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Master thesis (INDMAS)

INTEGRATED RISK ANALYSIS FRAMEWORK FOR QUICK CLAY LANDSLIDES IN NORWAY

An Implication to the Haugen Quick Clay Zone in Hvittingfoss, Kongsberg

Universitetet i Stavanger

INGRID SKIPENES LARSEN
UNIVERSITY OF STAVANGER
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Abstract

Quick clay landslides have caused a large number of natural disasters in Norway. These have resulted in loss of human lives and major damage on property, roads, railways, and infrastructure. Quick clay acts as a fluid when disturbed or overloaded, and therefore affects large areas away from the triggering point. Extensive accumulations of quick clay are found in residential areas, where the socio-economic consequences of a landslide can be enormous. Consequently, it is important to identify, assess and manage this risk.

The purpose of this thesis is to develop a complete risk analysis framework to undertake the risk associated with quick clay landslides in Norway. Currently, such a framework is not existent. There only exists partial analyses and guidelines focusing on single parts of the risk analysis process, which were discovered through a thorough literature study. This thesis puts an emphasis on a uniform and systematic framework, that includes several risk analyses to determine the hazards, consequences and risk of a study area, and that is followed by risk assessment and management. The framework provides a simple approach to risk of quick clay landslides and contains room for judgement and engineering experience to be included.

Further, an empirical exemplification of this risk framework was performed on the Haugen quick clay zone in Kongsberg, to enlighten the usefulness of the risk analysis framework. For this purpose; map studies, geotechnical investigations, fault tree analysis and creation of a landslide database were carried out. Potential hazard zones are classified according to hazard, consequence and risk level. The evaluation was carried out using a semi-quantitative analysis developed by NVE. This approach classifies the study area utilizing “engineering scores” by evaluating the local conditions, which resulted in a low hazard and severe consequence level. The risk is the product between the hazard and consequence scores, and was categorized as medium. Based on these results, in addition to evaluations of triggering events, landslide extent and return period, a risk matrix and activity matrix was developed. These matrixes were used as a base to make decisions of the required mitigation measures and remedial activities to reduce the classified risk. The risk mitigation measures should primarily be focused of the stability conditions toward the river in the south of the Haugen zone. Secondary, a stabilizing fill should be considered along the river. Further research should be performed on the Early Warning System for monitoring of the quick clay slopes and triggering events.

Acknowledgements

This thesis is executed for the Department of Industrial Economics, Risk Management and Planning at the University of Stavanger (UiS) and completes a two years' Master of Science in Industrial Economics. This thesis constitutes 30 study points and was carried out in the course of the spring semester 2017.

Before starting the work on this thesis my previous knowledge of the subject was limited, and after a lot of hard work I have realized that the subject is exiting, but also challenging. Throughout this thesis I have acquired new knowledge and insights into the world of risk analysis and quick clay landslides. My personal motivation was my previous knowledge in geology (Master level) and subjects in geotechnics. My knowledge concerning quick clay landslides, including mechanisms, triggering events, frequency and consequences, have increased greatly throughout this journey. This thesis presented a possibility of combining topics from risk with my interest in learning more about landslides. Living on a quick clay slope in Trondheim spiked my curiosity concerning quick clay slides and associated risk for human lives and material damage.

The subject of landslides is highly relevant in the Norwegian society, currently and in the future. The risk of future quick clay landslides increases with the climatic changes; therefore, something needs to be done to reduce the probability of new events harming human lives and property.

I wish to express my gratitude to those who have contributed and helped me along the way to make this thesis a reality. I wish to express my sincere thanks to Sigbjørn Tveterås for being my supervisor through the final part of this journey. I also thank him for valuable guidance on structure and content of this thesis during this process.

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Ingrid Skipenes Larsen

Stavanger, 15th of June 2017

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Nomenclature

EWE	Extreme Weather Event
ICG	International Centre for Geohazards
GEO	Geotechnical Engineering Office
GIS	Geographic Information System
IAEG	International Association of Engineering Geology
InSAR	Interferometric Synthetic Aperture Radar
LiDAR	Light Detection and Ranging
NIFS	Geohazard – Infrastructure – Flood – Landslide (Naturfare – Infrastruktur – Flom – Skred)
NGI	Norwegian Geotechnical Institute (Norges Geotekniske Institutt)
NGU	Norwegian Geological Survey (Norges Geologiske Undersøkelse)
NVE	Norwegian Water Resources and Energy Directorate (Norges Vassdrags- og Energidirektorat)
RAC	Risk Acceptance Criteria
SSB	Statistics Norway (Statistisk Sentralbyrå)
WP/WLI	International Geotechnical Societies' UNESCO Working Party on World Landslide Inventory

1. Introduction

1.1. Background

The largest and most damaging natural disasters in Norway's history have been caused by quick clay landslides. The socio-economic consequences of landslides are enormous, and they make the residents feel unsafe. Quick clay is a hidden hazard. Quick clay slides are triggered suddenly, and are harder to forecast than snow avalanches and extreme weather. A further challenge is that urban areas, both large cities and villages, are settled on top of quick clay slopes. It is therefore important to establish a complete risk analysis framework for quick clay landslides in Norway. The framework should include how to identify and map the quick clay zones, how to evaluate the hazards, consequences and risk, but also how to assess and treat this risk.

Currently, over 1750 quick clay zones have been mapped nationwide, where approximately 250 zones are classified as high and very high risk classes. 137 quick clay zones have been mapped in Buskerud county (L'Heureux et al., 2014). Buskerud is especially susceptible to quick clay landslides due to its geological history, and some large landslides have been triggered here in the past. It is estimated that more than 28 fatalities have been caused by clay- and soil slides in Buskerud in historical times (Furseth, 2006). In the Haugen zone, residential areas are resting on hills of quick clay which slopes into the river Lågen, and will have large consequences if the slope fails. Consequently, this area will be used to perform the empirical exemplification of the risk analysis framework.

Climate models show that an increase in landslide hazards can be expected in Norway as a result of the climatic changes. The models and forecasts predict an increase in the frequency and intensity of extreme weather events (EWEs) in the future (Dyrrdal et al., 2011). The global warming has led to changes in meteorological- and hydrological conditions, in addition to increased temperatures and amount of precipitation. Extreme rainfall can trigger quick clay slides in steep terrain and intensify the erosion in slopes adjacent to the rivers, but also increases the pore pressure in the clay which reduces the slope stability. Human activity and interventions in the terrain are also triggering factor for landslides. Risk management including structural and non-structural risk mitigation measures that can help reduce the hazard of landslides and consequently reduce the vulnerability and consequence level for the elements at risk.

Earlier the responsibility for safety associated with landslides were divided between multiple Ministries, without anyone having the overall responsibility. The Norwegian Water Resources and Energy Directorate (NVE) was in January 2009 assigned the overall responsibility for flood and landslide safety and risk. The governmental goal was to create safer communities and increase the civil protection through reduction of risk associated with landslides and floods. There are two landslides with a particular importance for the mapping and awareness concerning quick clay slides; the Rissa landslide in 1978 and the Kattmarka landslide in 2009. These and a few other major disasters helped to increase the awareness and “convince” the authorities of the need to take preventive measures. The national wide mapping of zones with potential quick clay hazard was started in the aftermath of the Rissa landslide. This process is further explained under previous work and is one of the main topics of this thesis.

1.2. Previous work

There have been published multiple articles and reports on the subject of geohazard and landslide risk, and how to assess and deal with this risk (Dai et al., 2002, Lavell, 2003, Mun, 2004, Fell et al., 2005, Lee, 2009, Nadim and Lacasse, 2009, Han et al., 2011, Lacasse et al., 2012, Rollins and Zekkos, 2012, Morello et al., 2014, AGS, 2000). In the 1980’s the attention towards risk and hazard assessments and mapping increased, and some of the later publications on this matter is by Karlsrud (2008), Rowe (2010), Clague et al. (2012), L’Heureux et al. (2014), Nelson (2014) and Ottesen et al. (2016). Gradually, the vulnerability and hazard assessment was implemented in natural hazards in the international community, which is reflected in the works by Cannon (1994), Wisner et al. (2003), Cutter and Finch (2008) and Cardona et al. (2012). The focus of mitigation measures as a tool to reduce the risk of landslides has increased the later years amongst engineers and geoscientists. It is now acknowledged that a proactive approach is required to deal with risk management.

Currently, risk and hazard is a natural part of the landslide analysis, and highly sophisticated geophysical and geotechnical investigation tools exist and should be included in the analysis (Lacasse et al., 2012). The new and improved scientific work enables more detailed estimates of magnitude, frequency, physical impacts of various landslide types. However, these scientific insights are not adequate to reduce risk, on its own, as it needs to be integrated with study performed by social scientists. The issues of coping capacity and vulnerability which needs to be incorporated into a hazard analysis (Clague et al., 2012). In the future, the scientific community must expand the knowledge of the mechanisms to be able to assist the authorities with up-to-date techniques, including investigation methods, hazard assessment, planning and mitigation measures (L'Heureux et al., 2014).

The Norwegian Geological Survey (NGU) started in 1970 to produce modern Quaternary geological maps of Norway. After the Rissa landslide, a national mapping of potential hazard zone for landslides was initiated. The mapping was conducted by the Norwegian Geotechnical Institute (NGI) and NGU, and focused on the locality and extent of the danger zones. This early mapping was performed in the Trøndelag and Østlandet regions, and was based on the Quaternary geological and marine limit maps. NVE initiated in 2001 a program with the aim of classifying the risk of the already mapped- and new quick clay zones, and to further investigate and implement mitigation measures in the zones of high or very high risk classes. The mapping and classification of risk required new procedures to be developed in the geotechnical community. Each danger zone was evaluated with respect to hazard, consequence and risk. The main focus of the quick clay mapping the last 2-3 decades have been large zones onshore (over 10 acres) and zones in close proximity to rivers or streams. The current methodology for mapping and preparation of danger maps are based on geological and geotechnical characteristics, topographical conditions, and observed changes in the terrain (L'Heureux et al., 2014). NVE performs quick clay mapping of selected areas, based on a risk priority in the urban areas of Norway. The results from the mapping are continuously updated in the NVE Atlas on www.nve.no. In connection with the Natural hazard-Infrastructure-Flood-Landslide (NIFS) project NVE and Statens Vegvesen have collaborated to improve the quick clay maps and the mapping methods (Ottesen et al., 2016). Increasing the rate of implementation of the quick clay mapping seems like an effective measure to avoid potential landslide events in the future.

1.3. Objective of study

The objective of this master thesis is to establish a complete risk analysis framework to undertake the risk of quick clay landslides in Norway. Until now, there have been partial analyses and guidelines published that focuses on single parts of the risk analysis process. The *Landslide Risk Management* framework compiled by the Australian Geomechanics Society (AGS) will be used as a base for the process of establishing a complete risk framework.

However, this framework needs to be greatly modified to fit the Norwegian practice for quick clay landslides. This framework encourages a uniform and systematic method to perform risk analyses, and includes several risk analyses to determine the hazards, consequences and risk, which is followed by risk assessment and mitigation measures. It should also contain room for judgement and engineering experience.

Another objective is to perform an empirical demonstration of this risk framework. The Haugen quick clay zone in Kongsberg is chosen for this purpose. The goal is to contribute in increasing the knowledge of how quick clay landslides are evaluated in terms of hazard, consequences, vulnerability and risk, and the importance of proactive risk management given its importance for the Norwegian society. The study can provide valuable information for the residents, other people working on problems connected to quick clay and to researchers. The study can hopefully inspire further work on the subject.

1.4. Problem statement

The focus of this thesis is the risk associated with quick clay landslides in Norway. There are two aspects of importance for this thesis. The first is how to develop a complete risk analysis framework for quick clay landslides. The second is how to demonstrate the use of the established risk analysis framework. Based on this the problem statement is divided into two:

1) **Develop a complete risk analysis framework for quick clay landslides in Norway.**
    - Establish a consistent terminology for landslide risk
2) **Perform an empirical exemplification of the risk framework on the Haugen quick clay zone in Kongsberg.**
    - Qualitatively evaluate the hazard, consequence and risk level
    - Estimate landslide run-out distance
    - Evaluate the triggering events
    - Perform a frequency analysis of landslides in Buskerud based on historical data
    - Quantify the vulnerability level of the Haugen quick clay zone
    - Create a risk matrix for the risk assessment, and provide information concerning the tolerable and acceptable levels of risk for loss of life
    - Propose structural and non-structural risk mitigation measures

Document analysis has been used for the purpose of answering the first problem statement, whereas a case study is used to answer the second problem statement. These methods are presented in the methodology chapter. The overall problem statements have not changed throughout the process. However, the types of analysis, methods and data used in the case study have been changed. Guidance is provided on methods used for the demonstration of the risk analysis framework.

The motivation for this thesis is the social significance of quick clay landslides in Norway. The society today has a focus on preventing disasters, and lack of knowledge as a cause is no longer tolerated. Hence, there is a need to increase the understanding of the factors controlling quick clay landslides. After the Kattmarka landslide, the inadequate method of the existing mapping method was debated, and changes were made. This work can hopefully contribute to a more effective hazard and risk mapping in the future.

1.5. **Limitations of study**

The focus of the study is to develop a complete risk analysis framework for quick clay landslides which have helped limiting the scope of the thesis. The main work was invested in the risks analysis, as they were important to achieve a risk estimate for the following risk assessment and management. The risk analysis performed is mainly qualitative, with exception of the frequency analysis and vulnerability analysis. This limitation is due to the time and data constrains. The focus of the analyses is limited to loss of life and property/structures, other elements at risk could have been included. The risk analysis of the Haugen quick clay zone focuses on the consequences onshore, and have not evaluated the potential of offshore landslides. Due to the time and resource constraint, the thesis lacks field surveys and onsite investigations.

1.6. **Outline of thesis**

Chapter 1: Is introductory, with objective of study, problem statement and limitations. The chapter also describes previous work in the field.

Chapter 2: Concerns quick clay, Quaternary geology and quick clay landslides in Norway, and provides a geological perspective for the rest of the thesis.

Chapter 3: Describes the methods and data gathering processes used in this thesis. The focus is on the data, document analysis and case study.

Chapter 4: Present the risk analysis framework for quick clay landslides which is the basis for the analysis. This chapter is based on document analysis.

Chapter 5: Is the case study part of the thesis. The focus is on the hazard evaluation, and several analysis and assessments are performed. The assessment and management of the landslide risk will be presented, and the theory from chapter 4 is used in practice.

Chapter 6: Presents the discussion of the main topics in the thesis.

Chapter 7 and 8: Is the closing part of the thesis and contains the conclusions of the work and recommendations for further work.

2. Understanding quick clay landslides

This chapter provides an overview of the geological framework needed to understand quick clay landslides. To study the possible causes of landslides we need to use theories from the fields of geotechnics[1] and quaternary geology[2]. The chapter introduces landslides in Norway, what quick clay is, where quick clay is found and how landslides occur.

2.1. Landslides in Norway

Landslides is the geohazards in Norway that represents the most severe risk for economic loss and loss of life. This is due to the Norwegian landscape, climate and the geological history (NGU, 2012, NGU, 2015c). During the last 200 years, approximately 2500 human lives have been lost due to landslides in Norway. Animals, injured people and material losses are not included in this estimate (Furseth, 2006, Jaedicke et al., 2008). Quick clay landslides contributed to 1150 of these fatalities (Furseth, 2006).

Landslides redistribute mass from areas of high elevation towards lower elevations, and in this way, contribute in the shaping the Earth’s surface. Landslides are most commonly found in, but not restricted to, mountainous areas. They can occur in any place with sufficient relief and slope angle to produce gravitational stresses able to cause soil or rock to fail (Clague et al., 2012). Geotechnical features, such as soil properties and slope gradient, determines the stability of the slope. Landslides are triggered when the strength of the slope decreases as a result of heavy rainfall climatic conditions, erosion, floods or human activity (Furseth, 2006). Consequences of such landslides can be destruction of infrastructure and cultivated land, such as roads and houses, as well as damaging habitats, and changing the local hydrology.

