kuala Lumpur.

ESRI. (2011). [ArcGIS Desktop 10 Help file]. Redlands: Environmental Systems Research Institute.

Fortin, A., Oullet, D., Paradis, S., & Demers, D. (2008). Développement au Ministère des Transports du Québec d'un portail informatique pour l'accès à des bases de données geotechniques. In: Locat, J., Perret, D., Turmel, D., Demers, D., Leroueil, S. (Eds.). *Proceedings of the 4th Canadian Conference on Geohazards: From Causes to Management.* Québec city: Presse de l'Université Laval.

Frödin, G. (1919). *Jordskreden och markförskjutningarna i Göta älvs dalgång.* (Meddelanden 19, 80pp). Uppsala: Kungliga Vattenfallsstyrelsen.

Gatubolaget. (2008). Kvibergsstaden. [Geotechnical survey data].

Gregersen, O. (1981). *The Quick Clay Landslide in Rissa, Norway-The Sliding Process and Discussion of Failure Modes* (Publication 135). Oslo: Norwegian Geotechnical Institute.

Göransson, G., Bendz, D., & Larson, P. (2009). Combining landslide and contaminant risk: a preliminary assessment: A study of the Göta Älv river Valley, Sweden. *Journal of Soils and Sediments 9*, 33-45.

Hardcastle, J. H., & Mitchell, J. K. (1974). Electrolyte concentration-permeability relationships in sodium illite-silt mixtures. *Clays and Clay minerals 22*, 143–154.

Hartlén, J., Alén, C., Högsta, U., Nordal, S., Sällfors, G., & Jendeby, L. (2007). *Skredet i Småröd december 2006. Rapport 1. Analys av skredorsaken.* Vägverkets oberoende utredningsgrupp.

Hillefors, Å. (1969). *Västsveriges glaciala historia och morfologi* (Doctoral Dissertation 60, 319pp). Lund: Lunds universitets geografiska institution.

Hultén, C., Olsson, M., Rankka, K., Svahn, V., Odén, K., & Engdahl, M. (2006). *Släntstabilitet i jord. Underlag för handlingsplan för att förutse och förebygga naturolyckor i Sverige vid förändrat klimat. Deluppdrag 1* (Varia 560:1). Linköping: Swedish Geotechnical Institute.

IBM. (2011). SPSS Statistics for Windows, Version 20.0 Software manual. Armonk, NY: IBM Corp.

INSPIRE, (2007). Directive 2007/2/EC of the European parliament and of the council of 14 March 2007 establishing an Infrastructure for Spatial Information in the European Community (INSPIRE). *Official Journal of the European Union, L108,* 1–14.

Jakobson, B. (1952). *The Landslide at Surte on the Göta River.* (Proc. No 5). Stockholm: Royal Swedish Geotechnical Insitute.

Järnefors, B. (1957). *Skredet vid Intagan år 1648* (Report C539). Stockholm: Geological Survey of Sweden.

Järnefors, B. (1958). *Quaternary deposits in the Göta älv Valley* [Geological map BA 20]. Stockholm: Geological Survey of Sweden.

Kalscheuer, T., Bastani, M., Donohue, S., Persson, L., Pfaffhuber, A., Reiser, F., & Ren, Z. (2013). Delineation of a quick clay zone at Smørgrav, Norway, with electromagnetic methods under geotechnical constraints. *Journal of Applied Geophysics 92,* 121–136.

Karlsson, L. 2011. *Stratigraphic boundaries determined by P-wave and S-wave refraction surveys in the Göta älv valley at Hjärtum, Lilla Edet municipality* (Department of Earth Sciences MSc thesis B630). Gothenburg: University of Gothenburg.

Karlsson, R. (1981). *Consistency limits. Performance and interpretation of laboratory investigations, part 6*. (Document; D9:1981) Stockholm: Byggforskningsrådet.

Karlsson, R., & Hansbo, S. (1989). *Soil classification and identification* (Document D8:1989). Stockholm: Byggforskningsrådet.

Keeney, R. L., & Raiffa, H. (1993). *Decisions with Multiple objectives: Preferences and Value Trade-Offs*. Cambridge: Cambridge University press.

Klingberg, F., Påsse, T., & Levander, J. (2006). *Bottenförhållanden och geologisk utvecklingen i Göta älv* (report K-43). Uppsala: Geological Survey of Sweden.

Komac, M. (2006). A landslide susceptibility model using the analytical hierarchcy process method and multivariate statistics in perialpine Slovenia. *Geomorphology 74*, 17–28.

