



The Tømte Symposium October 24th 2022
Quick clays – geological constraints and occurrences - Rosenqvist tribute

The Norwegian Academy of Science and Letters, Drammensveien 78, 0271 Oslo

Abstracts

Quick clay slide hazard – the value of combined geological and geotechnical data

Ellen Davis Haugen, The Norwegian Water Resources and Energy Directorate

The mapping of quick clay slide hazard builds on a combination of knowledge of geological and geotechnical conditions. The national hazard mapping depends on detailed geological mapping of surficial deposits from after the last ice age (quaternary geology). These maps give information on where there might be marine sediments, and thereby possible quick clay. Once potential hazard areas are identified, a more detailed mapping of the sediments is necessary. This is primarily done to determine the extent of quick clay, both in depth, internal layering and geometry. A combination of geophysical, hydrogeological and geotechnical investigations gives the best basis for identifying possible quick clay slide mechanisms and determining the actual areas which are at risk.

NADAG - Data for better understanding of the ground conditions

Inger-Lise Solberg, NGU

The National Database for Ground Investigations (NADAG) collects, stores and makes subsurface data available to the public. This is beneficial for the society as it makes the data easier to access, and re-use will lead to considerable savings. Importantly, the information will allow for better understanding of the ground conditions and potential landslide areas. In addition, the effectiveness of emergency planning and response will improve with quick access to existing and relevant information about the local ground conditions. The database contains data from geotechnical investigations. However, the web applications also give access to data from other sources, like Quaternary geological maps, groundwater and energy wells, quick-clay hazard zones, geophysical data and more.



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Paleoenvironmental conditions favoring the accumulation of (glacio)marine clays in Norwegian fjord valleys

Louise Hansen, NGU

This presentation addresses the range of depositional environments that favor the sedimentation of clay and silt, now being recorded onshore in Norwegian fjord valleys locally as sensitive clay or quick clay. Much of the deposits accumulated in glaciated fjord environments at high rates as sediment-loaded meltwater plumes encountered saline water giving rise to flocculation. Interbedded sandy layers accumulated locally during fluctuating meltwater pulses. Distinct clay and silt beds possibly accumulated in association to glacial-lake outburst floods. Holocene, non-glaciated fjord-marine environments are characterized by overall lowered sedimentation rates allowing for more bioturbation. Occasionally, fine-grained event beds accumulated rapidly during exceptional events such as floods or landslides. Knowledge on the geological preconditions, processes and paleoenvironmental context of sensitive clays and silts help to explain their occurrence

Sedimentological characteristics of glaciomarine clays

Jens Jahren, University of Oslo

Quick clay development based on material properties, natural depositional processes and post-depositional factors were summed up by Torrance in a paper published in *Sedimentology* in 1983. Torrance (1983) discussed marine, brackish water and freshwater sediments based on what was known about the above at that time. Since then most of the papers on quick clay have been focused on development of sound structure-mechanical explanations of landslides in soft sensitive clays. This work has been mainly geotechnical. This presentation will discuss some depositional and textural aspects of quick clay formation that might be relevant to investigate further.

Torrance, J. K. (1983). Towards a general model of quick clay development. *Sedimentology*, 30(4), 547-555.

Microstructural studies of quick clays

Helge Hellevang, University of Oslo

Rosenqvist pioneered our understanding of the formation of quick clays and lay the foundation for later research on the role of microstructure and sensitivity. Already in the 1950s, examinations of quick clays using electron microscopes provided indications of a random grain orientation, and a card-house-like structure. There seems to be little or no difference between the structures of unleached clays and highly sensitive leached quick clays. The porosity in quick clays seems to be divided into relatively small intra-aggregate pores supported by the card-house structure, and



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more variable and larger inter-aggregate pores. It is the inter-aggregate pores that mainly deform during compaction experiments. The porosity of quick clays can be higher than 60%, but is commonly in a range between 50-60% for weakly compacted clays. The mineralogy reflects the local source of mechanically weathered rocks. The grain size distribution vary strongly, with clay contents from ~20 to 80%. It is a bit surprising that the sensitivity of quick clays appear to show little dependency on the clay content, and there is still a need to better understand the fundamentals of quick clay formation and how leaching affects intra-and inter aggregate forces and thereby the mechanical strength.