Quick clay landslides have caused some of the largest natural disasters in Norway. The large extent of these landslides separates quick clay slides from other landslides. The landslides occur very abruptly and most often without warning; therefore, the consequences may be catastrophic. The quick clay landslide in 1345 in Gauladalen, which was followed by a flood, is the largest registered in the country, with 500 fatalities (Rokoengen et al., 2001). The quick clay landslide in Verdal, where 116 people were killed in 1893, is also well documented (L'Heureux et al.,

[1] Geotechnics: Oxford dictionary define geotechnics as: “The branch of civil engineering concerned with the study and modification of soil and rocks”. From OXFORD DICTIONARY 2017. Geotechnics. *In:* OXFORD (ed.).
[2] Quaternary geology involves geological processes occurring during the ice ages in the Quaternary period, the last 2-3 million years. From NGU 1995. Geologisk ordliste. *In:* NGU (ed.) *Geologien i Narvik*..

2013). The Rissa landslide in 1978 is photographed in Figure 2.1. It was triggered by a minor terrain intervention that lead to 5 million cubic meters of quick clay sliding out in a matter of minutes and resulted in one fatality (NVE, 2006a).

Figure 2.1: Shows the landslide crater after the Rissa landslide. The length of the crater measures 1,5 km (NVE, 2006a).

Landslides are fairly normal phenomena in a geological time perspective, although there may be several years between each large slide (Janbu et al., 1993). Furseth (2006) concluded that smaller landslides occur relatively often, however the large quick clay landslides have a frequency of 2-3 per hundred years. There does not exist a clear definition of what a “large” slide is. However, Aas (1981) defined that landslides covering areas greater than 80-100 000 m^2 or which involves volumes greater than 0,5-1 000 000 m^3 qualifies as large.

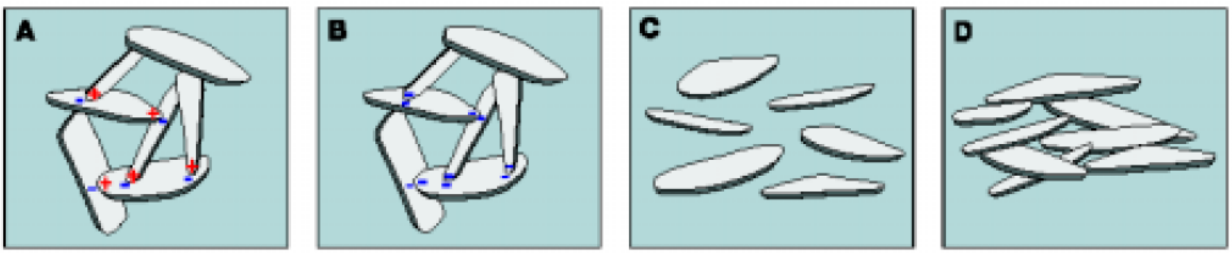
Landslides are defined as: “The movement of soil, rock and organic materials down a slope under the effect of gravity” (NIFS, 2014, p.12). Landslides are named and categorized after the type of masses involved in the slide. Further, geoscientists distinguish the slides based on the failure mechanism, speed and water content. According to the classification by Cruden and

Varnes (1996) quick clay landslides are defined as soil slides, based on the material and movement type. Other types of landslides are rock fall, snow avalanche and soil slides.

2.2. What is quick clay?

Clay is composed of microscopic particles formed by natural processes such as erosion and withering. For a soil to be classified as clay more than 30% of the particles must be smaller than 0,002 mm in diameter (Janbu, 1989). The soil is formed by withering and deposition of clay particles in quiet waters, especially in oceans. Clay is the most widespread sediment on Earth, as large parts of the deep ocean is covered by thick layers of pelagic clay.

What makes quick clay so special and feared, is the fact that it loses its firmness and floats as a liquid when disturbed or sufficiently overloaded. These properties are closely connected to the formation of the clay. Quick clay is deposited in saltwater, and is thus formed below the sea level. During the last ice age, Norway was covered with a thick icecap, adding weight and pushing the buoyant land downwards. When the ice started to melt approximately 12 000 years ago, the weight was gradually lifted, causing isostatic uplift of the land. Areas that had been located beneath the sea level now rose, bringing the deposited clay out of the saltwater and above the current sea level.
The particles precipitated in saltwater forms a loose, porous grain structures, where the particles create a skeleton and the pores are saturated with seawater, as seen in Figure 2.2 A (Janbu et al., 1993, Sveian et al., 2002). As seen in Figure 2.2 A, the tip of the grains is positively charged while the sides of the grains are negatively charged, holding the particles together. This charge is caused by the presence of ions from the saltwater.



Clay with pores filled with saltwater
Sheet-like grains in a open and loose, but stable structure.
The salt binds the particles together.

Quick clay before landslide
Open and unstable structure

Quick clay during landslide
Collaps of structure. Surplus of water. Low viscosity liquid clay.

Stirred quick clay after landslide
Closer and more stable structure.
This clay can never be quick again.

Figure 2.2: Quick clay structure before, during and after a landslide (Janbu et al., 1993).

Normal seawater has a salt content of approximately 35 grams per liter (Issler et al., 2012). If the salt content is retained the properties of the clay is kept normal and the clay is stable. However, if the salt content is slowly washed out and reaches a limit of 2-5 grams per liter, the ionic forces will be weakened, the loose structure becomes unstable and quick clay can be formed (Sveian et al., 2002). The presence of groundwater in the sediment or nearby river can wash out the salt and gradually reduce the concentration of ions in the pore water. When a landslide occurs the loose structure collapses, as seen in Figure 2.2, C and D, and the masses forms a low viscosity liquid, as seen in Figure 2.3, because the excess water originally located in the pores are released. An analogy for the structure of quick clay and its collapse is a house of cards; the smallest movement can cause failure of the structure.

Figure 2.3: Shows the liquid quick clay when stirred or overloaded (Issler et al., 2012).

The geotechnical definition of quick clay is a marine clay which in unstirred state has a remolded shear strength[3] $\geq 0{,}5$ kPa and a sensitivity[4] > 30 (NIFS, 2014).

[3] Remolded shear strength, Sr: The strength (measured in kPa) of stirred clay to resist loading. From: JANBU, N. 1989. *Grunnlag i geoteknikk*, Trondheim, Tapir.
[4] Sensitivity, St: is the ratio between the strength of the intact sample in relation to the strength of the disturbed sample of the same clay material.

It must be stressed that not all marine clay will become “quick” by leaching of its salt content. Quick clay is typically formed in lenses or pockets in hillsides and in slopes towards rivers or oceans. It is also important to note that quick clay in unstirred state is not a dangerous liquid mass in the ground waiting for a fracture to float through. Quick clay may initially be as firm as normal clay, and can withstand considerably strain if it is handled with sufficient care. However, if the salt has been washed out and the clay is overloaded, the structure can collapse causing a quick clay landslide (Janbu et al., 1993, Sveian et al., 2002).

2.3. Where is quick clay found?

The highest occurrence of quick clay in Norway are found in the eastern and middle parts of the country. In addition to small occurrences found in the Northern Norway as well as Western and Southern Norway (Jaedicke et al., 2008). Marine clay comprises about 5000 km² of Norway, where 20% consists of sensitive quick clay. Similar deposits are also found in parts of Sweden and Canada (NGU, 2015d).

The deposits of quick clay reflect the special glacial history in a period called Quaternary, hence, the last 2,6 million years. The Quaternary period consisted of fluctuating ice ages, superseded by milder interglacial periods. The thickness of the ice sheet covering Norway varied; it was generally thickest towards the center and thinning towards the coats. Following the melting of the ice, the uplift was largest where the thickness of the ice was greatest. It follows that the central part of Scandinavia has been uplifted (and is still uplifting) more than the Norwegian coast. There was a global sea level rise as the ice melted, around 120-125 meter since the last ice age. However, this sea level rise did not exceed the isostatic uplift in the Eastern Norway and in Trøndelag. Due to the country rising faster than the ocean, large areas around the fjords were elevated over the sea level and transformed to dry land. The phenomena of quick clay is thus connected to fjords in areas with a history of Quaternary glaciations and a subsequent isostatic uplift were the salt water clay (marine clay) has risen above sea level (Janbu et al., 1993, Sveian et al., 2002).

The highest sea level at the end of the last ice age, is referred to as the marine limit (ML). This level is the highest previous sea level after the disappearance of the ice and represents the highest point where we can find deposits of marine clay with the possibility of quick clay (NGU, 2015d). The height of the marine limit varies throughout Norway depending on the amount of uplift and thickness of the ice sheet. The highest marine limit, at 220 meters above the current sea level, is found in the areas around Oslo, whereas in Trøndelag the limit reaches 200 meters as illustrated in Figure 2.4 (Sveian et al., 2002). The prevalence of quick clay, and the danger of quick clay slides, are restricted to areas below the marine limit.

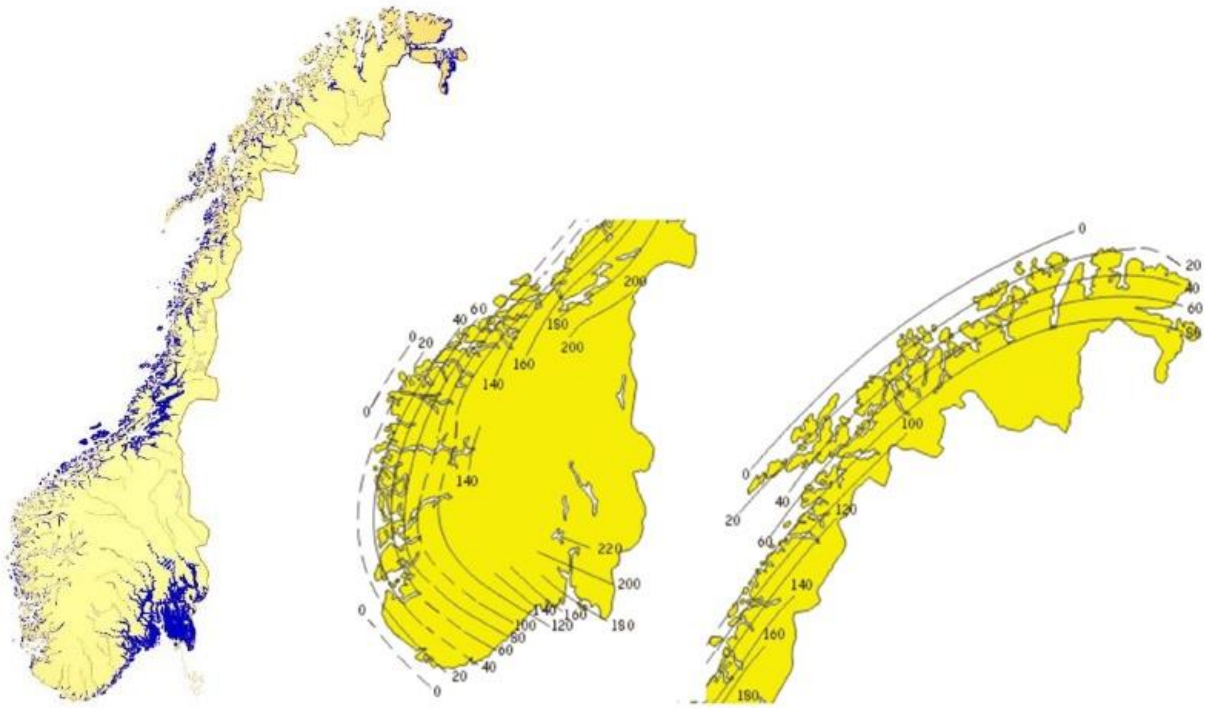


Figure 2.4: The blue areas shows areas located under the marine limit (Sveian and Solli, 1997). The marine limit in height over sea level in meters are shown. The numbers are highest were the ice sheet was thickest during the last ice age.

2.4. Why do landslides occur?

With some simplifications, it is easy to explain how landslides occur: the real cause of all landslides is forces of gravity. All soil particles will be affected by gravity, and will try to move to a lower level, if not inhibited to do so. It is the strength of the soil, the shear strength, that represents the hindrance. If the shear strength of the soil becomes considerably small in comparison to the forces trying to move a volume of soil downwards, a landslide will be initiated. As mentioned, the initiating events are either human intervention or natural events, such as heavy rainfall, erosion and earthquakes. This can be expressed by formulas and mathematical expression, which also can be used to calculate if a slope or area is sufficiently stabile (Janbu et al., 1993, Sveian et al., 2002).

In a hypothetical cut through a slope we can achieve a combinational effect, occurring simultaneously and operating in the same unfortunate direction: Heavy rain or significant snow melting can result in the groundwater level rising from “Low” to “High”, as illustrated in Figure 2.5. Water saturated soil is heavier than dry soil, hence the weight of the soil on the top of the slope will increase (increased driving forces). At the foot of the slope erosion may occur, especially if a river or stream is present, but also where the groundwater table trickles out of the ground (Janbu et al., 1993). Most important, however, are the processes occurring in the ground. The pore pressure will increase along potential fracture surfaces in the slope, and consequently the shear strength will be reduced. Both means reducing of the stability. When the driving forces exceeds the stabilization forces, the slope will fail and a landslide will be formed (Sveian et al., 2002).

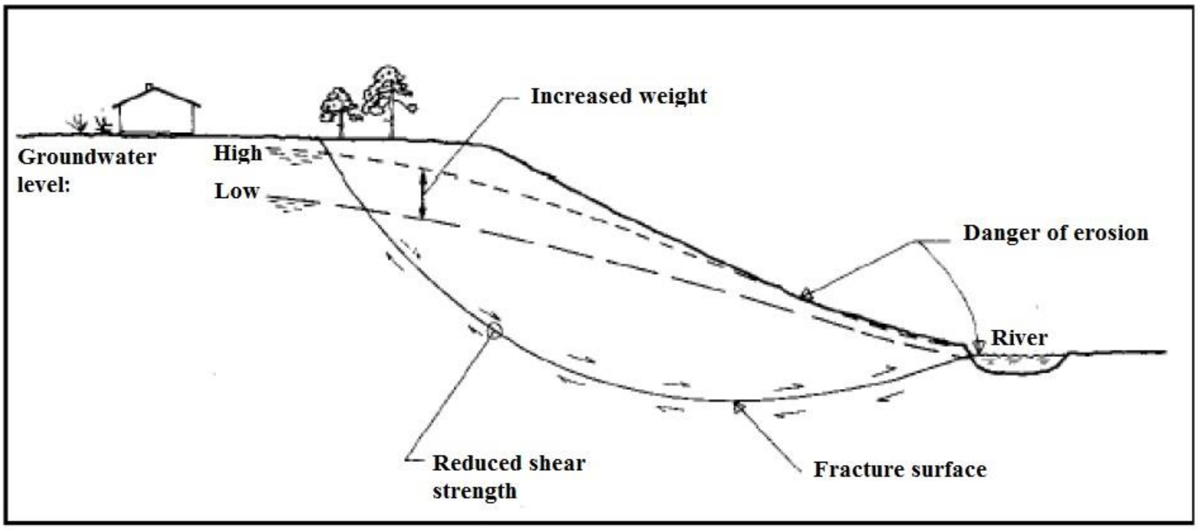


Figure 2.5: Cut through a slope with a typical circle-shaped fracture surface. Modified after Janbu et al. (1993).

Landslides can be triggered by natural causes, as has occurred in thousands of years. However, in present times most are triggered by human activity disturbing the natural balance and creating conditions for landslides (NGU, 2015d). This is done by either increasing the driving forces or by decreasing the stability, the same principal is valid for natural slides. Increased amount of load on top of the slope, most typically filling for roads, buildings etc., increase the strain. Digging at the foot of slopes, such as ditches, basements and road crossings, weakens the stabilization forces. Elevated supply of water out towards a slope may be risky in more than one way (Janbu et al., 1993, Sveian et al., 2002). Landslides triggered by human activity do not necessarily cause a landslide immediately. The slope may be apparently stable for years until periods of heavy rain and unfavorable conditions arise.

This knowledge is important to understand the geological/geotechnical framework for quick clay landslides and the risk they pose for the society. The knowledge is also useful for understanding the maps and risk analysis presented later in this thesis.

3. Methodology

This chapter provides an overview of the methods used to answer the problem statements and why these were chosen. The quality and uncertainty of the methods are discussed.

3.1. Data

The data forming the basis of this study is:

- Various databases of geotechnical reports, which includes public reports and documents regarding quick clay landslides, Quaternary geology, risk analysis methods, safety and risk mitigation measures.
- Database of soil investigation reports
- Newspaper articles of landslide events
- Information on the agencies websites (NVE, NGU, NGI, Statens vegvesen, Jernbaneverket etc.)
- Guidelines for quick clay mapping, stability requirements, and building and/or minor intervention in established quick clay zones
- Casework and articles involving quick clay problematics
- Multiple map portals
- Books on historical landslide events

All the documents used in the document analysis are available for the public. The data collection is based on strategical searches in the library databases, geotechnical databases, journal article databases, study of the reference list of reports and articles, and review of information available on the websites of the central agencies.