Larsson, R., Sällfors, G., & Ottosson, E. (1994). *Agnesbergsskredet* (Report 44). Linköping: Swedish Geotechnical Institute.

Larsson, R. 2008. *Jords egenskaper* (Information 1). Linköping: Swedish Geotechnical Institute.

Larsson, R., Bengtsson, P. -E., & Edstam, T. (2008). *Vägbyggande med hänsyn till omgivningens stabilitet* (The Swedish Road Administration region west assignment number 13494). Linköping: Swedish Geotechnical Institute (for The Swedish Road Administration).

Larsson, R. (2010). *Inverkan av förändringar I porvattnets kemi – främst salturlakning – på naturlig leras geotekniska egenskaper. Litteraturstudie.* (Varia 611, 37 pp.). Linköping: Swedish Geotechnical Institute.

Lefebvre, G. (1996). Soft sensitive clays. In: Turner, A. K., Schuster, R. L. (Eds.). *Landslides: Investigation and Mitigation.* (TRB Special Report, 247) Washington: National Academy Press.

Lerman, A. (1979) *Geochemical Processes: Water and Sediment Environments.* (481 pp.) New York: John Wiley.

Lessard G., & Mitchell, J. K. (1985). The causes and effects of aging in quick clays. *Canadian Geotechnical Journal 22*, 335–346.

LESSLOSS. (2007). Application of landslides zonation techniques to study areas. European Union Sixth framework programme (Deliverlable 94).

L'Heureux, J.S. 2012. A study of the retrogressive behavior and mobility of Norwegian quick-clay landslides. In: Eberhardt, E. Froese, C. Turner, A. K., & Leroueil, S. (Eds.). *Landslides and Engineered Slopes: Protecting Society through Improved Understanding* (Proceedings of the 11th International Symposium on Landslides and 2nd North American Symposium on Landslides Vol. 1:981–987, Banff, Alberta, Canada, 2–8 June 2012). CRC Press.

Locat, A., Leroueil, S., Bernander, S., Demers, D., Jostad, H. P., & Ouehb, L. (2011). Progressive failures in eastern Canadian and Scandinavian sensitive clays. *Canadian Geotechnical Journal 48*, 1696-1712.

Loke, M.H. (2010). *Res2DInv ver. 3.59.102. Geoelectrical imaging 2D and 3D.* [Instruction manual]. Geotomo Software. Available at: www.geoelectrical.com

Lundqvist, J., & Wohlfarth, B. (2001). Timing and east-west correlation of south Swedish ice marginal lines during the Late Weichselian. *Quaternary Science Review 20*, 1127–1148.

Lundström, K., Larsson, R., & Dahlin, T. (2009). Mapping of quick clay formations using geotechnical and geophysical methods. *Landslides 6*, 1:1–15.

Löfroth, H. (2008). *Undrained shear strength in clay slopes – Influence of stress conditions* (Report 71). Linköping: Swedish Geotechnical Institute.

Löfroth, H. (2011). *Kartering av kvicklereförekomst för skredriskanalyser inom Göta älvutredningen – Utvärdering av föreslagen metod samt preliminära riktlinjer* (GÄU interim report 29). Linköping: Swedish Geotechnical Institute.

Malehmir, A., Saleem, M. U., & Bastani, M. (2013). High-resolution reflection seismic investigations of quick-clay and associated formations at a landslide scar in southwest Sweden. *Journal of Applied Geophysics 92*, 84–102.

Mitchell, R. J., & Markell, A. R. (1974). Flowsliding in Sensitive Soils. *Canadian Geotechnical Journal 11*, 11-31.

Moore, G.E. (1965). Cramming more components onto integrated circuits. *Electronics 38*, 114–117.

Moum, J., Løken, T., & Torrance, J.K. (1971). A geochemical investigation of the sensitivity of normally consolidated clay from Drammen, Norway. *Géotechnique 21*, 329–340.

Moum, J., Løken, T., & Torrance, J.K. (1972). Discussion of Moum et al. 1971. *Géotechnique 22*:675–676.

MSB. (2009). *Analys av samhällsekonomisk kostnad - Skredet vid E6 i Småröd, 2006.* Karlstad: Swedish Civil Contingencies Agency.

MSB. (2010). *Översiktlig kartering av stabilitetsförhållanden. Kriterier för indelning av karteringsområden i stabilitetszoner och krav på stabilitetsutredningar* (Bilaga 4, Förfrågningsunderlag). Memorandum dated 2010-01-20 received 2014-01-22 from Karlstad: Swedish Civil Contingencies Agency.