Strategies in quick clay mapping

Tor Løken

Challenges related to quick clays with their mineralogy, pore water chemistry and geotechnical properties have always been important issues at NGI. Both chemical laboratory research with natural quick clay samples as well as field investigations of quick clay slide areas have been carried out since NGI was established. However, a programme of mapping areas of quick clay slide hazards was first initiated around 1970, but no funding was made available at that time. Then the Rissa slide occurred in 1978, the authorities realized that hazards maps of quick clays were needed. Then a systematic mapping programme started with a cooperation of NGU and NGI. NGU clarified maps with marine sediments in different areas of Norway, and NGI followed up with geotechnical investigations. This resulted in the first generation of hazards maps marking areas of "Potential danger of quick clay slide areas".

Geochemistry of quick clays

Tonje Eide Helle, Multiconsult

Leached clays originally deposited in a marine environment may develop high sensitivity as the salt content in their porewater decreases below 2 g/L. Originally sodium was the abundant cation in both the pore water and the adsorbed positions on the clay-mineral surfaces. Groundwater is normally of low salinity with an ion composition dominated by calcium and/or magnesium and bicarbonate. Therefore, leaching dilutes and alters the ion composition in the porewater. Chloride is practically removed, but the continuous ion exchange on the mineral surfaces retards the removal of sodium from the clay-water system as sodium is released to the porewater and the introduced calcium and magnesium are adsorbed. Consequently, the porewater composition in quick clays is still dominated by sodium with bicarbonate as the abundant anion. Leaching is a continuous ongoing process, and with time low-saline clays render non-quick as the potassium,



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magnesium and calcium ratio exceeds 20 %. Geochemical knowledge may aid in developing effective ground improvement by chemical additives such as the introduction of potassium to the clay-water system which causes a permanent improvement of the post-failure properties, rendering the clays non-quick, inhibiting retrogressive landslides and reduces the risk for progressive landslides.

Quick clays - Hydrogeological considerations

Per Aagaard, University of Oslo

Glaciomarine clays develop their quick behavior due to leaching of pore fluid salinity. This leaching is a very slow process due to low hydraulic conductivity of clays, and it requires diffusive ion transport from saltier pore water in the clay to low salinity regions of higher permeability where groundwater flow can take place. The concentration gradient needed for diffusion prevails due to a steady replenishment of fresh groundwater. The overall leaching process of coupled diffusive and advective transport is due to permeability contrast among different geological material. This is well documented in the Champlain clays in Eastern Canada (Lefebvre, 2017), where one found that only a conductivity contrast of 10 between clays and underlying till was able to cause artesian conditions and upward hydraulic gradient. Even underlying bedrock may have higher hydraulic conductivity than clays, causing groundwater flow and leaching of the adjoining clays. The hydraulic regime is thus also decisive in controlling pore pressures and effective stress conditions.

Lefebvre, G (2017) Sensitive Clays of Eastern Canada: From Geology to Slope Stability. In Thakur, V., L'Heureux, J.-S. and Locat, A. (Eds) Landslides in Sensitive Clays. From Research to Implementation. Springer. p 15-34

Geostatistical estimation of bedrock topography as a tool for risk assessment of sensitive clays

Nils-Otto Kitterød, Norwegian University of Life Sciences

From a physical and chemical point of view, the sensitivity of clay is well understood after Rosenqvist (1946) started to explore the problem. However, a general approach to identify potential risk areas still needs more research. Identification of potential risk areas can be done by different methods: Geophysics can be used to identify geological structures and electrical anomalies which can be followed by geotechnical test drilling. The final conclusive step is usually core sampling and geotechnical laboratory tests. These methods yield empirical data which indicate spatial extension of risk areas. The same data can also be used for estimation and



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geological structures. In this context, the bedrock topography might be used as a prior screening procedure to identify areas for further investigation. Such estimates provide information of sediment thickness in terms of probability density functions, which indicate local areas with significant deposits. The bedrock geometry is also important for the water flux and transport of ions in the clay. Cross validation of geostatistical methods shows that estimation uncertainty can be reduced by combining point information of sediment thickness with geographical information of bedrock outcrops (Kitterød, 2017; Kitterød and Leblois, 2021). Because bedrock outcrops and point information of sediment thickness is available in public databases (viz GRANADA, NADAG), validated algorithms can be applied for continuous estimates of bedrock topography for all parts of mainland Norway.

