A REVIEW OF STATE OF THE ART ON EROSION-DRIVEN QUICK CLAY LANDSLIDES

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KEYWORDS

Quick Clay Landslide, Literature Review, Erosion.

ABSTRACT

About 5000 km^2 of Norway is covered by soft marine clay deposits. Nearly 20% of this area consists of highly sensitive or quick clay. Landslides on this sensitive clay cause loss of life and adversely impact infrastructure, environment and communities. Most of the Quick Clay Landslides (QCLs) are caused due to human activities. However, continuous soil erosion activity along the riverbeds is one of the significant natural factors for QCLs. Recently, many researchers have incorporated soil erosion as the triggering factor for analyzing QCLs. The main goal of the present study is to review the research conducted on erosion driven QCLs in Norway and propose a framework for QCL risk assessment and management. We have reviewed some relevant articles and highlighted their limitations with future scope of work. Mitigating all quick clay deposits can be very cumbersome and hence first preference should be given to the extremely high QCL hazard zones. The accurate use of multi-temporal erosion data and its analysis can improve the prediction accuracy of QCL hotspot zones. The study also highlights the research gaps in monitoring soil erosion for predicting erosion driven QCL.

1. INTRODUCTION

On average around one large Quick Clay Landslide (QCL) occurs in Norway per year (L'Heureux et al. 2018), causing damage to infrastructure, or even loss of lives. QCL is one of the most devastating landslide types triggered by changes in the near-surface properties of the clay through human intervention and natural factors (Rørstadbotnen et al. 2023). Natural triggering factors include mainly terrain changes such as from erosion from a nearby drainage network (Gregersen, 1981; Regjeringen, 2021). These sensitive clays are known for their potential for large landslides, which poses a serious risk to human lives,

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infrastructure, and surrounding ecosystems within their reach. More is discussed below in Section 3 about the characteristics of quick clay in Norway. QCL can have large consequences as was recently seen in the quick clay landslide in Gjerdrum where 11 people lost their lives and more than 1600 people had to be evacuated from their homes. This landslide also caused extensive damages that cost almost 2 billion Norwegian kroner in damages and reparations after the event (NOU, 2022). Other such historical catastrophic landslides include, e.g., Sørum in 2016, Skjeggestad in 2015, Statland in 2014, Byneset in 2012, Saint-Jude in 2010, Lyngen in 2010 and Kattmarka in 2009.

The work to obtain information about the risk of quick clay landslides has been ongoing since 1980 and was initiated after the quick clay landslide in Rissa (1978). NGI (Norwegian Geotechnical Institute) was then commissioned by the Ministry of Agriculture to carry out overview mapping of "potentially landslide-prone quick clay areas" in Eastern Norway and in Trøndelag based on Quaternary geological maps from NGU. The program described in NVE report 14/2011 "Plan for landslide hazard mapping" (NVE 2011) is an update of NGI report 20001008-2 from 2008 (NGI 2008). As of today, overview mapping has been carried out under the auspices of NVE in large parts of the country (NVE, 2020a). This paper reviews some of the latest remarkable work describing the state of the art on erosion driven QCL and proposing a framework for QCL risk assessment and management.

2. TYPES OF QUICK CLAY SLIDES

Landslides in Norwegian clays can be classified as rotational, retrogressive, and flake slides (NVE, 2020b). In real situations, a landslide can be a combination of several types. For example, the 1978 Rissa landslide is a combination of initial slide, flake type and flow (Gregersen 1981). In the case where the rotational slide triggers further slides, it is referred to as the initial slide (NVE, 2020b). Flake slides happen when large flakes in gentle slopes release and quickly break up into large chunks or disintegrate (Torrance, 2012). This can occur in thin layers of quick clay that collapse and liquefy because of loading at the top of a slope or cuts or erosion at the bottom of the slope leading to a progressive failure along the quick clay layer releasing the flake.