NLSS. (2010). *GSD grid 50+* [50 m Digital elevation model]. Gävle: National Land Survey of Sweden.

NLSS. (2012). *GSD grid 2+* [2 m Digital elevation model]. Gävle: National Land Survey of Sweden.

Odenstad, S. (1951). *The Landslide at Sköttorp on the Lidan River* (Proceedings no 4). Linköping: Swedish Geotechnical Institute.

Odenstad, S. (1958). Jordskredet i Göta den 7 juni 1957. *Geologiska Föreningen i Stockholms Förhandlingar 80*, (1)76–86.

van Olphen, H., 1977. *An introduction to clay colloid chemistry* (2nd ed, 318pp.). New York: Interscience Publ.

Persson, M.A., & Stevens R.L. 2012. *Predictive modeling of quick-clay distribution in SW Sweden* (Department of Earth Sciences report C. 93, Project report delivered to the Swedish Civil Contingencies Agency, Karlstad). Gothenburg: University of Gothenburg.

Pfaffhuber, A. A. (2014). *AEM ground investigations* (NGI reference project). Document retrieved 2014-04-01 from the Norwegian Geotechnical Institute website at:
http://www.ngi.no/en/Contentboxes-and-structures/Reference-Projects/Reference-projects/Airborne-Electromagnetic-AEM-Ground-Investigations/

Pusch, R. 1973. Influence of salinity and organic matter on the formation of clay microstructure (pp. 161 – 175). In: *Proceedings of the International Symposium on Soil Structures*, Gothenburg.

Påsse, T. (1996). *A mathematical model of the shore level displacement in Fennoscandia* (Technical report 96–24). Stockholm: Swedish Nuclear Fuel and Waste Management Company.

Påsse, T., & Andersson, L. (2005). Shore-level displacement in Fennoscandia calculated from empirical data. *Geologiska Föreningen i Stockholm Förhandlingar 127*(4), 253–268.

Quinn, P. E, Hutchinson, D. J., Diederichs, M. S., Rowe, R. K., & Alvarez, J. (2008). Susceptibility mapping of landslides in Champlain clay from a digital landslide inventory. In: Locat, J., Perret, D., Turmel, D., Demers, D., Leroueil, S. (Eds.). *Proceedings of the 4th Canadian Conference on Geohazards: From Causes to Management.* Québec city: Presse de l'Université Laval.

Quinn, P. E. (2009). *Large landslides in sensitive clay in eastern Canada and the associated hazard and risk to linear infrastructure* (Doctoral Dissertation). Kingston, Ontario: Queens University.

Quinn, P. E., Hutchinson, D. J., Diederichs, M. S., & Rowe, R. K. (2010). Regional scale landslide susceptibility mapping using the weights of evidence approach: an example applied to linear infrastructure. *Canadian Geotechnical Journal. 47*, 905-927.

Quinn, P. E., Hutchinson, D. J. Diederichs, M. S., & Rowe, R. K. (2011). Characteristics of large landslides in sensitive clay in relation to susceptibility, hazard and risk. *Canadian Geotechnical Journal 48*, 1212-1232.

Quirk, J. P., & Schofield, R. K. (1955). The effect of electrolyte concentration on soil permeability. *The Journal of soil science 6*, 163–178.

Rankka, K., Andersson-Sköld, Y., Hultén, C., Larsson, R., Leroux, V., & Dahlin, T. (2004). *Quick clay in Sweden* (Report 65). Linköping: Swedish Geotechnical Institute.

Rengasamy, P., & Sumner, M. E. (1998). Processes involved in sodic behaviour, In: Sumner M. E., & Naidu R. (Eds.). *Sodic Soils. Distribution, Properties, Management, and Environmental Consequences* (pp. 35–50). New York: New York Press.

Reusch, H. (1901). *Aarbog for 1900* (nr. 32). Kristiania: Geological Survey of Norway.

Rosenqvist, I. Th. (1946). *Om leirers kvikkagtighet.* (Meddelande Nr 4). Oslo: The Road Laboratory, Norwegian Public Roads Administration.

Rosenqvist, I. Th. (1953). Considerations on the sensitivity of Norwegian clays. *Géotechnique 3*, 195–200.

Rosenqvist, I. Th. (1955). *Investigations in the clay-electrolyte-water system* (Publication 9, 36pp.). Oslo: Norwegian Geotechnical Institute.