3.2. Document analysis

The first part involves establishing a complete risk analysis suitable for quick clay landslides, and a thorough document analysis was performed. Document analysis consist of a systematical review of written sources. What makes such an analysis special is that as sources are reviewed, the problem statement is illuminated and the understanding of other sources and the context is increased. Such an analysis distinguishes between central and peripheral documents. This study will mainly focus on the central documents. Further the lists of references of these articles/reports was studied. Primary sources of the document were used to be able to judge the credibility, and assess them relative to the context in which they were designed (Thagaard, 2003). For the risk analysis of quick clay slides the combination of the following keywords were used in the data gathering process: quick clay landslides, landslide risk, risk analysis for geohazards, quick clay, mitigation measures and risk assessment. The choices of literature were based on the relevance for quick clay landslides in Norway.

Sources of special importance for the risk analysis was: *Landslide Risk Management Concepts and Guidelines* by AGS (2000), *Method for Mapping and Classification of Hazard Zones, Quick Clay* by Gregersen (2001), *Learning to Live with Geohazards: From Research to Practice* by Lacasse and Nadim (2011), *Risk Assessment and Mitigation in Geo-Practice* by Lacasse et al. (2012), *Extent and Run-out Distance for Quick Clay Landslides based on a Catalogue of Landslide Events in Norway* by L'Heureux and Solberg (2012), *How to Calculate a Recurrence Interval* by Sciencing.com (2017) and guidelines by NVE, NGI and Statens vegvesen.

The most important landslide and risk terminology is collected in appendix A, and is used throughout this thesis to establish a consistent terminology. If you come across unknown terms, use appendix A as a reference to find the relevant definitions.

3.3. Case study

The case study of this thesis concerns the exemplification of the risk analysis framework on the Haugen quick clay zone in Hvittingfoss, Kongsberg. The quick clay zone as a unit is the focus of the analysis, not particular individuals or buildings. The purpose of the case study is to achieve a parallel understanding of the zone being studied and its connection to other conditions (Thagaard, 2003). To answer the second problem statement, the methods for gathering relevant maps, geotechnical investigations, fault trees and creation of landslide database are presented.

3.3.1. Gathering relevant maps

The purpose of the maps was to find the areas of potential landslide hazard and use this information to evaluate the hazard level. The maps used in this thesis was gathered from the map services found at nve.no (NVE, 2017a) and ngu.no (NGU, 2017a). Quaternary geological maps, marine limit maps and slope angle maps were used with the purpose of producing hazard maps. The hazard maps can be used for land-use planning, and public awareness.

Quaternary geological maps

Quaternary geological maps use polygons in various colors to provide an overview over the different types of sediments, their prevalence in the landscape and their formation. The maps also provide an overview over processes forming the landscape over time, as well as the distribution of the sediments and their expected characteristics. This information is of great importance for management of the landscape, including evaluation of vulnerability and landslide hazards (NGU, 2015b).

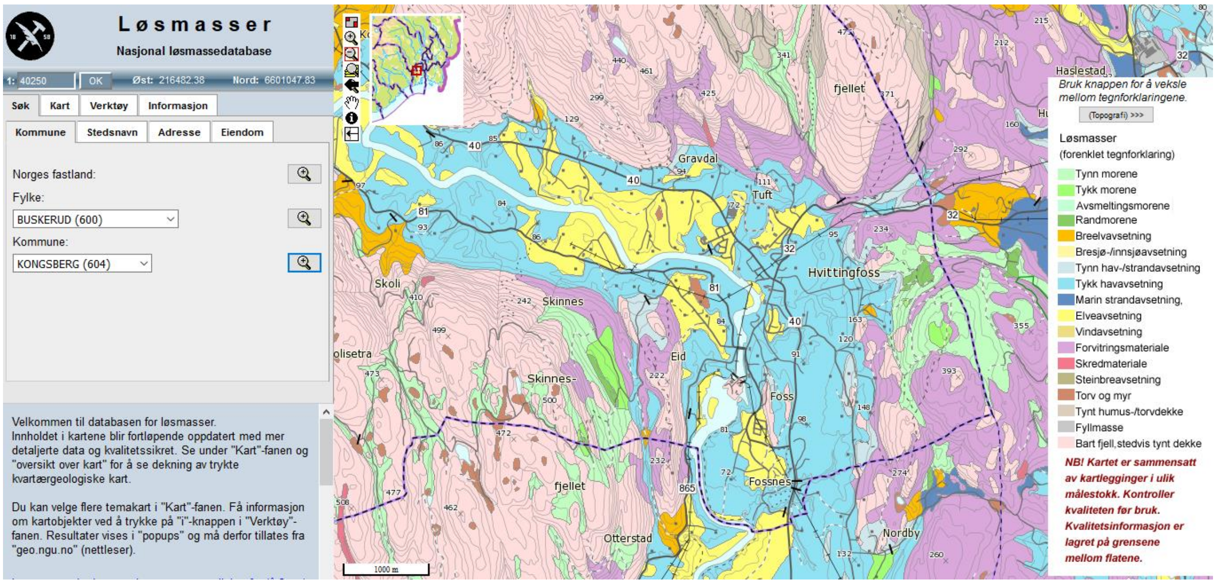


Figure 3.1: Quaternary geological map collected from www.ngu.no (NGU, 2017a).

The polygons are based on multiple Quaternary geological map products in different scales. This results in some simplifications in comparison to the complete Quaternary geological maps, because not all of the information is included. These maps are created by NGU, which have the national responsibility for the mapping, maintenance, updating and development of maps. The quality of these maps depends on the scale and the quality which they were mapped in. The production of the Quaternary maps includes detailed studies of airplane photographs, LiDAR data, extensive data collection in the field, and in some cases, also laboratory analyses. To develop these maps a solid competence in Quaternary geology is required. The map products are continuously improved to ensure the best possible quality (NGU, 2015b).

Marine limit maps

The maps showing the marine limit are useful in land-use planning and quick clay mapping. The marine limits are presented as points (ML-registrations), lines (modelled ML) and polygons (area over and under ML) in the map, see Figure 5.3 for reference (NGU, 2017b). NGU have created an additional map service “Marine limit and Quaternary sediments” which enables the readers to easier read the Quaternary geological maps, and identify areas with potential of quick clay, see Figure 5.3 for reference (NGU, 2016b).

The ML registrations are based on literature, geological maps and field observations by experienced geologists. It should also be taken into account that there may be some uncertainty associated with the ML registrations, and that the coverage of registrations varies. The uncertainty in the individual registrations will rarely exceed 10 m in height, and the most important areas of quick clay will be captured in the model presented in the map database. The uncertainty connected to the modelled ML will be somewhat larger, especially in areas with few ML registrations. However, the maps are continuously updated as new information is gathered (NGU, 2017b). The “Marine limit and Quaternary sediments“-service is based on a filtered and simplified version of the Quaternary maps, coupled with the data set for marine limits. It is important to check the scale of the mapping, and remember that there may be uncertainties in the underlying marine limits (NGU, 2016b).

Slope angle map

The maps of the slope angles are used to identify hazard zones, and decide whether the slope criteria are fulfilled (see chapter 4.1.2 for more information). An example is found in Figure 3.2. The colors range from white (0 degrees) to red (45-90 degrees), and are presented by polygons.

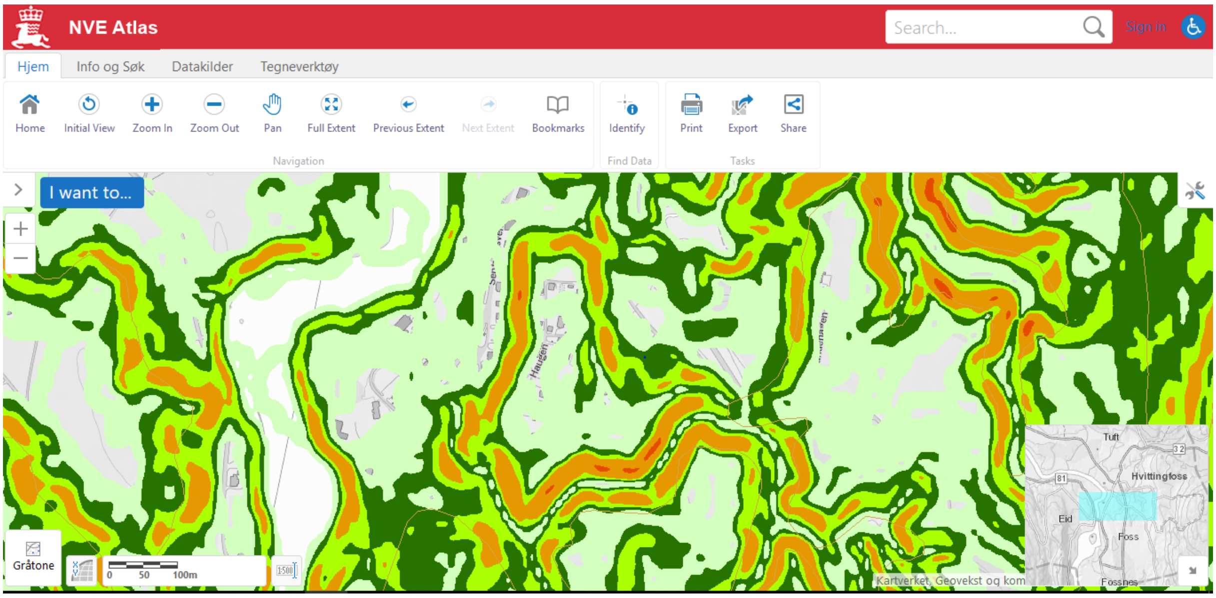


Figure 3.2: Shows the slope angle of the Hvittingfoss area (NVE, 2017a). The white areas are flat, whereas the red color presents the steepest slopes with the highest slope angles.

The polygons may include some simplifications and the registrations may be associated with some degree of uncertainty.

3.3.2. Geotechnical investigations

The geotechnical information from the Rambøll: Tveit et al. (2016) report was mainly used to evaluate the hazard level of the Haugen quick clay zone, but also to learn about the stability and safety factors of the area to decide which mitigation measures were needed.

NVE do not perform their own geotechnical investigations, but orders investigations associated with quick clay mapping, landslide situations, safety projects and detail investigations of quick clay zones (Ottesen et al., 2016). Rambøll was hired as consultants for the geotechnical investigations of the quick clay evaluations of the Haugen zone. GeoStrøm carried out the soil investigations in the Haugen area during 2012 and 2013. Data from previous investigations by GeoStrøm, Statens Vegvesen, Løvlien Georåd and NGI have also been included in the report by Rambøll: Tveit et al. (2016). This information is considered to be based on expert knowledge.

3.3.3. Fault tree

The purpose of the fault tree analysis was to show all the elements that need to be present for a quick clay landslide to occur. The fault tree analysis is a logical chart showing what is required for an top event to take place. The diagram shows how the various activities relate to each other and the undesired event. In the context of this thesis, the undesired event is the occurrence of a quick clay landslide, which presents the *top event*. The direct causes of the quick clay landslide are called *basic events* and are represented with rectangles. There are *logical gates* (symbols) connecting the basic events to the top event (Aven, 2008). These symbols with the interpretations are presented in Figure 3.3.

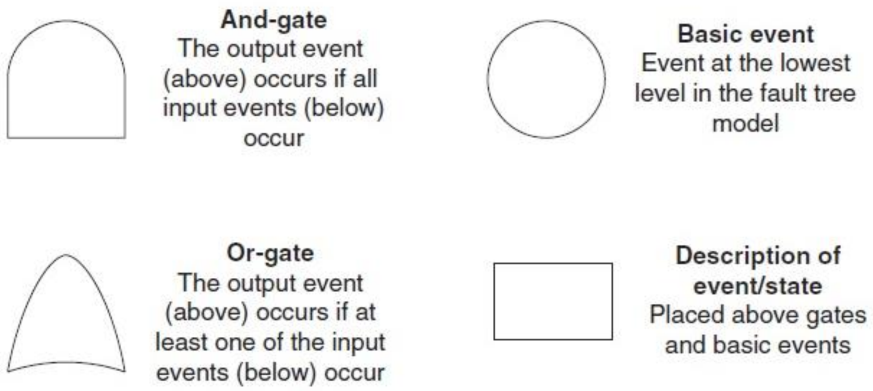


Figure 3.3: Symbols used in fault tree diagrams (Aven, 2008). The basic events in this thesis is presented as rectangles.

The fault tree presented by the author in Figure 5.5 was created using the software SmartDraw 2017. This software helps to create visuals quickly and includes various templates to choose from (SmartDraw, 2017).

The fault tree does not include numbers. This is because they would have been qualified guesses and not of any great value. However, the fault tree gives a simple overview of the factors that is required for a quick clay landslides to occur.

3.3.4. Creation of landslide database

This landslide database gathers data of previous and historical landslide events that have occurred in Buskerud county. The purpose of this data is to assess the frequency of landslides in the area and present the data statistically. Information concerning landslide events wass compiled in a landslide database, and is collected from different sources, which are explained below. The complete database is presented in Appendix C.

National landslide database

In the national landslide database, historical landslide events are registered with point coordinates, as shown in Figure 3.4. The database contains information from different sources, such as field observations, technical reports, historical documents, old church books and newspapers. The national landslide database is available on web at www.skrednett.no and www.skredatlas.nve.no. NVE is responsible for developing the database and web portals, coordinate data gathering and registrations (Ottesen et al., 2016).

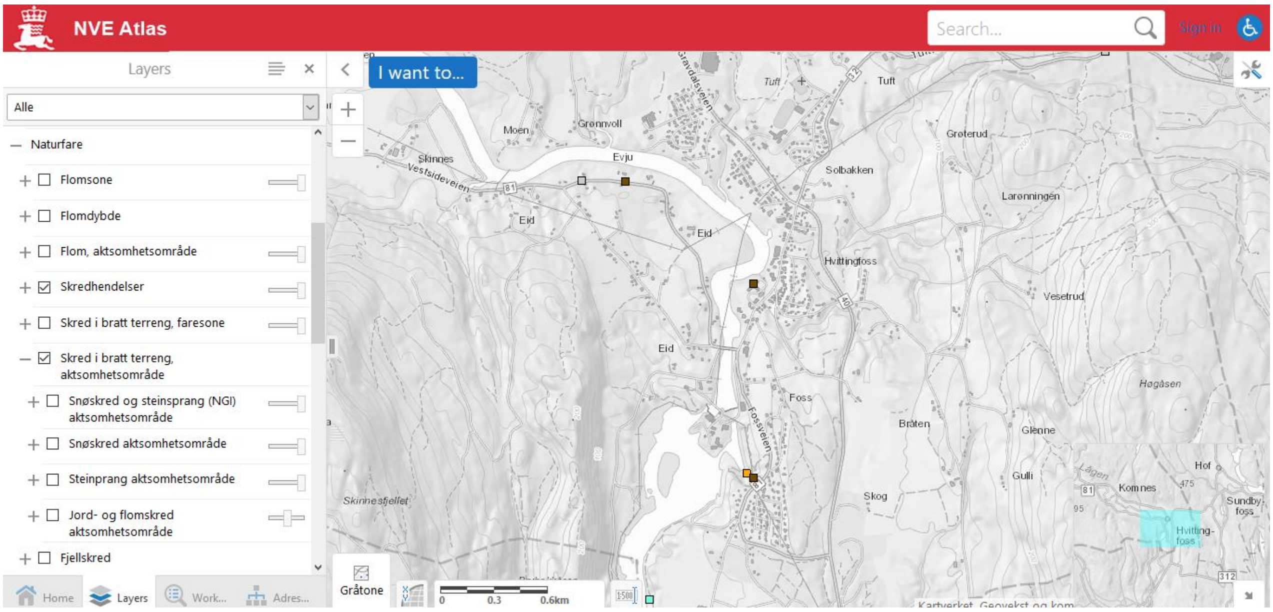


Figure 3.4: Shows an examples of landslide registration in the NVE Atlas (squares). The events are: orange square is a quick clay slide, white square is a snow avalanche and finally the brown square is an unspecified soil slides (NVE, 2017b).