3. QUICK CLAY IN NORWAY

The Norwegian landscape is characterized by large u-shaped valleys, fjords, and alpine relief – shaped by glacial variations throughout history. Over the past 2.6 million years, Norway has been subjected to more than 40 glaciations, resulting in many glacial processes influencing the Norwegian geography (Ramberg et al., 2008). The ice sheet exerted immense loads on the underlying crust, causing an isostatic depression amounting to several hundred meters. When the overburden ice disappeared, the underlying crust began to rise by means of isostatic uplift. Scandinavia is still rising at present-day. The

Oslofjord and Trondheim area has risen 36 cm the past century (Ramberg et al., 2008).

Quick clay can be found in places that are lower than the marine limit, which corresponds to the highest sea level during and after the last ice age. The marine limit is used as the upper boundary for delineating land areas that was depressed under sea water during the last ice age in Norway, and because of the postglacial land uplift the marine clay is now on land. The marine limit ranges in Norway vary from 0 to 220 meters above the current sea level (NGU, 2021). Sensitive clays are leached marine clays that may change from a stiff and brittle material into a viscous liquid when remolded (Rosenqvist 1953). The classification of a quick clay is in Norway based on the remolded undrained shear strength and sensitivity of the soil. A geotechnical definition is clays that have a remolded shear strength less than or equal to 0.5 kPa (NGF 2011) or 0.33 kPa in ISO 1789-6:2017. According to Thakur et al. 2014, clays with a remolded shear strength of less than 1 kPa, pose a risk for large, retrogressive flow-slides. The NVE uses a more conservative approach and classifies all brittle materials in surficial deposits, clays or silt with a remolded shear strength less than or equal to 2 kPa (NVE 2020b).

The clay in saltwater forms an open card house like structure, where the edges and planes have a different charge and are attracted to each other. The salt contributes to the binding forces keeping the card house structure stable. As the salt is washed out, the card house structure stays the same, but the binding forces are weakened (Regjeringen, 2021). As quick clays become liquid when remolded, these clays pose a serious risk for catastrophic QCL in inhabited areas, especially in mid-Norway and the southeast part of Norway.

4. EROSION AS THE TRIGGERING FACTORS

The foremost two triggering factors of quick clay landslides can be divided into anthropic factors (filling, excavation, construction activities, urbanization) or natural causes, mainly erosion destabilizing the slope (L'Heureux et al., 2018). Most erosion-initiated landslides in clay soils occur on the banks of watercourses where the toe is subjected to erosion. Erosion in riverbeds and ravines is progressively developed due to wet seasons and years of high precipitation with high water flow in rivers. An increase in precipitation and runoff because of climate change is also expected (IEA, 2022) which could lead to an increase in erosion and erosion-triggered quick clay landslides (Ryan et al. 2022). River erosion can cause destabilization in the long-term situation and erosion protection design should be built (Pytten et al. 2017). In the QCL in Gjerdrum, one of the causes of increased erosion in the river was additional runoff from the urbanization in the catchment (Regjeringen, 2021), exemplifying how quick clay landslides can result from a mix of anthropic factors and natural factors. The autumn season in 2020 was the wettest season in Gjerdrum since autumn 2000, and part of the conclusion for why the quick clay landslide released in 2020 and not in 2000 was the effect of the erosion over the years reducing the stability of the slope.

Erosion, unfavorable pore pressure conditions and terrain changes are the most common causes of landslides, and these can be due to both natural conditions and human influence (NGU Report 2022). Terrain changes due to natural erosion can lead to a disturbance of the stability equilibrium of a slope are an important contributor to quick-clay landslides (Solberg et al., 2024). According to Alene et al. (2024), a partially collapsed riverbank with fallen trees and exposed rock can suggest representing erosion directly. River channel morphology changes such as migrating of river course toward the riverbank adjacent to the toe of a given slope could be one indicator of dangerous erosion. In addition, river water level rise could represent erosion indirectly as a river flow increase exacerbates erosion.