Rydell, B., & Öberg, M. (2013). *Geoteknisk sektorsportal – Nationell datainfrastruktur för tillgång till geotekniska undersökningar* (Publikation 1). Linköping: Swedish Geotechnical Institute.

Saaty, T. L. (1977). A scaling method for priorities in hierarchical structures. *Journal of mathematical psychology* 15, 234-281.

Saaty, T. L. (1980). *The Analytic Hierarchy Process.* New York: McGraw Hill.

Saaty, T. L. (2008). Decision making with the analytic hierarchy process. *International Journal of Services Sciences 1*(1), 83-98.

Schälin, D., & Tornborg, J. (2009). *Evaluation of CPT-R and resistivity measurements in quick clay area – possible gain of CPT-R probing and potential of combining methods* (Master thesis No. 98072). Gothenburg: Chalmers University of Technology.

SGI. (2011). Landslide database retrieved 2012-01-17 from the Swedish Geotechnical Institute website at: http://gis.swedgeo.se/skred/

SGI. (2012a). *Skredrisker i Göta älvdalen i ett förändrat klimat* (Final report parts 1-3). Swedish Geotechnical Institute. Linköping.

SGI. (2012b). *Borrhåltidigarepaketet, SGI/120801* (Göta älv River valley data recorded before the GÄU project, full data references listed in the dataset).

[Geotechnical survey data compilation]. Files retrieved from The Swedish Geotechnical Institute.

SGI. (2012c). *Borrhålspaketet, SGI/120801* (Göta älv River valley data recorded during the GÄU project). [Geotechnical survey data compilation]. Files retrieved from The Swedish Geotechnical Institute.

SGU. (2010). Local bedrock [database mapped for presentation in 1:50,000] received from the Swedish Geological Survey 2010-02-10.

SGU. (2012a). Local surficial deposits [map dataset JOGI A, mapped for presentation in 1:50,000] received from the Geological Survey of Sweden 2012-02-22.

SGU. (2012b). Regional surficial deposits [map dataset JOLC, mapped for presentation in 1:100,000] received from the Geological Survey of Sweden 2012-02-22.

SGU. (2012c). Stratigraphic diary [database] received from the Geological Survey of Sweden 2012-02-22.

SGU. (2012d). Well log archive [dataset BARK] received from the Geological Survey of Sweden 2012-02-22.

SGU. (2012e). Glacial striae [database] received from the Swedish Geological Survey 2012-02-22.

SJ. (1922). *Statens järnvägars geotekniska kommission 1914-22. Slutbetänkande angivet till Kungliga Järnvägsstyrelsen.* 190pp. Stockholm: Statens Järnvägar.

SJ. (1989). Göteborg–Torp. The Partille – Jonsered section. [Geotechnical survey data] received from the Swedish Transport Agency.

Skredkommisionen. (1995). *Anvisningar för släntstabilitetsutredningar* (Skredkommisionen rapport 3:95, 205pp.). Linköping: Royal Swedish Academy of Engineering Sciences.

SMHI. (2012). Flowlines [dataset Vd_1_2012_2]. Norrköping: Swedish Meteorological and Hydrological Institute.

Solberg, I. -L., Rønning, J. S., Dalsegg, E., Hansen, L., Rokoengen, K., & Sandven, R. (2008). Resistivity measurements as a tool for outlining quick clay extents and valley fill stratigraphy: feasibility study from Buvika, Central Norway. *Canadian Geotechnical Journal 45*, 210–225.

SOU. (1962). *Rasriskerna i Götaälvdalen* (Statens offentliga utredningar 1962:48, 160pp). Betänkande avgivet av Götaälvskommittén. Stockholm: Ministry of the Interior.

Suer, P., Löfroth, H. & Andersson-Sköld, Y. (2014). Ion Exchange as a Cause of Natural Restabilisation of Quick Clay – A Model Study. In: L'Heureux, J. S., Locat, A., Leroueil, S., Demers, D., Locat, J. (Eds.). *Landslides in Sensitive Clays – From Geosciences to Risk Management.* (Advances in Natural and

Technological Hazards Research, Vol. 36. pp. 51–62) Springer Science+Buisness Media Dordrecht.

Stevens, R. L., Hellgren, L. G., & Häger, K. Ö. (1984). Depositional environments and general stratigraphy of clay sequences in south western Sweden. *Striae 19*, 13–18.

Stevens, R. L. (1985). Glaciomarine varves in late-Pleistocene clays near Göteborg, southwestern Sweden. *Boreas 14*, 127–132.