Landslides are registered using the RegObs (RegObs, 2017) and Skredregistrering.no (NVE, 2017c) tools. RegObs is a tool for geohazard related observations, amongst others, landslides. The tool is found as a mobile application and web-platform. Everyone can register observations. The observations in RegObs are transferred to the national database regularly, whereas Skredregistrering.no registers landslide events directly into the national database (Ottesen et al., 2016). The landslide registrations are classified according to the masses involved, such as snow avalanche, submarine slide and quick clay slides.

Technical reports and literature

Quick clay landslides are one of the landslide types especially well documented through technical reports. Technical reports and literature are collected from NVE, NGU and NGI, and are described below:

- NVE and NGI have collaborated on multiple technical reports concerning quick clay events and processes (Gregersen, 2001, NVE, 2006b, Sandven et al., 2012, Dahlin et al., 2013, L'Heureux, 2013, Ottesen et al., 2016).
- The NIFS project, which is a collaboration between NVE, Jernbaneverket and Statens vegvesen, have recorded historical quick clay landslides, which have been gathered in the database (L'Heureux et al., 2014, Sokalska et al., 2015).
- NGU have through the local historian Astor Furseth gathered landslide events from the whole country as far back as the oldest historical sources are found (from before year 1000) and until today (Furseth, 2006). Hazardous landslide events are defined as landslide events which have resulted in loss of life or property. Hence, landslides that did not cause any harm are not included.

Quality and uncertainty

In most cases the data from the technical reports and literature are of good quality, and the information concerning place, date and landslide type is quite precise and detailed. However, the data quality varies from source to source. Generally, the data quality is better for the new data than the old. In the future, every registration will be flagged with a quality level, and routines for quality control are under development.

Accurate localization of the landslide events is often hard to find. This is especially the case for the older events, but also relatively new events where information often is collected from media. The positioning is often related to where the landslide has caused damage and not where the landslide was initiated. Therefore, positioning of the area were the slide was triggered or the extent of the slide is a more comprehensive process. For other types of information, such as landslide type, timing and extent of damages there are more uncertainty associated with the older events. The location of the registered quick clay slides should be double checked according to the marine limit maps, and erroneous placements can be identified. Landslides in mountainous areas occur on a daily basis, but most of these are not registered or observed as they don’t generate any harm or damage (NGU, 2015c).

The knowledge gained in this chapter allows for a better understanding of the execution of the risk analysis, and where the data is gathered from and the associated uncertainties. These methods will now be put into the risk analysis framework.

4. Risk analysis for quick clay landslides

The aim of this chapter is to establish a reliable risk analysis framework for quick clay slides in Norway. This chapter will present the relevant analyses and guidelines, and is divided into risk analysis, risk assessment and risk management.

4.1. Risk analysis

The *Landslide Risk Management* framework compiled by the Australian Geomechanics Society (AGS) will be used as a base for the process of establishing a complete risk framework. The AGS framework is shown using a flowchart in Figure 4.1, and provides an overview of the risk analysis process and how the various elements are related. This framework has been modified to fit the Norwegian practice for quick clay landslides. The risk framework will follow the same steps, so Figure 4.1 can be used as a reference throughout this chapter.

The risk analysis includes the following sub-chapters: scope definition, hazard identification, frequency analysis, consequence analysis and risk estimation. The differences from the AGS framework is that classification of landslides, evaluation of landslide extent and increased focus on the triggering events. This thesis lacks the qualitative risk calculations. The risk assessment includes the following sub-chapters: individual risk and social risk. The chapter considers the risk evaluation process for the Norwegian practice, but lack the owner/client/regulators risk acceptance and tolerable criteria. The risk management includes structural and non-structural mitigation measures. How the framework should be implemented is included in the discussion. This process is similar to the process defined in the ISO 31000. The process is integrated, and includes risk assessment and mitigation under continuous consultations, communication, monitoring and review (ISO 31000, 2009E). Further, the individual elements will be discussed.

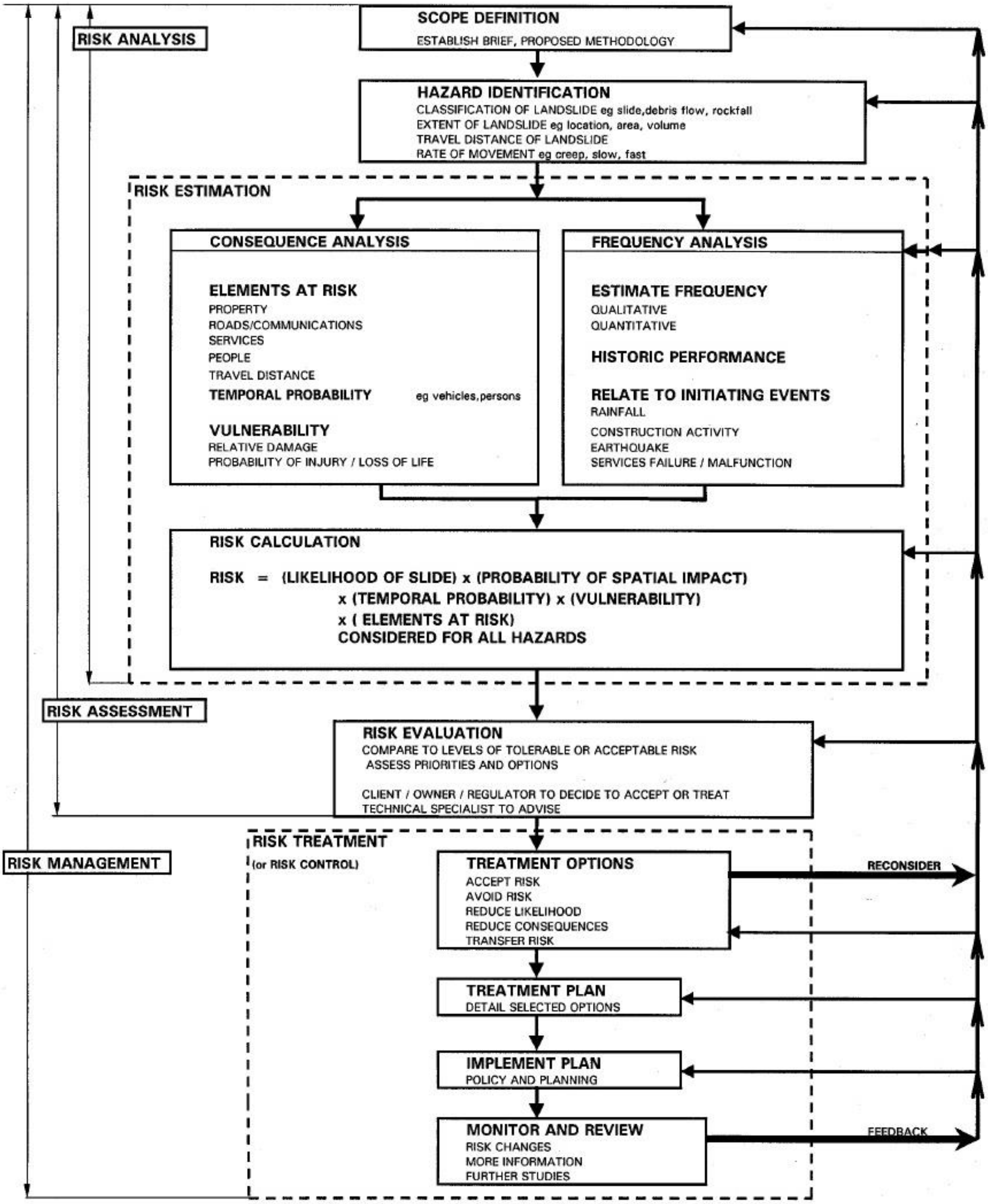


Figure 4.1: Flowchart over the risk management framework for landslides (AGS, 2000).

The terms and definitions is, as mentioned, presented in the appendix A.

4.1.1. **Scope definition**

A scope definition is carried out to ensure that the relevant issues are addressed, and to define the limitations of the analysis. But, also to define the following points (AGS, 2000):

- The site of interest.
- Geographical limits of the site and processes that may affect processes onsite.
- Should the scope be limited to including only loss of life or property, or also include injury to people?
- Types of analysis.

These points should be clearly defined prior to beginning the analysis together with the client. Another recommendation includes to specify the degree of quantification is defined. Some degree of quantification is recommended, as this enables easier communication of the results. However, a qualitative analysis may be appropriate. For analyses involving fatalities, it is recommended that the risk is quantified, even as an approximation, to allow a comparison with the tolerable and acceptable risk criteria.

4.1.2. **Hazard identification**

General principles

The identification of landslide hazards requires a good understanding and knowledge of geology, geotechnics, hydrology, vegetation and climate, and slope processes. This understanding can be used to (AGS, 2000):

- Classify the potential types of landslide. The classification by Cruden and Varnes (1996), is used for this purpose. This classification is used worldwide, and is included in Appendix B.
- Evaluate the characteristics of the material involved in the slide, and the mechanism behind it.
- Estimate the anticipated velocity and travel distance of the slide, also include the movement rate (fast, creep or slow).
- Assess the extent of the potential landslides, which should include the run-out area, regression and volume of masses involved.
- Identify the triggering factors for quick clay landslides.

Identification of hazard zones

There are two main preconditions which must be in place, simultaneously, for a landslide to occur; the quick clay must be sensitive and the stress in the clay close to fracture point (as mentioned in chapter 2). These conditions form the base of the identification and mapping of quick clay zones. The mapping of hazard zones is based on topographical criteria, which are based on study of previous landslide events in Norway. According to Gregersen (2001) the topographical criteria chosen are as follows:

- Steadily sloping terrain steeper than 1:15 (gradient) or 3,81˚ (degrees) is assessed.
- Differences in height of the terrain exceeding 10 m is assessed
- The maximum length of the landslide will correspond to 15*H (were H is defined as the height from the foot of the hill to the top of the potential quick clay slope)

The lower limit of 1:15 and 10 m will include most of the areas with potential danger for large landslides. When the slope reaches the critical values for height or slope, a landslide will occur. Hence, landslides are direct consequences of steep and high slopes. However, landslides can occur with less critical topographical conditions than established above and in any future time when these criteria are fulfilled.

In addition to these topographical criteria, marine limit and Quaternary geological maps were used to identify the potential hazard areas. For a zone to be identified as a quick clay zone it must be located under the marine limit (ML) and thick marine deposits must be present. After the zones of potential quick clay hazard are identified, the hazard level is evaluated using a qualitative method.

Hazard level evaluation (probability)

A qualitative evaluation of risk is fully subjective with respect to the evaluation of probabilities and the associated consequences of an event. The method uses predefined classification scales for ranking the hazard and consequence level. The classification scales used in this thesis is based on the method developed by NGI (Gregersen, 2001) and Lacasse et al. (2012). However, they were somehow modified to fit the evaluation of quick clay landslides. This method is simple, but practical. The hazard and consequence level of potential landslide areas is evaluated by obtaining scores for each individual zone according to these predefined classification criteria. These “engineering scores” are based on an assessment of the local conditions, the geology and the people exposed. The hazard classes are defined as low, medium and high, whereas the consequence classes are not severe, severe and extremely severe. Further, the risk is divided into five classes depending on the weighted scores from the hazard and consequence scores, and is based on the work by Lacasse et al. (2012).

The hazard level is dependent on the topography, geotechnical characteristics, geology, hydrological and new conditions, which include erosion and human activities. Table 4.1 shows the weights given to the various hazard factors, and is dependent on the importance of the factors in relation to each other. The hazard classes are dependent on the conditions and defined as:

1) ***Low***: Favorable soil characteristics and topography; no active erosion; sufficient investigations onsite; no previous sliding; the planned changes will lead to improvements in stability or no planned changes.
2) ***Medium***: Less favorable soil characterization and topography; active erosion; not sufficient investigations onsite; previous sliding; the planned changes lead to no or little improvements in stability.
3) ***High***: Unfavorable soil conditions and topography; active erosion; not sufficient investigations onsite; previous extensive sliding; the planned changes leads to a reduction in stability.

For a hazard zone to be characterized as "low hazard", with a low probability of failing, a weighted score of 0 to 17 is required. For "medium hazard", with a not critical, however higher probability of failing, a score of 18 to 25 is required. Zones characterized as "high hazard", with a high probability of failing compared to the other zones, a score of 26 to 51 is required.

Table 4.1: Evaluation of hazard level for quick clay landslides in Norway. Modified after Gregersen (2001).

Factor of hazard	Weight	Score for hazard			
		3	**2**	**1**	**0**
TOPOGRAHPY					
Previous sliding	1	Frequent	Some	Few	None
Height of slope, H	2	>30 m	20-30 m	15-20 m	<15 m
GEOTECHNICAL INVESTIGATIONS					
Overconsolidation ratio (OCR)	2	1.0-1.2	1.2-1.5	1.5-2.0	>2.0
Pore pressures[I]					
*In excess (kPa)	3	> + 30	10-30	0-10	Hydrostatic
*Under pressure (kPa)	-3	> - 50	-(20-50)	-(20-0)	Hydrostatic
Thickness, quick clay layer[II]	2	>H/2	H/2-H/4	<H/4	Thin layer
Sensitivity, St	1	>100	30-100	20-30	<20
NEW CONDITIONS					
Erosion[III]	3	Active	Some	Little	None
Human activity					
*Worsening effect	3	Important	Some	Little	None
*Improving effect	-3	Important	Some	Little	None
MAXIMUM SCORE		51	34	16	0
% of maximum score		100%	67%	33%	0%
[I]: Relative to hydrostatic pressure					
[II]: In general, the extent and location of the quick clay are so important.					
[III]: Erosion at the bottom of a slope reduces stability.					

Consideration should be made to hazards located on site, but also off site as these can impact the possibility and extent of a slide.

Landslide run-out distance and velocity

A better understanding of the landslide mechanisms can be used to improve the hazard mapping and evaluation. The velocity and run-out distance of a slide determines the landslide extent and the degree of people and property affected. The run-out distance is dependent on (AGS, 2000):

- Characteristics of the slope: type of material, height and slope.
- Failure mechanism and movement type: slide, flow, fall, collapse or influence of water.
- Characteristics of the downslope path: accumulation potential, vegetation and gradient.

One of the problems is that the landslide debris is hard to trace following a landslide event. This is because the masses often ends up in streams, rivers and fjords or are quickly eroded, and are therefore difficult to map (L'Heureux, 2012). However, based on theoretical and practical considerations the factor of 15*H is chosen for the maximum extent (L) from the landslide trigger zone until the masses comes to a stop. The factor 15 (L/H) was proposed by Gregersen (2001), and is currently used to evaluate the extent of quick clay zone in the Norwegian mapping program. L'Heureux and Solberg (2012) study of extent and run-out distance of 37 quick clay landslides in Norway shows that numerous historical landslides have L/H > 15. This factor must be used with discretion, as some types of landslides propagated with larger distances than the criteria dictates. The Rissa landslide is an example with a L/H of 25, as shown in Figure 4.2.

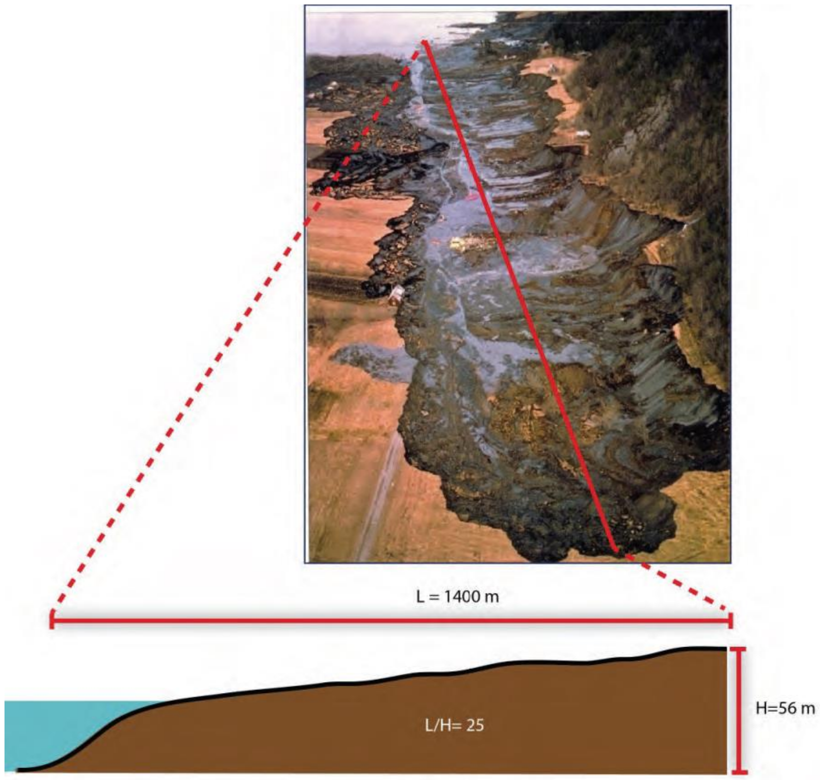


Figure 4.2: Studies of the slope from the Rissa landslide shows a critical L/H of 25 (L'Heureux and Solberg, 2012).