In the aftermath of the landslide at Gjerdrum in 2020, the Norwegian Public Roads Administration (NPRA) has initiated to work proactively with assessments and protection of quick clay areas connected to the road network. Grøndalen et al. (2021) prepared a new working methodology with more focus on qualitative assessments of the dangers. They first evaluated the significant parameters for slope stability, which includes change in slope geometry, historical landslide activities, geometrical conditions in nearby slopes, stage in the formation of the valley, slope angle, erosion activity. Among them, the slope geometry (regardless of whether it is changing or not) was used as a basis for classifying the slopes stability. The other parameters were considered for additional information. They classified slopes into three main groups with slopes without change in geometry, slopes in change, and slopes with modified geometry. For each group, different stability conditions such as stable, potentially unstable, and assumed unstable were adopted. Central to their methodology was emphasis on the triggering causes of quick clay landslides and assessment of the extent to which they were present in an area with quick clay. The factors investigated were primarily ongoing erosion, landslide activity, slope gradient and height differences. To get a complete overview of the erosion conditions along a watercourse, site inspections and mapping the condition visually was carried out. They used GIS analyzes to get an overview of these factors in the many thousands of quick clay areas in Norway. This helped them in prioritizing areas that should be mapped and assessed first. They initially took the DTM for the study area and identified the streams. Then they calculate the height difference in the slopes adjacent to the waterways by creating a buffer zone of 50 m width. Then they selected the areas with a height difference greater than 10 metres by selecting steep areas (> 20 degrees) within 75 meters from the streams. This new approach was tested in eastern and central Norway and shown promising results with possibilities for further applications.

Godoy et al. (2023) introduces a new method, which is under development at the NVE, which aims to identify areas that may be vulnerable to naturally triggered quick clay landslides. He used publicly available lidar datasets (hoydedata.no/LaserInnsyn2), and automatically identified the terrain changes along ravines and watercourses using machine learning technique. The terrain changes were calculated as a regular raster algebra based on two digital terrain models (DTM) from lidar scans at different times. The data set consists of over 4,000 terrain change polygons that were validated with field visits. This data was divided into training (70%) and testing (30%) of the machine learning U-Net model. To train the model, they correlated the 70% training terrain change data with four chosen terrain parameters (change in height, change in plane curvature, change in slope and change in tangent curvature). The trained model then identified the same type of changes automatically. Further, the identified terrain changes were used as a basis for calculating maximum release areas for potential landslides incorporating NVE’s inhouse tool. NVE has developed a tool to calculate the maximum release area based on a given initiation zone. By using a slope of 1:15, landslide's maximum detachment area can be estimated (NVE, Jernbaneverket and Statens vegvesen, 2016). The slope ratio of 1:15 was taken in the steepest direction (normally on the elevations) (NVE, 2020b). By assuming the entire slope profile consists of brittle fracture material and retrogressive landslide development, they run the tool to calculate potential maximum detachment areas over the continuous deposits of marine clay (MSML) if an initial landslide starts at automatic identified terrain changes. Moreover, they estimated the potential risk from these release areas in a semi-quantitative approach by multiplying consequences and danger. Consequences were derived by correlating loosening area with geodatabases from Statistics Norway such as population data or infrastructure information. The degree of danger was estimated qualitatively by using three parameters: Slope (average), Height difference (maximum) and terrain changes/erosion (average volume). This risk assessment by estimation of both hazard and consequence helps in identifying the vulnerable areas that require prior investigation and mitigation measures. However, they have also mentioned the limitation of their work as it delimits very large loosening areas as it assumes that there is quick clay/fractured material everywhere within the MSML.