References

- Kitterød, N.-O., 2017: Estimating unconsolidated sediment cover thickness by using the horizontal distance to a bedrock outcrop as secondary information. *Hydrol. Earth Syst. Sci.*, 21, 4195–4211, 2017, doi.org/10.5194/hess-21-4195-2017.
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- Rosenqvist, I.T., 1946: Om leirers kvikkaghtighet. Statens Vegvesen, Oslo, rapport nr. 4.

Characterizing potential quick clay with a 3D resistivity model and comprehensive data integration in the mid-Norwegian Orkdal valley

Sofie Gradmann, Vikas Chand Baranwal, Jan-Steinar Rønning, Inger-Lise Solberg, Atle Dagestad, Louise Hansen, Bjørn Eskil Larsen, Ivanna Penna, Pia Sunde, Georgios Tassis. Geological Survey of Norway.

We perform an integrated study of the Quaternary deposits of the Orkdal valley in mid-Norway using geophysical, geotechnical and geological approaches. A 3D resistivity model of the subsurface is derived from a helicopter frequency EM (HEM) survey using a full 3D inversion approach. The model, which reaches down to 150 m depth, nicely shows the distribution of low-resistivity marine clays, potential leached clays, glacio- and fluvial deposits as well as bedrock. The inversion results are tested against and locally refined by several ground electrical profiles. Data interpretation and comparison with geotechnical drillings that aim at detecting quick clay occurrences are ongoing. The different methods are in very good agreement and complement each other well. Furthermore, we link the potential distribution of quick clay derived from the HEM data with a terrain analysis to identify areas of potential landslide hazard. This comprehensive study demonstrates how HEM can improve the 3D understanding of quaternary deposits and – combined with other methods such as ground geophysics (ERT and GPR) and ground observations – provide a more detailed picture of the subsurface and lay the basis for detailed geohazard analysis.



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Identification of quick clay using electrical resistivity methods

Mike Long, University College Dublin

Formation of quick clays involves the leaching of salt from the pore fluid. Thus it has been recognised that electrical resistivity measurements could be useful in delineating leached and unleached clays. This presentation seeks to assess the applicability, repeatability and reliability of the various geophysical techniques to the study of sensitive clays. It also attempts to understand the factors which control the measured resistivity and in particular to determine the limitations of directly obtaining the remoulded shear strength from the resistivity measurements. It was found that borehole, surface and airborne resistivity measurements are accurate and compatible. For the 30 Norwegian sites studied, up to 2017, see Long et al. (2017), it was found that resistivity is primarily defined by the pore water salt content with minor additional influence by clay content / plasticity and porosity. A relationship exists between resistivity and remoulded shear strength but this is limited to material deeper than the dry crust and a surface weathering zone of about 7.5 m thickness. High resistivity ($>10\Omega\text{m}$) may indicate quick or weathered clay but low resistivity ($<10\Omega\text{m}$) conclusively points to stable, unleached clay.

The 2017 findings are subsequently trialed on newer Norwegian data, in particular from the Norwegian Geo-Test Site project (NGTS) soft clay and quick clay sites at Onsøy and Tiller Flotten.

Long, M., Pfaffhuber, A.A., Bazin, S., Kåsin, K., Gylland, A. and Montafia, A. (2017). "Glacio-marine clay resistivity as a proxy for remoulded shear strength – correlations and limitations". Quarterly Journal of Engineering Geology and Hydrogeology (QJEGH), Vol. 51, pp 63-78. <https://doi.org/10.1144/qjegh2016-136>.