The maximal run-out distance can be calculated from the following equation:

Maximal run-out distance (L_u) = 3 * L (length of retrogression) **Equation 4.1**

Locat et al. (2008) study of Canadian quick clay landslides showed that there was a connection between the retrogression length and the volume of the landslide masses. The run-out distance increases with the volume of mobilized masses. Large retrogression and run-out distances is most likely to occur in valleys with steep gradients and close to deep lakes, and only when the sensitivity, St=30, and the remolded shear strength, Sr=0,5 kPa according to L'Heureux and Solberg (2012).

For landslide velocity estimates, it is satisfactory to classify the type of mass movement, based on the classification in Figure B. 2 (Appendix B), and find the typical velocities.

4.1.3. Frequency analysis

The purpose of the frequency analysis is to present the number of occurrences statistically. The frequency analysis is composed of historic landslide performance and frequency estimation in form of return period. This is the most time-consuming part of the risk analysis, but one of the most important.

Historic landslide performance

Knowledge about historic landslide events contribute to increase the understanding of landslide hazard in an area, and is therefore of importance for the hazard mapping process. The gathering of relevant historical data, from landslides that have occurred in similar geology, climate and topography, is important for the analysis. Previous landslide activity is used as a base in hazard level evaluation of the quick clay landslides, as recently explained.

The information of previous and historical landslide events is important for identifying future hazard zones, as future landslides are more likely to occur in close proximity to former landslide craters (Sokalska et al., 2015).

Frequency estimate

The recurrence period or return period is calculated for the landslide database of historical landslides in Buskerud to be able to estimate the frequency or how often landslides occur in the area. The frequency estimate is determined quantitatively based on statistics of landslides in space and time. There are two methods presented on Sciencing.com (2017) for calculating the recurrence interval:

1) ***Simple recurrence interval*** is calculated by finding the number of landslide occurrences and the numbers of observed years. The formula for a simple recurrence interval is:

$$\boldsymbol{RI = \frac{observed\ time\ (years)}{number\ of\ events}}$$

Equation 4.2

The result presents a frequency estimation for a chosen study area, which is the average time period between landslide events in the area.

2) ***Detailed recurrence interval*** is calculated using the number of events per chosen period and their ranking accordingly. The periods are ranked after number of events, where the period with most events is ranked 1 and the higher the ranking the less severe is the number of events. The probability of occurrence and recurrence period are calculated using the formulas from Sciencing.com (2017).

The probability, in percent, is calculated as:

$$\boldsymbol{Probability = \frac{Rank}{n+1}} \qquad \textbf{Equation 4.3}$$

where n is the number of periods. The recurrence is calculated using the formula:

$$\boldsymbol{RI = \frac{n+1}{Rank}} \qquad \textbf{Equation 4.4}$$

The results are often plotted graphically in excel.

4.1.4. **Consequence analysis**

The purpose of the consequence analysis is to identify the elements at risk and their vulnerability. The consequences in a consequence analysis are not limited to injury/loss of life and damage of property, but also includes public outrage, effects on reputation, political effects, litigation costs etc. However, in landslide assessment they are not often included as they are not easily quantifiable and require a lot of judgement. The consequence evaluation is a qualitative analysis, whereas the vulnerability study is a quantitative analysis.

Consequence evaluation

The consequence level is dependent on the degree of urbanization in the zone: number of residents (dwellings), industry buildings, roads, railways, powerlines etc., and is evaluated in Table 4.2. This evaluation is based on the classification by Gregersen (2001). However, they were somehow modified to fit the evaluation of quick clay landslides. The factors have been assigned a weight, 1-4, dependent on the importance of the factors in relation to each other. The score for each factor is the product of the assigned score and weight. The sum of theses scores decides the consequence level of the zone. The chosen consequence classes are as follows:

1) ***Not severe***: Small or no danger of loss of human life; valuable consequences and damages.
2) ***Severe***: Danger of loss of human life, property, social loss or extensive economical loss.
3) ***Extremely severe***: Great danger of loss of human life or large social or economic losses.

For a consequence zone to be characterized as "not severe" a weighted score of 0 to 6 is required. For "severe" a score of 7 to 22 is required. Zones characterized as "extremely severe" requires a score of 23 to 45.

Table 4.2: Evaluation of consequences for quick clay landslides in Norway[5]. Modified from Gregersen (2001).

Loss	Weight	Score for consequences			
		3	2	1	0
HUMAN LIFE AND HEALTH					
Number of dwellings[I]	4	> 5 (close)	> 5 (wide)	< 5 (wide)	0
Industry buildings, people	3	> 50	10-50	< 10	0
INFRASTRUCTURE					
Roads (traffic density), ÅDT	2	>5000	1001-5000	100-1000	<100
Railways (importance)	2	Main	Required	Level	None
Power lines	1	Main	Regional	Network	Local
PROPERTY					
Buildings, value[II]	1	High	Significant	Limited	0
Flooding impact[III]	2	Critical	Medium	Small	None
MAXIMUM SCORE		45	30	15	0
% of maximum score		100%	67%	33%	0%
[I]: Permanent residents in sliding area (close means closely spaced. Wide means widely spaced).					
[II]: Normally no one on premises, but building(s) have historic or cultural value.					
[III]: Sliding may cause water blockage or even dam overflow, flooding may cause new slides; need time for evacuation; losses depend on interaction of several factors.					

Vulnerability analysis

The physical vulnerability is defined as the degree of loss expected within a system from a particular threat. This vulnerability is quantified with a number between 0 and 1, where 0 is no loss and 1 is total loss (Rollins and Zekkos, 2012). Vulnerable elements include people,

[5] ÅDT (average annual daily traffic): Is the number of vehicles that pass a point on one road section in a year divided by the number of days in a year. From: STATENS VEGVESEN 2017. Årsdøgntrafikk trafikkregistreringspunkt Buskerud.

lifelines, structures, vehicles, infrastructure, and the environment. The vulnerability level to landslides is fundamental in deciding the severity of consequences for various groups of human beings, and affects the ability to recover from a disaster (Wisner et al., 2003). The factors affecting the vulnerability is different, depending on the vulnerability category being analyzed, and will now be discussed (AGS, 2000):

Factors that influences the vulnerability of people, or the likelihood of loss of life/fatalities are:

- The type of landslide, including initiating event and velocity.
- The volume of landslide masses.
- Whether the person(s) gets buried by the landslide masses.
- Whether the people are located in a building or vehicle.
- Whether the building or vehicle collapses under the impact or not.

Factors that mostly affects the vulnerability of structures or property are:

- The landslide volume in relation to the property (or other elements at risk).
- The position of the property, e.g. immediately downslope or on top of the landslide.
- The rate of the landslide movement.
- The magnitude of displacement due to the landslide.

This vulnerability model addresses the physical vulnerability in a quantitatively way. The vulnerability evaluation uses the VIS formula developed by NGI (Lacasse and Nadim, 2011):

$$\boldsymbol{V = I * S} \qquad \textbf{Equation 4.5}$$

where V is the vulnerability; I is the intensity of the landslide and S is the susceptibility of the various vulnerable elements. The landslide intensity is expressed as the possible damage caused by the landslide characteristics, both its kinematics (displacement, depth and volume) and kinetics (momentum, velocity). Lacasse and Nadim (2011) proposed the following method:

$$\boldsymbol{I = K_s * \ [r_G * I_G + r_D * I_D]} \qquad \textbf{Equation 4.6}$$

Where Ks is the spatial impact ratio; r_G and r_D is the geometric and dynamic relevance factor; and I_G and I_D is the geometric and dynamic intensity components.

K_s expresses how much a group of vulnerable elements are affected spatially and is defined by a number between 0 and 1. In Figure 4.3 K_s is the ratio between A_i/A_t.

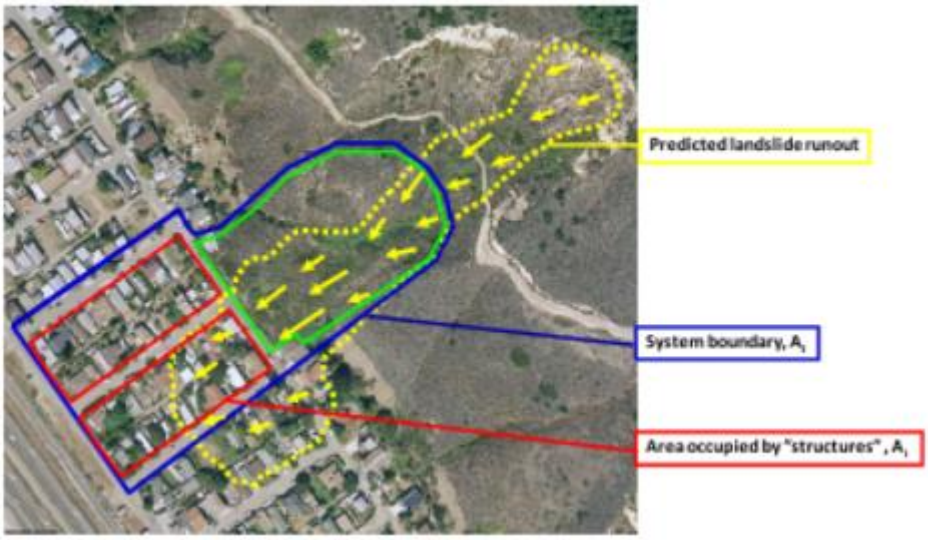


Figure 4.3: Shows an illustration of how the spatial impact ratio, K_s, is found (Lacasse and Nadim, 2011).

Following, the relevance factors is specified for each landslide with respect to the vulnerable categorize and landslide type, and should reflect all the available knowledge on losses caused by the geometric and dynamic landslide characteristics. Table 4.3 shows the relevance factors used for quick clay landslides in this vulnerability analysis. The total values of the relevance factors should sum to unity ($r_G + r_D = 1$).

Table 4.3: Relevance factors used in the vulnerability calculations. Modified after Lacasse and Nadim (2011).

Category	Landslide	rD	rG
People	Rapid	0.75	0.25
Structures	Rapid	0.90	0.10

I_D expresses the losses caused by the momentum and kinetic energy of a landslide, and is defined by a number between 0 and 1. I_G expresses the dimensional properties of the landslide, which includes the run-out distance, volume and depth, and is defined by a number between 0 and 1.

The second part of the VIS formula, the susceptibility of quick clay landslides, expresses the disposition of the vulnerable categorize to experience loss. The susceptibility depends of the geometry and resistance of the individual elements. The model for susceptibility calculations is expressed:

$$S = 1 - \prod_{i=1}^{n}(1 - \varepsilon_i)$$ **Equation 4.7**

where ε is the susceptibility factor, which is dependent on the vulnerability category and expresses the user’s degree of belief (knowledge) of the susceptibility. The various factors are given scores of 0 to 1.

Factors influencing in the susceptibility determination for people (S_{PSN}) in vehicles or outdoors are age, population density and income, and the following model is proposed using Equation 4.8:

$$S_{PSN} = 1 - (1 - \varepsilon_{PDN})(1 - \varepsilon_{GDN})(1 - \varepsilon_{AGE})$$ **Equation 4.8**

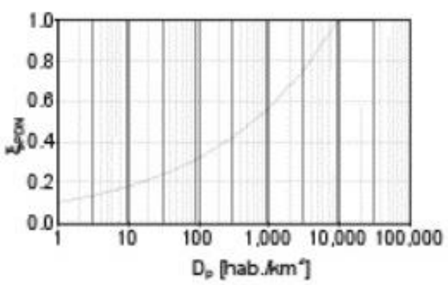
The following influence factors are used in the approach:

Table 4.4: Susceptibility of persons (in vehicles and outdoors) (Lacasse and Nadim, 2011).

Age (years)	ε_AGE	Age (years)	ε_AGE
0-5	1	55-60	0.3
5-10	0.9	60-65	0.5
10-15	0.7	65-70	0.7
15-20	0.3	70-75	0.9
20-50	0	>75	0.95
50-55	0.1		

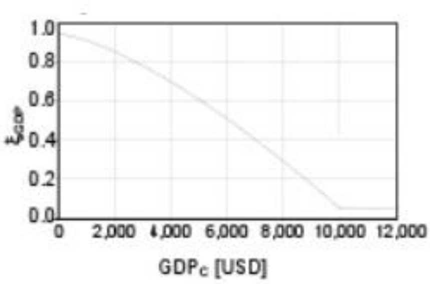
Susceptibility as a function of population density, ε_PDN

$$\varepsilon_{PDN} = \begin{Bmatrix} 0{,}1 * D_p^{0{,}25} & D_p \leq 10\,000 \\ 1{,}0 & D_p > 10\,000 \end{Bmatrix}$$



Susceptibility as a function of income, ε_GDP

$$\varepsilon_{GDP} = \begin{Bmatrix} 0{,}95 - 0{,}90 * \left(\dfrac{GDP_c}{10\,000}\right)^{1{,}4} & GDP_c \leq 10\,000 \\ 0{,}05 & GDP_c > 10\,000 \end{Bmatrix}$$



Factors influencing the susceptibility determination for structures (S_{STR}) and the people inside are maintenance state and structure type, and the following model is used/proposed:

$$S_{STR} = 1 - (1 - \varepsilon_{STY})(1 - \varepsilon_{SMN})$$ **Equation 4.9**

The following influence factors are chosen for the approach:

Table 4.5: Susceptibility of structures (Lacasse and Nadim, 2011).

Type	Resistance	ε_STY	Maintenance	ε_SMN
Light and simple structures	None	1.00	Very poor	0.50
Light structures	Very low	0.90	Poor	0.40
Rock, concrete and timber	Low	0.70	Medium	0.25
Brick and concrete	Medium	0.50	Good	0.10
Reinforced concrete structures	High	0.30	Very good	0.00
Reinforced structures	Very high	0.10		

The result of the analysis is a vulnerability estimate quantified with a number between 0 and 1.

4.1.5. Risk estimation

In cases where the amount of numerical data is inadequate, a qualitative analysis should be used. The following method is semi-qualitative. The risk scores are used to define a risk class for the defined hazard zones, which is acquired from the following relationship:

$$R_S = H_{WS} * C_{WS}$$ **Equation 4.10**

where R_s presents the risk score, H_{WS} presents the weighted score from the hazard evaluation and C_{WS} is the score from the consequence evaluation. The numbers for risk score is achieved by multiplying the score from the hazard evaluation (%) with the score from the consequence evaluation (%). The risk scores are divided into 5 risk classes. This is done to divide the lowest risk zone from the highest. The classification of the risk classes are as follows (Lacasse et al., 2012):

1) ***Low (risk class 1):*** Includes all zones with score between 0 to 170.
2) ***Intermediate (risk class 2):*** Includes all zones with score between 171 to 630.
3) ***Medium (risk class 3):*** Includes all zones with score between 631 to 1900.
4) ***High (risk class 4):*** Includes all zones with score between 1901 to 3200.

5) ***Very high (risk class 5):*** Includes all zones with score between 3201 to 10000.

The risk class of the zone decides the priority of the risk mitigation measures. An activity matrix is proposed for the need of remedial measures and further investigations.

4.2. Risk assessment

A risk analysis has limited benefits alone, hence the steps of risk assessment and risk mitigation are crucial. The main objective is to decide whether the risk should be accepted or treated, and to set the desired priorities.

The risk evaluation judges the estimated risk in form of acceptability and significance. This process might involve comparisons to other assessed risks or acceptance criteria associated with financial losses, loss of life or other values (Lacasse et al., 2012). In some situations, this value judgment can easily be made if the client is the only affected party of the risk. However, if this is not the case, environmental effects, politics, public reaction and business must be considered before making the decision whether the risk is acceptable. The process is often iterative, and requires assessments of the sensitivity of the assumptions and calculations, but also development modifications and revision of measures to mitigate risk (AGS, 2000).