5. PROPOSED FRAMEWORK

Following framework is proposed for erosion-driven QCL risk assessment and management (Figure 1). This framework is based on the GIS-based conceptual integrated system for landslide risk assessment and management (Dai et al. 2002). of the proposed framework on erosion-induced QCL risk assessment starts by establishing a comprehensive physical, monitoring, QCL, and socio-economic databases. The framework than proceeds to identify critical features or parameters controlling slope stability, erosion processes, and consequences of QCLs. This will be then used to address both aspects of risk assessment, namely hazard and consequences. Hazard estimates can be obtained by physical or data-driven models in a sequential approach. The likelihood of erosion will be estimated, followed by the estimate of the likelihood of the initial slide. This will be estimated through the use of fragility curves. Estimates of consequences will be based on vulnerability assessment, which represents the likelihood of losses (e.g., economic, fatalities) in a QCL release and runout zones. Finally, the risk assessment will be used for determining the optimal risk management measures.

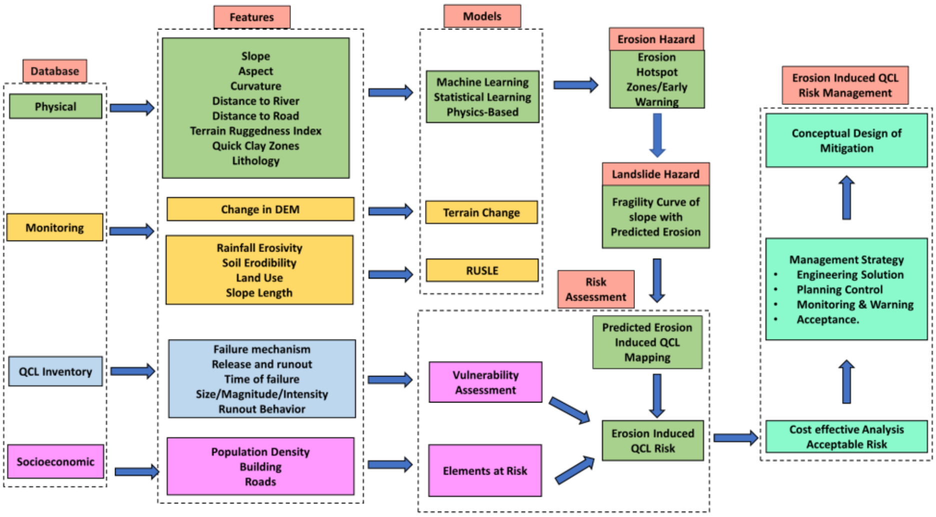

Figure 1 Framework for Erosion Induced QCL Risk Assessment and Management.

6. CONCLUSIONS

This review paper is dedicated to the growing community of scholars, practitioners and policy makers concerned with the different scientific aspects of erosion-induced quick clay hazards in Norway. Here, we have discussed work from various government and private organizations and their contributions in mitigating this hazard. Since landslides in sensitive clays possess huge destructive capabilities, there is a need for accurate assessment and prediction of landslide potential in such materials considering significant triggering factors such as erosion. This study proposes a comprehensive and quantitative erosion induced QCL risk management framework that complements and extends existing efforts by providing a more explicit treatment of coupled erosion and landslide hazards through a fragility function and assessment of consequences with a vulnerability function.

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REFERENCES

Alene, G.H., Depina, I., Thakur, V. et al. QuickAware: a virtual reality tool for quick clay landslide hazard awareness. Nat Hazards 120, 1869–1898 (2024).

Cristian Godoy. (2023). Proactive prevention of quick-clay landslides: use of data and technology for effective identification of vulnerable areas.

Dai, F.C., Lee, C.F. and Ngai, Y.Y., 2002. Landslide risk assessment and management: an overview. Engineering geology, 64(1), pp.65-87.

Gregersen, O. (1981). The quick Clay Landslide in Rissa, Norway. Norwegian Geotechnical Institute, Oslo, Norway. Publication No. 135, pp. 421–426.

Grøndalen, G.S., Juvik, E.S., Ottesen, H.B., Degago, S.A., Hellum, Ø. and Kveli, J., 2021. Håndtering av kritiske grunnforhold.