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Ultra-high-resolution multicomponent seismic characterization of quick-clay settings
Alireza Malehmir, Uppsala University

Land seismic data inevitably contain both compressional (P-wave) and shear (S-wave) information. Different wave modes usually leak from one domain to another although might be dominant in one domain depending on the instrumentation and setup used. Thanks to a decade of studies close to the historical 1957 Lilla Edet (Göta älv) quick-clay landslide site in southwest of Sweden, I show a reasonable number of shear-wave reflections can be extracted from typical so-called P-wave type surveys. The extreme slow shear-wave velocity (60-110 m/s) in most quick-clay settings allow a good separation of P-wave from S-wave reflections. It is important that this possibility is recognized, and methods developed to extract this information at the same time and when designing a seismic survey. The minimum is to make sure shear-waves in such an extremely slow-velocity media are not aliased and properly sampled. The extreme slow shear velocity implies a proper imaging is only possible using fine source and receiver spacing. Since 2020, we have acquired several high-fold (up to 250) ultra-high-resolution seismic profiles using 0.5-1 m shot and receiver spacing and showcase how these have allowed to obtain super resolution images of the subsurface and shed light on V_p/V_s variations along the profiles and their relevance for quick-clay landslide studies and preparedness works.

“Unlocking the value of geophysical and geotechnical data through machine learning illustrated by quick clay volume delineation based on airborne geophysics, lab samples and total soundings”
Andi A. Pfaffhuber and Craig Christensen

We illustrate the applicability of airborne geoscanning (AEM) to delineate sensitive clay through Machine Learning. First, we derive bedrock topography combining geophysical 3D-models with sparse bedrock elevation from drillings. We then combine geophysics with geotechnical soundings and samples to estimate brittle clay probability in 3D. We evaluate this method using randomized cross-validation, varying the number of used boreholes. Results indicate that while the predictions are imperfect, they can give early indications of where the presence of sensitive clay can be either ruled out, confirmed, or deemed uncertain. These insights can be useful for planning more efficient follow up site investigations, reducing overall risk, time, and cost.



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Geotechnical slope stability considerations: Relevance for understanding initiation of quick clay slides.

Prof. Gustav Grimstad, NTNU

How are quick clay landslides initiated?

Given quick clay in the ground, the terrain must have height differences that are large enough for even a minor local disturbance/overload to cause further propagation. We can roughly sort the triggering events (initiation) into two main categories: Directly man-made via construction work (e.g., filling, excavation); Natural processes (e.g., erosion). To assess the stability of a slope, an equilibrium calculation is made. The stability is found by comparing the strength of the material to the stress state in the material along the most critical potential failure mechanism (a critical failure mechanism is a failure/landslide that has the lowest resistance to occur). This presentation shows how geotechnical slope stability evaluations are used to understand the initiation of quick clay slides.

Landslides in quick clays area – hazards and mitigating measures"

Håkon Heyerdahl, NGI

Potential landslides involving quick clay constitute a notable risk over large parts of the most densely populated areas in Norway. The frequency of quick clay landslides is low, compared to other natural hazards as; e.g.; rockfalls, snow avalanches and debris flows, however, the sudden development and catastrophic character put them in a special position.

The first step in landslide risk reduction is mapping of the landslide hazard. A system for assessing quick clay landslide hazard and risk has been developed in Norway through several decades. When the hazard and risk is known, prioritization of mitigation is the next step. Landslides are generally caused by mechanical instability. Stabilizing measures may be done in many ways, and as a combination of measures. Basic mitigation is achieved through erosion protection. Stabilising measures can be achieved by topographic changes. Soil improvement of various kinds may be applied, generally to a considerable cost. For choice of proper measures, practical considerations must be done. Securing areas before or after a slide is widely different, which will be illustrated with examples.

Chemical stabilization of quick clay - a new approach

Håkon Rueslåtten

A new method for stabilizing quick clay has been developed to achieve sufficient shear strength of the subsoil in hours rather than weeks. This enables faster and safer progress, as the drilling rig can move into newly stabilized areas without long waiting times.



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Another objective is to ease the drilling by injecting strong dispersion agents, e.g., sodium- and/or potassium-silicate ('water glass'), to be stirred into the clay during the downward drilling, making a soft slurry of the sediment, that will reduce drilling energy, and assure homogenous mixing of the cementing materials into the drilled column.

The soft slurry will also provide an easier escape route for the propellant gas used to inject the dry powdered cementing chemicals during the mixing stage. This also reduces the build-up of pore pressure that displaces pore water from the treated clay volume; pore water necessary for hydration of the dry cementitious materials.

Finally, the main goal of this invention is that it allows a reduction of cement by more than 50%. This is obtained by injecting 'water glass' and replacing cement with industrial waste products having pozzolanic properties, e.g., ash from papermills.