4.2.1. Risk acceptance criteria

An important part of the risk assessment process involves comparing the estimated risk against the acceptance criteria, but also to recognize that there is a difference between the risk desired by the society and the risk they may tolerate and live with. This applies to both loss of life and property, and it is always the client/owner/regulating authority that assesses if the risk is acceptable in the specific situation (AGS, 2000).

Loss of life

There do not exist any established acceptable risk criteria for potential loss of life, not in Norway or internationally. However, some principles and information from other industries can be used as a guideline for acceptance criteria for quick clay landslides. Some of these are (AGS, 2000):

- The risk of quick clay landslides should not be significantly larger than other risk which a person is daily exposed to.

- The risk of the hazard should be reduced, whenever reasonably practicable. Hence, ALARP principle should be implemented.
- If the possibility of a landslide causing multiple fatalities is high, the probability of it occurring should be low. This is based on the society's intolerance of such incidents.
- People with limitation, financial or others, will tolerate higher risk regarding the acceptable risk because they are unable to reduce or control it.

Property

There are many factors that affects an individual's attitude towards risk acceptance or tolerance, such as availability of resources for risk treatment, presence of insurance, whether the results of the risk analysis is considered true, policy or regulatory requirements, prior exposure to risk associated with landslides in Norway and the character and age of the individual (AGS, 2000).

The risk acceptance criteria can be difficult to establish. The 'F-N curves' can be used as a guidance for the level of risk the society is willing to accept. The curve visualizes the annual frequency (F) of event causing fatalities versus the number of fatalities (N). The N term can be replaced by another measure of consequences, for example cost. The F-N curve expresses the societal risk and the level of safety for a particular case or study. Figure 4.4 presents the recommended risk criterions for natural landslides in Hong Kong (GEO, 1998).

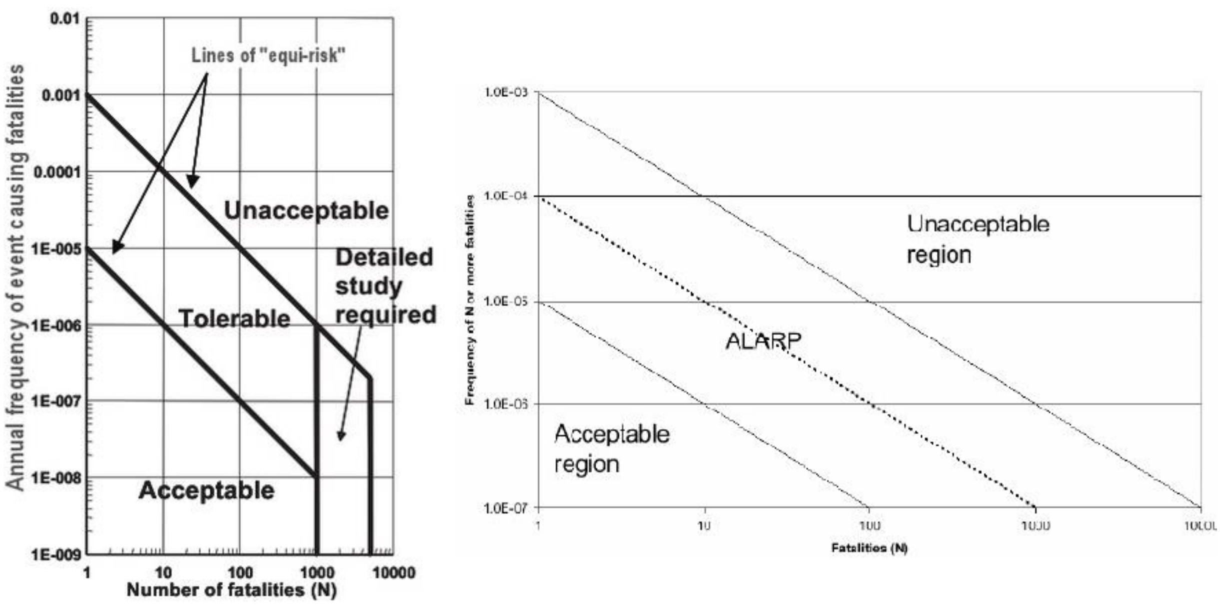


Figure 4.4: Examples of F-N curve. Left: GEO (1998). Right: Diamantidis et al. (2006).

Risk acceptability is dependent on a variety of factors, amongst others, involuntary vs. voluntary exposure, unfamiliarity vs. familiarity, long vs. short term effects, uncontrollability vs. uncontrollability, nature and type of consequences, presence of other alternatives, media coverage, gained benefits, personnel involved and information availability. Generally, the voluntary risk is higher than the involuntary risk (Lacasse et al., 2012). In the landslide context, voluntary risk is the residents choosing the live in close proximity to a natural slope, whereas involuntary risk is the resident living close to an engineered slope. Part of the country where landslides are frequent have another level of risk acceptance compared to the parts where landslides occurs rarely.

4.2.1. Risk matrix

A risk matrix can be used as a tool for assessing and describing the risk of quick clay landslides. Due to the general lack of numbers, a qualitative approach is chosen. By combining the level of severity for the possible hazard consequences and the probability of the hazard occurring a risk matrix can be created (Lee, 2009). A risk matrix provides a simple and quick overview over the potential risks, and can help in decision making processes. The matrix can help to make priorities regarding supervision of possible dangerous situations, and to develop risk mitigation strategies. In this context, the definition of risk as the product of probability and consequences (Risk=Probability*Consequences) is used. To create this risk matrix a thorough understanding of the occurrence and consequences of quick clay landslides is required.

4.3. Risk management

Risk management includes the risk treatment and mitigation processes, and is composed of organized activities intended to assess, control and direct the risk posed by landslides, but also to develop mitigation strategies (Lacasse et al., 2012). The overall purpose of the risk management is risk reduction. To achieve this, the probability (frequency) of the landslide event or the exposure and/or vulnerability of the vulnerable elements must be reduced (Lacasse et al., 2008). The bow-tie diagram in Figure 4.5 shows the components of risk and hazard mitigation.

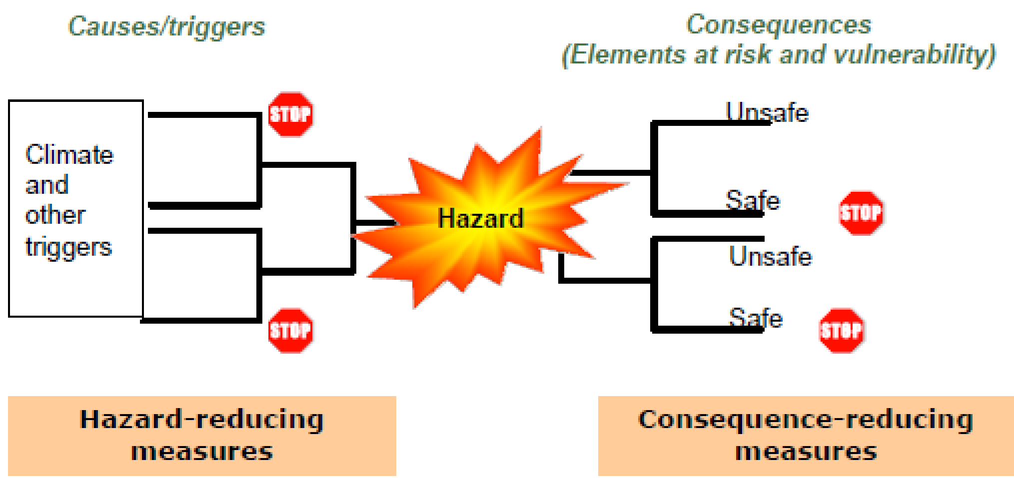


Figure 4.5: Risk bow-tie showing risk reducing measures (Nadim and Lacasse, 2009).

Typical risk mitigation strategies include increased communication of risk, often through public awareness campaigns, and pro-active strategies. The risk associated with landslides are more often categorized as: (1) structural measures to stabilize slopes to reduce the severity and frequency of the hazard, and (2) non-structural measures, which includes early warning systems, public awareness, community preparedness and land-use planning to reduce the consequences of the hazard (Lacasse et al., 2012). The process of identifying the optimal mitigation strategy considers: (1) the potential triggering scenarios of the landslide, and the hazard level; (2) a variety of different consequence scenarios; (3) the assessment of potential risk reducing measures for possible consequences; (4) the recommendation of remedial actions; and (5) the communication and knowledge sharing with the society and the authorities in charge (Nadim and Lacasse, 2009). The structural and non-structural measures will now be discussed.

4.3.1. **Structural measures**

The structural measures include physical measures and active interventions in the nature, which requires engineering work. Construction of barriers on slopes as physical protection, erosion protection, drainage improvements, ground and vegetation improvement are some of the physical protection measures. These measures aim to reduce the severity and frequency of the landslide hazards, and should therefore be part of community plans to reduce the negative impacts of geohazards (Lacasse and Nadim, 2011). Some of the most used structural measures will now be discussed:

- ***Protection barriers or walls*** aims to delay or stop the landslide impact, but also to reduce the severity of the impact and dissipate the loads or energy induced by the slides.

The protection barrier may be hard structures, such as stone or concrete walls, or soft structures, such as embankments or dikes (Nadim and Lacasse, 2009).

- ***Erosion protection*** aims to prevent erosion of base of slopes that may slide out due to reduced stability. In some more drastic cases, the streams/rivers are redirected or even closed to protect slopes from erosion (Rambøll: Tveit and Aasland, 2016).
- ***Drainage improvements*** aims to drain the water after rainfall to reduce the risk of this triggering factor (Rambøll: Tveit and Aasland, 2016)..
- ***Adding of lime/cement*** has a favorable effect on the strength properties of the clay. This method has been used extensively the last 20-30 years to restore the stability of the quick clay (NVE, 2006a).

The need for these structural measures will be based on the safety factors (FS) obtained from the stability analyses. The safety factors indicate whether the slope is stable or not. The types of stability analyses are defined in Appendix B.

4.3.2. Non-structural measures

The non-structural mitigation measures include improvements of land-use plans, enforcement of sound construction practices and building codes, public awareness and preparedness campaigns and early warning systems (Lacasse et al., 2012). The purpose of these measures is to reduce the vulnerable elements and the consequences of a potential landslide.

In cases were landslides may cause fatalities/injuries or property damage early warnings systems should be considered. The purpose of these systems is to monitor potential slopes that may fail and forewarn the public of impending danger (Nadim and Lacasse, 2009). In Norway NVE prepares daily warnings for landslides in soil which describes the caution level and landslide type for the various counties. The aim is to avoid loss of life and property damages due to landslides. This system has been operating since 2013 (NVE, 2015). Collaboration between NVE, Statens vegvesen, Jernbaneverket, met.no and Kartverket have resulted in an expert tool for warning, monitoring, but also forecasting and emergency response of landslides. This tool is called xgeo and found at www.xgeo.no, and includes maps with data from models and stations with field and event observations (NVE, 2017d). This map service includes information which may lead to triggering of landslides, such as precipitation, groundwater level, soil saturation, rainfall and so one. Early warning systems for quick clay slides, will be discussed further in chapter 5.4.

This chapter have presented the risk analysis framework for quick clay landslides, and considerations associated with these analyses. The next chapter will demonstrate the use of this framework on the Haugen quick clay zone in Kongsberg. This will be carried out by following the approach from the flowchart in Figure 4.1.

5. Risk analysis of Haugen quick clay zone

The purpose of this chapter is to perform the established risk analysis on the Haugen quick clay zone in Kongsberg. In this process, the hazard, consequences and risk level will be qualitatively evaluated, the landslide type classified, the run-out distance estimated, a frequency analysis performed, triggering events evaluated, vulnerability level quantified, risk matrix created and structural and non-structural mitigation measures proposed. The result of the analyses will be interpreted. The chapter is divided into three main parts: risk analysis, risk assessment and risk management.

5.1. Scope definition

The study area is located in Hvittingfoss village which is located in the south-east part of Kongsberg municipality in Buskerud county. The Hvittingfoss area has a population of 1090 people per 2015 (Statistisk sentralbyrå, 2015). The Haugen quick clay zone is located on a plateau south of Hvittingfoss center. The locality is especially susceptible to landslides, quick clay slides in particular. There is a long history of landslides and several residential areas are resting on hills of quick clay which slopes into the river Lågen.

The geographical limits of the study area are limited to the Haugen area in Hvittingfoss, as shown in Figure 5.1. The Haugen site is mapped as a quick clay zone by NVE. In Buskerud 137 quick clay zones have been mapped (L'Heureux et al., 2014). However, some of the surrounding areas are included in the analyses, as processes outside may affect processes within the Haugen site.

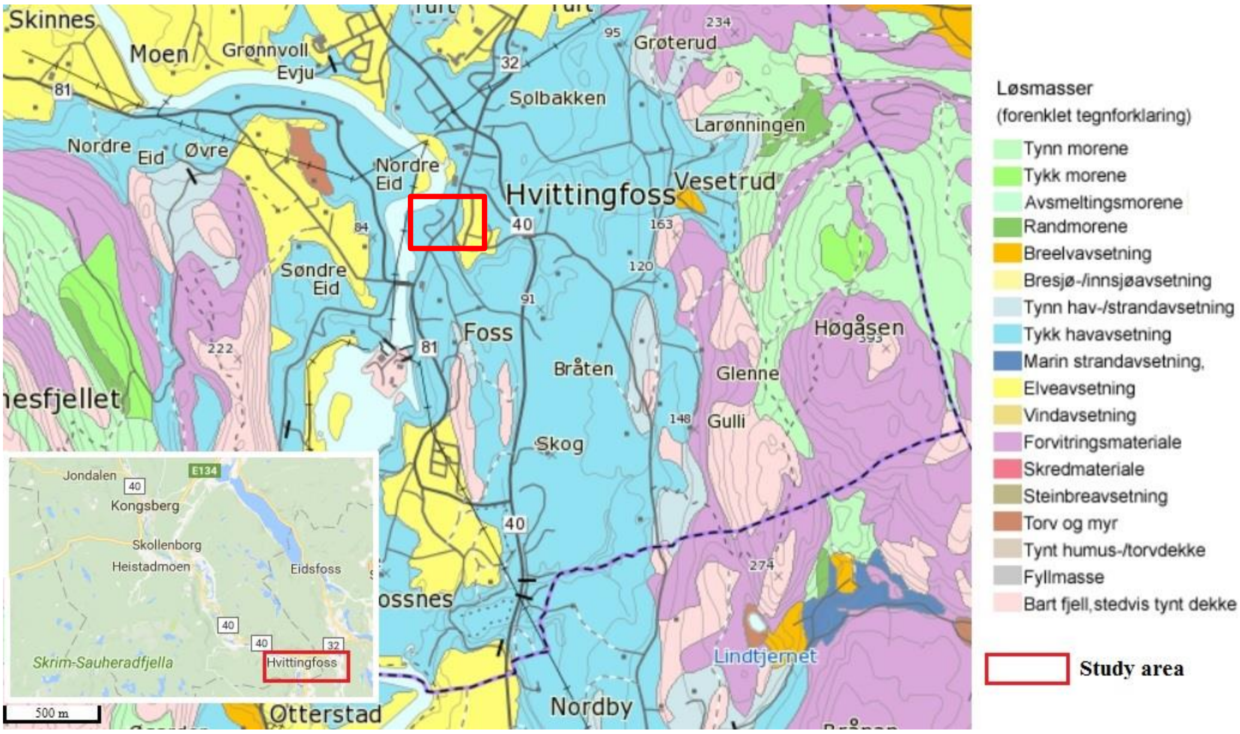


Figure 5.1: Shows the location of the study area and the sediments dominating the area (NGU, 2017a). The Hvittingfoss area is dominated by marine sediments, but fluvial and glacial sediments are also found.

The study area is situated in a populated, urban area, where loss of life is the main focus of the analysis. Loss of life or injury of the population have a higher impact in the society; hence the main attention will be on this element at risk. Therefore, the quick clay zones located in populated areas should be fully investigated. Some considerations of loss of property will also be included. Large economical values are often tied up in property along rivers and there is an increasing pressure for urbanization in these areas. Accordingly, there is a need for mapping areas of hazard and high risk and evaluate the need of safety measures and prioritize these for existing property and infrastructure.

The analyses carried out in this thesis uses information from the geotechnical investigations performed by Rambøll: Tveit et al. (2016) as explained in the methodology chapter. But, the hazard, consequences and risk evaluations and the other analyses are performed by the author. A variety of analyses are carried out: Identification of hazard areas, hazard evaluation, assessment of landslide extent and triggering events, frequency analysis, consequence evaluation, vulnerability analysis and risk estimation. In addition to these analyses a risk assessment is carried out, followed by risk mitigation propositions.