Stevens, R. L. (1986). Glaciomarine varves and the character of deglaciation, Säveån valley, southwestern Sweden. *Boreas 15*, 289-299.

Stevens, R. L., April, R. H., & Wedel, P. O. (1987). Sediment color and weathered preglacial sources of Quaternary clays in southwestern Sweden. *Geologiska Föreningen i Stockholm Förhandlingar 109*, 231-253.

Stevens, R. L., Rosenbaum, M. S., Hellgren, L. G. (1991). Origins and engineering hazards of Swedish glaciomarine and marine clays. In: Forster, A., Culshaw, M. G., Cripps, J. C., Little, J.A., Moon, C. F. (Eds.). Quaternary Engineering Geology. Geol Soc Eng Geol Spec Publ 7, pp. 257–264.

Söderblom, R. (1959). Aspects on some problems of geotechnical chemistry. *Geologiska Föreningen i Stockholm Förhandlingar 81*, 727–732.

Söderblom, R. (1969). *Salt in Swedish clays and its importance for quick clay formation. Results from some field and laboratory studies.* Proceedings 22. Swedish Geotechnical Institute, Stockholm.

Söderblom, R. (1974). *New lines in quick clay research* (Reprints and preliminary reports No 55). Stockholm: Swedish Geotechnical Institute.

Söderblom, R. 1983. Studies of the rapidity number. In *Symposium on Slopes on Soft Clays* (Report No. 17. pp. 381–395). Linköping: Swedish Geotechnical Institute.

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

Talme, O. A. (1968). *Clay sensitivity and chemical stabilization* (Doctoral Dissertation, Rapport 56:1968.). Stockholm: Byggforskningen.

Tavenas, F., Chagnon, J. -Y., & La Rochelle, P. (1971). The Saint-Jean Vianney landslide: Observations and eyewitness accounts. *Canadian Geotechnical Journal 8*, 463–478.

Thakur, V., & Degago, S.A. (2012). Quickness of sensitive clays. *Géotechnique Letters 2(3)*, 87–95.

Torrance, J. K. (1979). Post-depositional changes in the pore-water chemistry of the sensitive marine clays of the Ottawa area, eastern Canada. *Engineering geology 14,* 135–147.

Torrance, J. K. (1983). Towards a general model of quick clay development. *Sedimentology 30,* 547–555.

Torrance J. K., Hedges S. W., Bowen, L. H. (1986) Mössbauer spectroscopic study of the iron mineralogy of post-glacial marine clays. *Clays and Clay Minerals 34,* 314–322

Torrance, J. K. (1990). Oxide minerals in the sensitive post-glacial marine clays. *Applied Clay Science 5,* 307–323.

Torrance, J. K., (1995). Post-Depositional Processes in High-Sensitivity, Fine-Grained, Collapsible Sediments. In: Derbyshire, E., T. Dijkstra, T., & Smalley, I. J. (Eds.). *Genesis and Properties of Collapsible Soils: Proceedings of the NATO Advanced Research Workshop on Genesis and properties of Collapsible Soils* (Loughborough, U.K., 1994). Dordrecht: Kluwer.

Torrance, J. K. (2009). *CLAYS: Mineralogy, geochemistry and geotechnical properties.* Notes for a Research course held at the Department of Earth Sciences, University of Gothenburg May 11–15, 2009.

Torrance, J. K. (2012) Landslides in quick clay. In: Clague, J. J., Stead, D. (Eds.). *Landslides: types, mechanisms and modeling.* Cambridge: Cambridge University Press.

Torrance, J. K. (2014). Chemistry, sensitivity and quick-clay landslide amelioration. In: L'Heureux, J. S., Locat, A., Leroueil, S., Demers, D., Locat, J. (Eds.). *Landslides in Sensitive Clays – From Geosciences to Risk Management.* (Advances in Natural and Technological Hazards Research, Vol. 36, pp. 15–24). Springer Science+Buisness Media Dordrecht.

Turesson, A., & Lind, G. (2005). Evaluation of electrical methods, seismic refraction and ground-penetrating radar to identify clays below sands - Two case studies in SW Sweden. *Near Surface Geophysics 3(2)*, 59-70.

Verwey, E. J. W., & Overbeek, J. Th. G., (1948). *Theory of the Stability of Lyophobic Colloids.* Amsterdam: Elsevier.

VV. (1997). *Road E20/E6 Åbromotet.* [Geotechnical survey data]. Files extracted from the document database CHAOS, Swedish Road Administration.