IEA. (2022). Norway Climate Resilience Policy Indicator – Analysis (Climate Resilience Policy Indicator). IEA.

Kristiansen, J.B., 2023. Precipitation and Erosion Threshold for Quick Clay Landslides Using Machine Learning Models (Master's thesis).

L'Heureux, J.-S., Høydal, Ø. A., Paniagua Lopez, A. P., & Lacasse, S. (2018). Impact of climate change and human activity on quick clay landslide occurrence in Norway. Second JTC1 Workshops on Triggering and Propagation of Rapid Flow-like Landslides.

NGF (Norwegian Geotechnical Society) (2011) Veiledning for symboler og definisjoner i geoteknikk: Identifisering og klassifisering i jord. Norwegian Geotechnical Society, Oslo, Norway, NGF-notification no. 2, 2nd revision.

NGI 2008, "Method for mapping and classification of danger zones, quick clay," Program for increased safety against mudslides. Report No. 20001008-2, rev.3.

NGU. (2021, February 10). Marin grense | Norges geologiske undersøkelse. https://www.ngu.no/emne/marin-grense Jeg er ikke sikker at man kommer på riktig side med denne lenke- sjekk

NGU Report (2022), Penna, I; Solberg, IL, Statistical analyzes of morphological parameters for mudslides in Trøndelag and Viken.

NOU. (2022). On safe ground — Better management of quick clay risk https://www.regjeringen.no/no/dokumenter/nou-2022-3/id2905694/

NVE 2011, "Plan for landslide hazard mapping," Report 14/2011.

NVE, Jernbaneverket and the National Road Administration. (2016). Method for assessment of loosened and outlet areas for area landslides. The natural hazard project: Sub-project 6 Quick clay. NIFS report 14/2016

NVE. (2020a). Overview mapping and classification of the degree of danger, consequence and risk for quick clay landslides. Method description, NGI. NVE External report no. 9/2020

NVE. (2020b). Safety against quick clay landslides. Assessment of area stability in land planning and development in areas with quicksand and other soils with brittle fracture properties. Guidelines for planning and development in danger areas along waterways. Guide No. 1/2019.

Pytten, E., Flobak, T., Ottesen, H.B. (2017). Fv. 287 Strandgata: Kjøreplass bru. Road Construction in Quick Clay. Advances in Natural and Technological Hazards Research, vol 46. Springer, Cham.

Ramberg, I. B., Solli, A., Nordgulen, Ø., Binns, R., Grogan, P. & NORSK GEOLOGISK, F. 2008. The Making of a land: geology of Norway, Trondheim, The Norwegian Geological Association

Rørstadbotnen, R.A., Dong, H., Landrø, M., Duffaut, K., Growe, K., Kakhkhorov, U., Wienecke, S. and Jacobsen, J., 2023. Quick clay monitoring using distributed acoustic sensing: A case study from Rissa, Norway. Geophysics, 88(5), pp. B267-B283.

Rosenqvist IT (1953) Consideration on the sensitivity of Norwegian quick-clays. Geotechnique 3:195–200

Regjeringen. (2021). Årsakene til kvikkleireskredet i Gjerdrum 2020.

Ryan, I., Bruvoll, A., Foldal, KM, Hæreid, GO, Muthanna, TM, Nordal, S. Ottesen, HB & Solberg, IL, 2022. On safe ground. Better management of quick clay risk. Norway's public studies, NOU 2022:3. Report to the OED submitted on 28 March 2022.

Solberg, IL. Landslide and ravine distributions related to ground conditions in elevated marine deposit in Mid-Norway. Nat Hazards (2024).

Thakur, V. and Degago, S.A., 2012. Quickness of sensitive clays. Géotechnique Letters, 2(3), pp.87-95.

Torrance, J. K. (2012). Landslides in quick clay. In D. Stead & J. J. Clague (Eds.), Landslides: Types, Mechanisms and Modeling (pp. 83–94).