The analyses are primarily qualitative. However, some forms of quantification are performed in the vulnerability analysis and frequency estimation.

5.2. Hazard identification

The first step in the risk analysis process is to identify the hazards posing a danger for the study area, and quantify them if possible.

5.2.1. Classification of landslide

Based on the classification from Cruden and Varnes (1996), found in appendix B, a quick clay landslide is classified as a slide in fine-grained soil (marine clay). The rate of movement associated with quick clay slides are characterized as extremely rapid mass movements. Typical velocity of the masses is 5 m/sec or 18 km/hour, which makes escaping the masses not likely. Based on the water content in the pores quick clay is classified as wet. The large and fast moving landslides poses the greatest threat to human lives and causes the largest economic losses, especially when the quick clay floats as a liquid when disturbed or overloaded.

5.2.2. Identification and mapping of hazard zones

The identification of quick clay zones is based on topographical criteria, map studies and the presence of marine clay from onsite drilling and soil investigations.

The topographical criteria established by Gregersen (2001) proposed that areas with slope greater than 3,81° and height difference in the terrain exceeding 10 m should be assessed. These criteria are used as the basis for identifying and mapping hazard zones. The investigation of the slope angle, marine limit and quaternary geological maps are also used for this purpose. The areas that match all the criteria for landslides, are marked as potential danger zones. Areas under 10 acres in extent and areas located in the shoreline are not included in the mapping. Figure 5.2 shows the slope of the terrain within the Haugen zone.

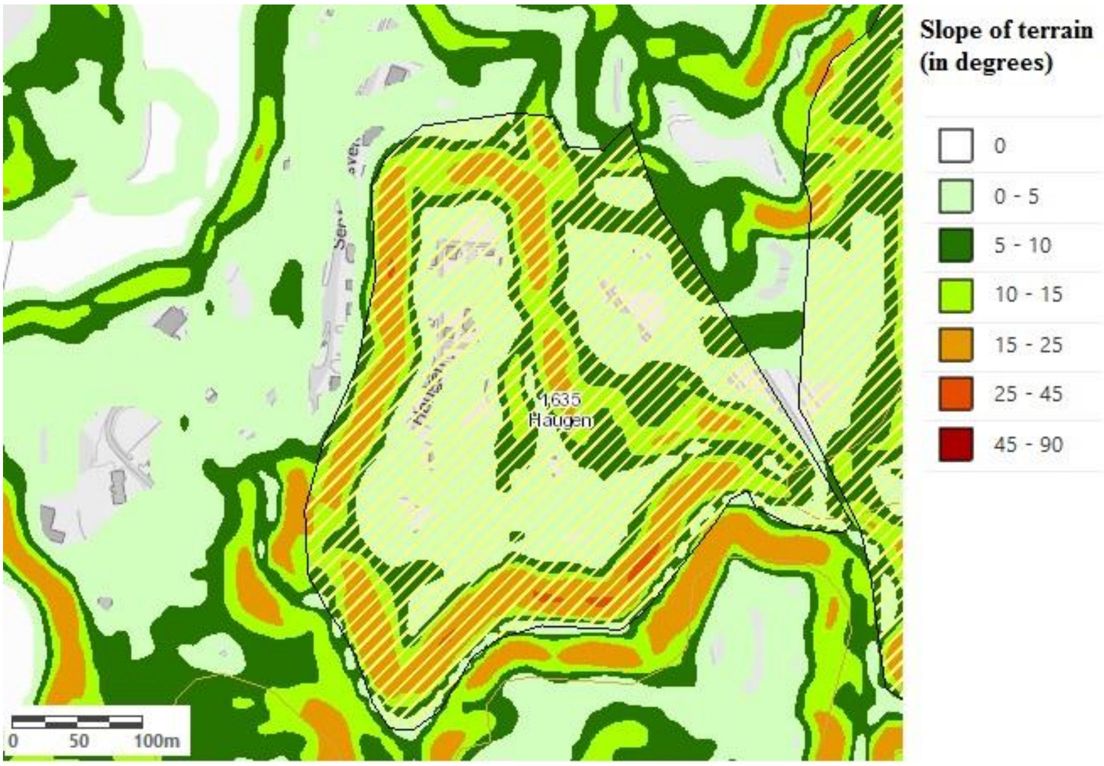


Figure 5.2: Slope angles of the terrain in the Haugen quick clay zone (NVE, 2017a). There may be danger of landslides if the angles > 3,81˚.

This map shows that the Haugen zone is surrounded by steep slopes, with angles over 45˚ at some points. The height difference cannot be read from this map. However, if the height exceeds 10 m in the slopes surrounding the zone, they can be marked as hazard zones. The height difference is found from onsite investigations.

Quaternary geological maps including marine limits are used as a basis for detecting possible hazard zones. The fine-grained marine deposits, including marine clay and quick clay, is only found within the sediment type named thick marine deposits (in the map: light blue) and ***under*** the marine limit. When these criteria are combined some of the surrounding areas can be excluded as hazard areas, as presented in Figure 5.3. However, other types of deposits under the marine limit should be investigated as the quick clay may be covered by beach sediment or river deposits. All the zones that match the criteria with respect to topography, sediment types and marine limit are marked as potential hazard zones.

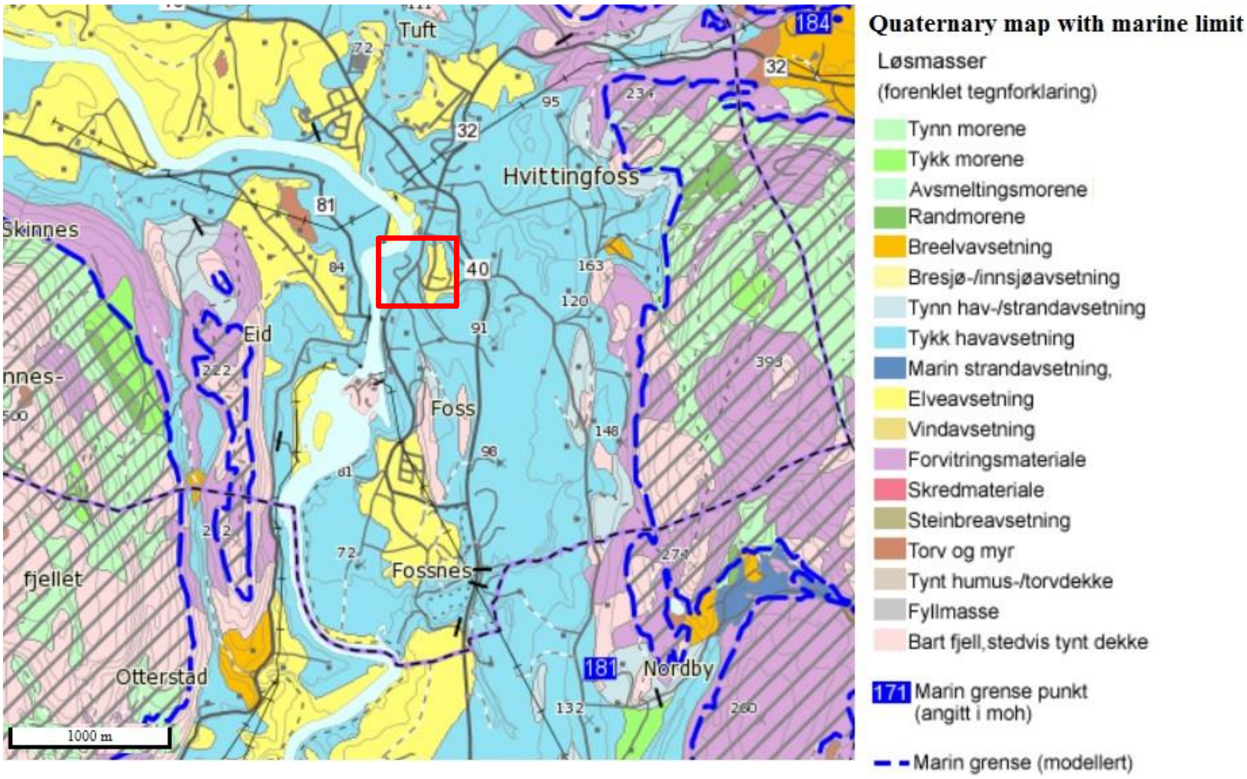


Figure 5.3: Map of sediment types and marine limit (NGU, 2017a). The shaded area is located over the marine limit. The marine limit in meters above sea level is marked by the numbers, in this case the marine limit is located at 182-184 m. The dashed line shows the modelled marine limit and the red box the location of the Haugen quick clay zone.

This map shows that the Haugen zone is located in the area under the marine limit and that the main deposits are thick marine sediments. This zone is an evidently a hazard zone that should be further assessed.

The next step is to perform inspection of the marked hazard zones. The inspection includes the collection of knowledge concerning local conditions, possible interventions in the terrain and study the possibility of field investigations. Following, systematic geotechnical investigations of the soil conditions were carried out in the Hvittingfoss area, which includes the Haugen zone, as these areas was set as a priority by NVE. The investigations were carried out by Rambøll and GeoStrøm, which are assumed to be experts at this type of investigations. The assumptions behind the expert knowledge is that the staff has the adequate technical competence and knowledge of the equipment and procedures, and that the appropriate standards were followed.

Interpretation of results

Gregersen (2001) has a lot of expertise in geology and geotechnics, and is regarded as an expert. His guidelines are used in numerous other publications, which shows that other experts agree with his method. According to these and the map study, the Haugen zone was a clear hazard area for quick clay landslides. This conclusion was expected as NVE has mapped this zone as a quick clay zone. The Haugen zone being located in an urban area, also coincides with the prioritization from NVE's guidelines. Therefore, further investigations and analyses of this area with respect to hazard, consequence and risk level is necessary.

5.2.3. Evaluation of hazard level

The hazard level reflects the degree of uncertainty associated with the stability of the area. The method for evaluating the hazard level of a potential hazardous landslide area, as presented in chapter 4, is used for evaluating the Haugen quick clay zone. Table 5.1 presents the factors that should be included in an evaluation, but also which type of data/tool is used to obtain the relevant information and what type of information this is. In cases with lack of sufficient information a conservative assumption should be made. The basis of each factor will be explained before a decision of score is made; hence the judgement will be more transparent.

Table 5.1: Parameters which should be included in an evaluation of hazard level and where this information is found.

Factor of hazard	Map studies	Soil investigations	Type of information
Previous sliding	X		Topographic
Height of slope, H	X		
Overconsoliation ratio (OCR)		X	Geotechnical
Porepressure		X	
Thickness, quick clay layer		X	
Sensitivity		X	
Erosion	X		Changes affecting the slope stability
Intervention	X		

This hazard evaluation is based on information gathered from Quaternary geological maps, topographical maps and onsite soil investigations. The obtained results are based on the proposed method of hazard evaluation which is based on the existing practice described by (Gregersen, 2001). The hazard evaluation of the Haugen quick clay zone is evaluated based on:

<u>Previous sliding:</u> Based on the previous landslide history and the Quaternary geological maps there appears to be a good deal of landslide activity in the Hvittingfoss area. There are observed and documented multiple historical landslide events in the area on www.skrednett.no. Signs

after landslides events, such as landslide craters, are found in the east part of the Haugen zone. These may be an indication of possible landslide activity. There is a steep slope surrounding the plateau, which is favorable for future sliding. The previous sliding is given the highest score. Hence, the hazard score of 1(weight) * 3(score)=3 points.

Height of slope, H: Based on topographical maps and data from the onsite investigations the slope height is considered to be between 10-20 m. There are some local differences across the slopes, but the slope is relatively flat is this area. Therefore, the most conservative height is chosen, and slope height is assigned a score of 1.

Overconsolidation ratio (OCR): The number tells us how the current terrain level is compared to previous levels. Areas that previously have been situated at higher elevations, can give information about the danger of landslides. The lowering in the terrain may be caused by landslide activity or erosion, and results in a higher OCR ratio than normal at that specific terrain level. A "Ødometerforsøk[6]" was performed from a depth of 6,5 m, and showed pre-consolidation stress of 100 kPa over the current assumed stress level, which corresponds to a OCR of 2 at this level. Three other samples were tested closer to Lågen, and they recorded high overconsolidation ratios of 1.4, 1.8 and 3.8 at depths of 10,6-13,2 m depth (Rambøll: Tveit et al., 2016). Due to the large difference in OCR a conservative ratio is chosen. The OCR is assigned a score of 1. Hence, the hazard score of 2(weight) * 1(score)=2 points.

Pore pressures: The pore pressure was collected by a "piezometer". The pressures were assumed to be generally low, which is favorable for the stability of the slope (Rambøll: Tveit et al., 2016). No over pressure was recorded, and a score of 0 (hydrostatic) was assigned. Under pressures of 18 kPa to 27 kPa was recorded, and a score of 2 was assigned. Hence, the hazard score of -3(weight) * 2(score)= -6 points.

Thickness, quick clay layer: The thickness of the quick clay layer is of importance for the danger of triggering a potential landslide, but also for the extent of the slide. The quick clay is found under a sand layer. The drilling onsite shows a thickness of the clay/silt layer of 16-21 m, which

[6] Ødometerforsøk: This test provides information about the deformation characteristics of a soil, for example shear strength and overconsolidation ratio (OCR). This test is widely used in the geotechnical environment. From: JANBU, N. 1989. *Grunnlag i geoteknikk*, Trondheim, Tapir.

were found at a depth of 20-25 m. The thickness is decided to H/0,6 in one of the profiles (Rambøll: Tveit et al., 2016). The quick clay thickness is assigned the highest score of 3.

Sensitivity, St: The sensitivity is of importance for the extent of the landslide. The sensitivity is measured to 98 by NGI (Rambøll: Tveit et al., 2016). This clay is located at the border of high and “normal” sensitivity. Therefore, a score of 2 is assigned.

Erosion: Erosion in the quick clay zones consists of river- and streams which creates ravines. In the northern and southern part of the zone there is streams at the bottom of the slopes. However, these streams are eroded down towards the level of Lågen. The stream in the south is situated about 12 m over Lågens' level. During inspections of the area some exposed mountain in the west part of the stream were found, which prevents the stream from eroding further towards the level of Lågen (Rambøll: Tveit et al., 2016). A score of 1 is assigned. Hence, the hazard score of 3(weight) * 1(score)=3 points.

Human activity: There are no observable signs of human activity having a worsening or improving effect. Hence, scores of 0 are assigned to both.

The results from the hazard level evaluation gives a total score of 12, which responds to a low hazard level (24% of the maximum score) as shows in Table 5.2.

Table 5.2: The results of the hazard evaluate is plotted in the table modified from Gregersen (2001). The hazard scores are colored after their weight; the red color represents the highest weight and green the lowest weight.

Factor of hazard	Weight	Score for hazard				Points
		3	**2**	**1**	**0**	
TOPOGRAHPY						
Previous sliding	1	Frequent	Some	Few	None	3
Height of slope, H	2	>30 m	20-30 m	15-20 m	<15 m	2
GEOTECHNICAL INVESTIGATIONS						
Overconsolidation ratio (OCR)	2	1.0-1.2	1.2-1.5	1.5-2.0	>2.0	2
Pore pressures[I]						
*In excess (kPa)	3	> + 30	10-30	0-10	Hydrostatic	0
*Under pressure (kPa)	-3	> - 50	-(20-50)	-(20-0)	Hydrostatic	-6
Thickness, quick clay layer[II]	2	>H/2	H/2-H/4	<H/4	Thin layer	6
Sensitivity, St	1	>100	30-100	20-30	<20	2
NEW CONDITIONS						
Erosion[III]	3	Active	Some	Little	None	3
Human activity						
*Worsening effect	3	Important	Some	Little	None	0
*Improving effect	-3	Important	Some	Little	None	0
MAXIMUM SCORE		51	34	16	0	12
% of maximum score		100%	67%	33%	0%	24%
[I]: Relative to hydrostatic pressure						
[II]: In general, the extent and location of the quick clay are so important.						
[III]: Erosion at the bottom of a slope reduces stability.						

The low hazard level is shows in Figure 5.4.