VV. (2002). Road E6 Torp–Gläborg (Hogstorp–Kallsås section). [Geotechnical survey data]. Files extracted from the document database CHAOS, Swedish Road Administration.

VV. (2004). Road E6 Lindholmsmotet–Lundbyleden section. [Geotechnical survey data]. Files extracted from the document database CHAOS, Swedish Road Administration.

VV. (2005a). Road E6 Torp–Gläborg (Småröd–Saltkällan section). [Geotechnical survey data]. Files extracted from the document database CHAOS, Swedish Road Administration.

VV. (2005b). Road E6 Torp–Gläborg (Fläskeberget–Håby section). [Geotechnical survey data]. Files extracted from the document database CHAOS, Swedish Road Administration.

VV. (2006a). Road E6 Uddevalla–Svinesund (Rabbaldshede–Solhem section). [Geotechnical survey data]. Files extracted from the document database CHAOS, Swedish Road Administration.

VV. (2006b). Road E6 Uddevalla–Svinesund (Nordby–Svinesund section). [Geotechnical survey data]. Files extracted from the document database CHAOS, Swedish Road Administration.

VV. (2006c). Road E6 Torp–Gläborg (Saltkällan–Fläskeberget section). [Geotechnical survey data]. Files extracted from the document database CHAOS, Swedish Road Administration.

VV. (2006d). Roads E45/E20 Partihallsförbindelsen. [Geotechnical survey data]. Files extracted from the document database CHAOS, Swedish Road Administration.

VV. (2006e). Road E6 Torp–Gläborg (Kallsås–Småröd section). [Geotechnical survey data]. Files extracted from the document database CHAOS, Swedish Road Administration.

VV. (2006f.) Road E6 Uddevalla–Svinesund (Tanumshede–Lugnet section). [Geotechnical survey data]. Files extracted from the document database CHAOS, Swedish Road Administration.

VV. (2006g). Road E6 Uddevalla–Svinesund (Knäm–Lugnet section). [Geotechnical survey data]. Files extracted from the document database CHAOS, Swedish Road Administration.

VV. (2007a). Road E6 Uddevalla–Svinesund (Lugnet–Skee section). [Geotechnical survey data]. Files extracted from the document database CHAOS, Swedish Road Administration.

VV. (2007b). Road E6 Uddevalla–Svinesund (Solhem–Pålen section). [Geotechnical survey data]. Files extracted from the document database CHAOS, Swedish Road Administration.

VV. (2007c). Road E45 Nödinge–Nol section. [Geotechnical survey data]. Files extracted from the document database CHAOS, Swedish Road Administration.

VV. (2007d). Road E45 Älvängen–Stallbacka (Torpa–Stenröset section). [Geotechnical survey data]. Files extracted from the document database CHAOS, Swedish Road Administration.

VV. (2008a). Road E45 Älvängen–Stallbacka (Norr Göta–Edet Rasta section). [Geotechnical survey data]. Files extracted from the document database CHAOS, Swedish Road Administration.

VV. (2008b). Road E45 Älvängen–Stallbacka (Edet Rasta–Torpa section). [Geotechnical survey data]. Files extracted from the document database CHAOS, Swedish Road Administration.

VV. (2008c). Road E45 Älvängen–Stallbacka (Stenröset–Gärdhem section). [Geotechnical survey data]. Files extracted from the document database CHAOS, Swedish Road Administration.

VV. (2010). Road E45 Älvängen–Alvhem (Alvhem–Kärra section). [Geotechnical survey data]. Files extracted from the document database CHAOS, Swedish Road Administration.

Yalcin, A., Reis, S., Aydinoglu, A. C. & Yomralioglu T. (2011). A GIS-based comparative study of frequency ratio, analytical hierarchy process, bivariate statistics and logistics regression methods for landslide susceptibility mapping in Trabzon, NE Turkey. *Catena 85,* 274-287.

Yoshimatsu, H. & Abe, S. (2006). A review of landslide hazards in Japan and assessment of their susceptibility using an analytical hierarchic process (AHP) method. *Landslides 3,* 149–158.

Åhnberg, H., Larsson, R., & Holmén, M. (2013). Degradation of clay due to cyc
lic loadings and deformations (pp. 1411–1414). In: Delage, P., Desrues, J., Frank, R., Puech, A., & Schlosser, F. (Eds.). *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris 2013.*

Ågren, J., & Svensson, R. (2007). *Postglacial Land Uplift Model and System Definition for the New Swedish Height System RH 2000* (LMV-Rapport 2007:4). Gävle: The National Land Survey of Sweden.

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