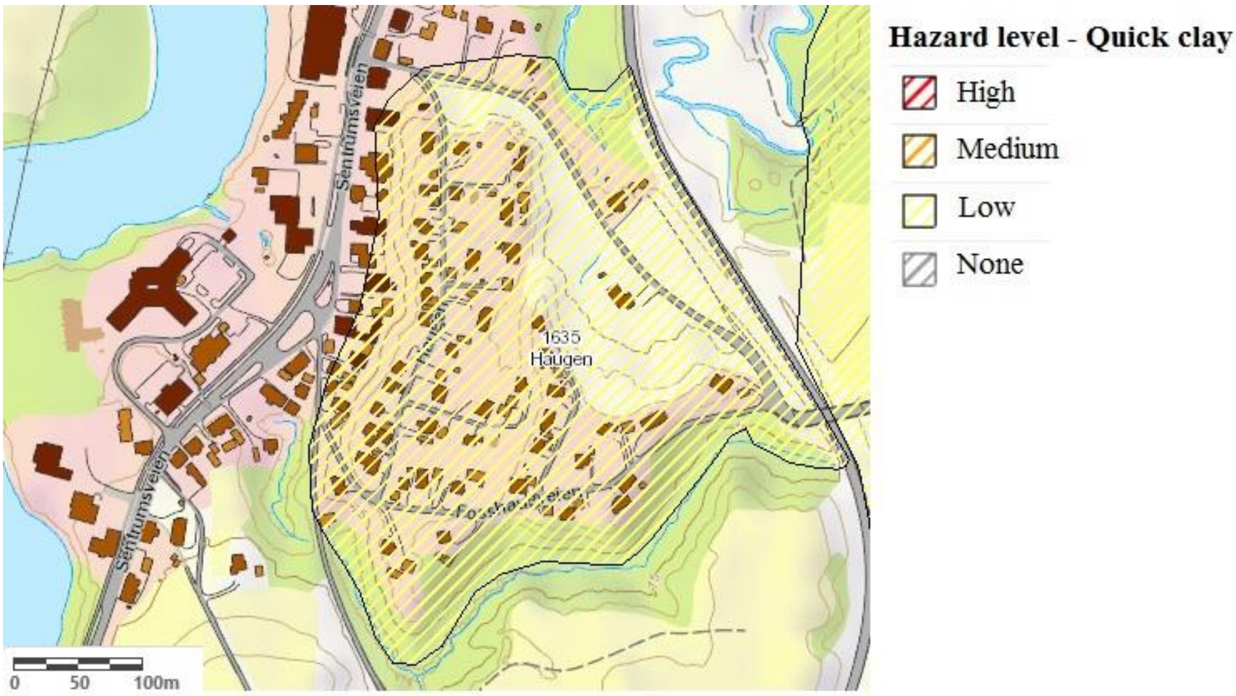


Figure 5.4: Shows the hazard level in the Haugen zone (NVE, 2017a).

The quick clay zone, as seen in the figure above, indicates the presumed maximal extension of a potential quick clay landslide. The size of the zone is based on the topographical criteria previously explained, but also onsite geotechnical investigations. The maximal extension of a zone can only occur if the topographical and soil conditions are as unfavorable as possible in the whole zone. Due to the large extent of the landslides they often affect areas far away from the trigger area. Consequently, it is not sufficient to analyze the hazard level locally when planning to build. The possibility of landslides triggered in other parts of the zone affecting the building site must be evaluated.

Interpretation of results

A score of 12 was determined, which was classified as a low hazard level. The definition of a low hazard included favorable soil characteristics and topography; no active erosion; sufficient investigations onsite; no previous sliding; the planned changes will lead to improvements in stability or no planned changes. These facts are not quite correct, as frequent previous sliding, some active erosion and thick quick clay layers was discovered. However, the total engineering score fall into the low hazard level.

The limitation of this method is that a lot of the information is dependent on a geotechnical investigation. Therefore, if such an investigation is not performed, the results will be biased and based on qualified guesses. To improve the hazard evaluation the zone should have been extended down to the river Lågen. This is because this area is downhill for the western part of the quick clay zone, and if a large landslide occurs in this part of the zone the shoreline will be affected and the possibility of a minor tsunami may arise. Other triggering factors will now be discussed.

5.2.1. **Triggering events**

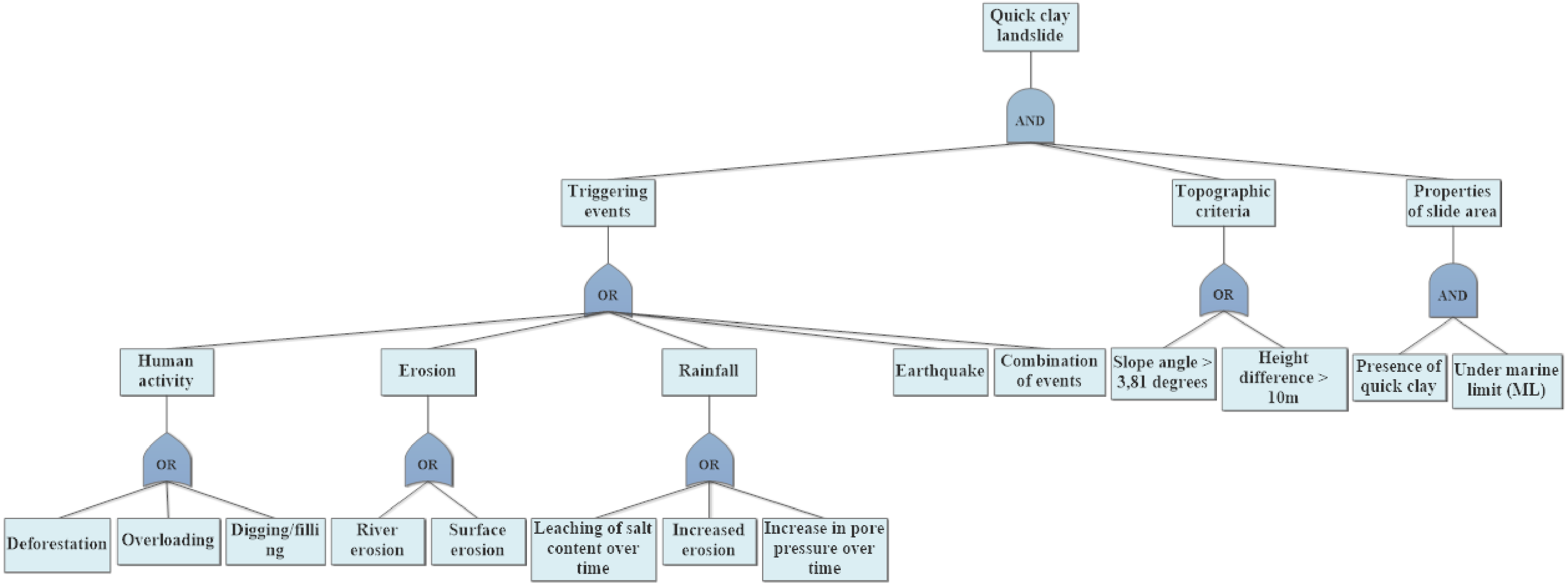


Figure 5.5: Fault tree of factors required to form a quick clay landslide, with focus on triggering events. The fault tree was created by the author using the software SmartDraw 2017.

The fault tree shows that three factors needs to be present for a quick landslide to occur; a triggering event, fulfilled topographical criteria ***and*** favorable properties of the slide area. For the favorable properties of slide area to be fulfilled quick clay must be present ***and*** the area must be located under the marine limit. For the topographical criteria to be fulfilled the slope angle must exceed 3,81˚ ***or*** the height difference must exceed 10 m. For the triggering events, one of them need to occur, either human activity, erosion, rainfall, earthquake ***or*** a combination of events.

The human-induced landslide triggers are caused by changes of slope geometry caused by digging or filling, changes of the effective stress by overloading or erosion, and reduction of forest which binds the soil. The natural landslide triggers include erosion, rainfall and earthquakes. Erosion steepens the slope and reduces the slope strength, and may result in rupture of clay layers. Prolonged and heavy rainfall can modify the geotechnical properties of the material and result in a less stable structure with reduced friction between the clay grains. Increased water flow also leads to changes in pore pressure. Earthquakes may disturb the structure and form fractures or faults were the quick clay can escape. The timing of the failure may be immediate or delayed.

ICG (2011) performed an analysis on the triggering factors of large historical landslides reported by Furseth (2006) in NGU's database. The results are shown in Table 5.3.

Table 5.3: Triggering events based on historical events in Norway (ICG, 2011).

	Analysis of triggering/cause of historical slides			
	Human	Partly human	Natural	Unknown
Clay slide	40	3	79	253
Earth slide	28	21	546	350
Clay slide	33 %	2 %	65 %	Not included
Earth slide	5 %	4 %	91 %	Not included

The table shows that the natural triggering events causes clay slides 65% of the times, whereas human triggered event have caused 33% of the events. The most common natural triggering events are rainfall, floods and river erosion. The intensity, duration and extent of these events affects the landslide impact.

Interpretation of results

The fault tree provided a graphical overview of the factors needed for a quick clay landslide to occur. This allows the complex system to be illustrated in a simple way. The fault tree also increases the understanding of how these factors are connected and the logic resulting in the top event. The focus was on identifying the triggering events that result in quick clay landslides.

A limitation of the fault tree is the lack of probabilities assigned to the basic events affecting the occurrence of the top event. However, finding accurate values for the probabilities requires a thorough analysis by experts on the individual elements and the complete system. Even with an analysis the exact values are usually impossible to find, and the process is very time consuming and costly. Therefore, no numbers are included in the fault tree.

Some of the landslide mechanisms, such as run-out distance and retrogression will now be discussed.

5.2.2. Landslide extent, run-out distance and velocity

As mentioned, the factor of 15*H is chosen for calculations of the maximum extent (L) from the landslide trigger zone. The factor 15 (L/H) was proposed by Gregersen (2001), and is currently used to evaluate the extent of quick clay zone in the Norwegian mapping program.

Principles for calculating the run-out area

Maximal run-out distance is calculated from Equation 4.1: (L_u) = 3 * L (length of retrogression).

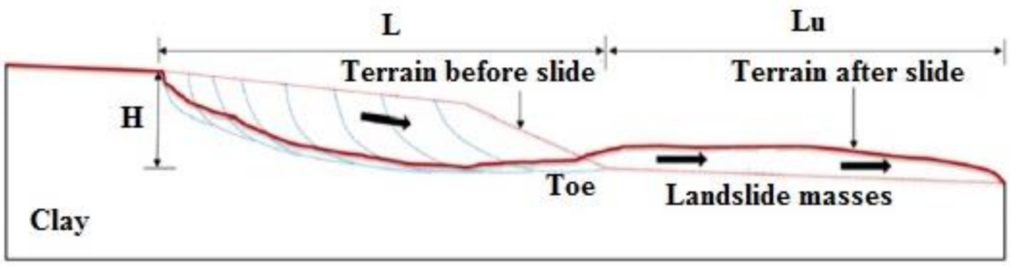


Figure 5.6: Sketch for calculation of the maximal run-out distance. The figure shows the critical length and height for slopes in quick clay. L is defined as the retrogression distance; L_u is defined as the run-out distance from the toe to the end of the landslide deposits, and H is defined as the landslide crater depth.

The critical height, H, can be found from the hazard evaluation results. H includes the height of the quick clay layer with the overburden sand layer. This height is found to be between 10-20 m. However, as we want to find the most critical height the most conservative answer of 20 m is used. In the Haugen zone the maximal extent is calculated: L = 15*20m = 300 m. To put this number into context the L of the Rissa landslide was 1400m, so the L is less than ¼ of the Rissa slide. Following the maximal run-out distance is calculated using Equation 4.1: L_u = 300 m*3 = 900 m = 0,9 km. However, this estimate must be used with discretion, especially if several million m^3 of masses are involved.

As established, the run-out distance increases with the volume of mobilized masses. The volume (and area) data gathered in the landslide database is used to find the ranges in the data and to find an average volume and area estimate.

Based on the classification by Cruden and Varnes (1996) a typical velocity of approximately 18 km/hour for quick clay landslides was predicted from Figure B. 2. To set this number in perspective; the velocity of the Rissa landslide is estimated to 30 km/hour as in the Rissa landslide in 1978, and a velocity of 60-70 km/hour is presumed for the Verdalen landslide in 1893 (Janbu et al., 1993, Sveian et al., 2002).

Interpretation of results

There is uncertainty connected to the landslide run-out estimate. The volume of landslide masses is the factor with largest effect on the run-out distance and extent of the landslide. If many millions of m^3 is involved, the run-out distance cannot be estimates using a topographic and simple dynamic model. Another uncertainty is connected to the 15*H factor proposed by Gregersen (2001) for the maximal run-out distance, which is advised to use with discretion. The run-out distance is dependent on the amount of mobilized landslide masses. The study by L'Heureux and Solberg (2012) defined the maximum run-out distance of 37 large quick clay landslides in Norway and found that many had a L/H > 15. There may be a connection between these large slides with extensive volume and the L/H factor larger than the factor proposed by Gregersen (2001). However, an estimate of the run-out distance gives an increased understanding of the areas where damages and loss may occur.

5.2.3. Frequency analysis

In this frequency analysis, the historic landslide performance of Buskerud county is addressed and the frequency is estimated.

Historic landslide performance

Information from 99 historical landslides in Buskerud have been collected and the results are presented in Appendix C. Figure 5.7 provides an overview of the registered landslide events in Buskerud over time.

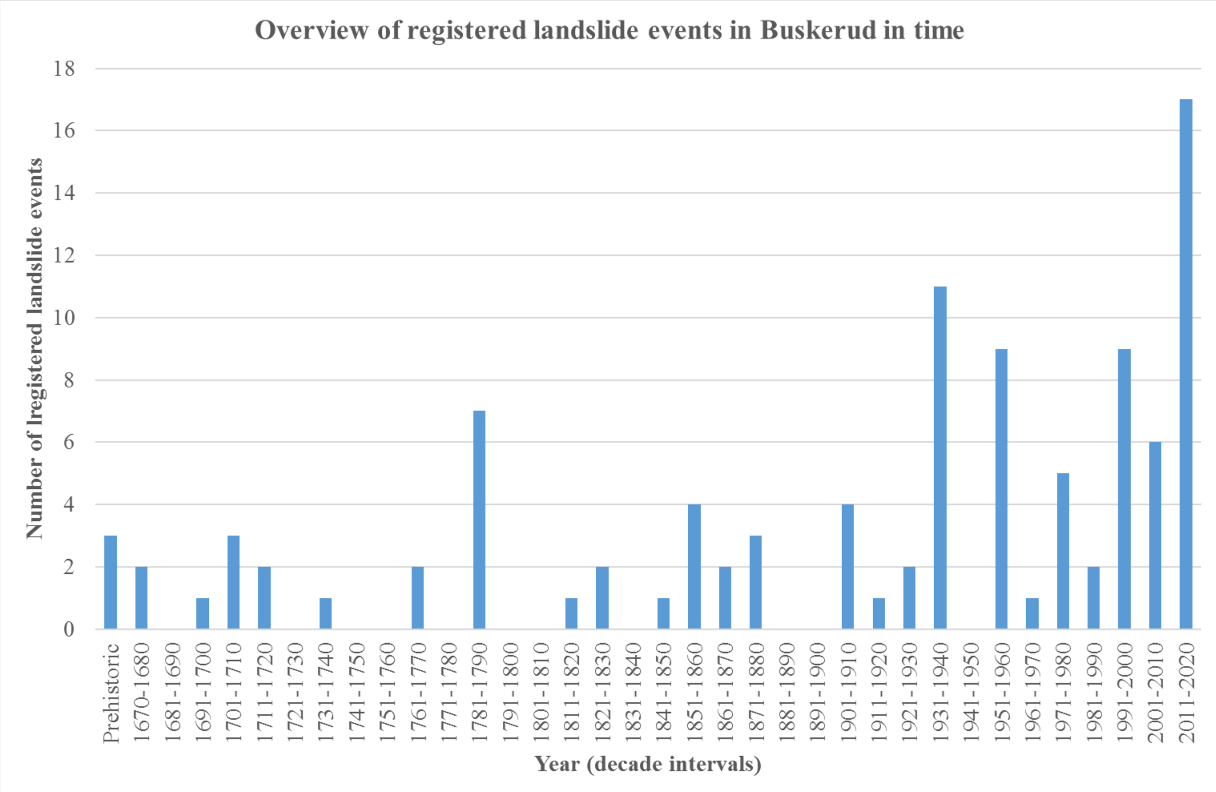
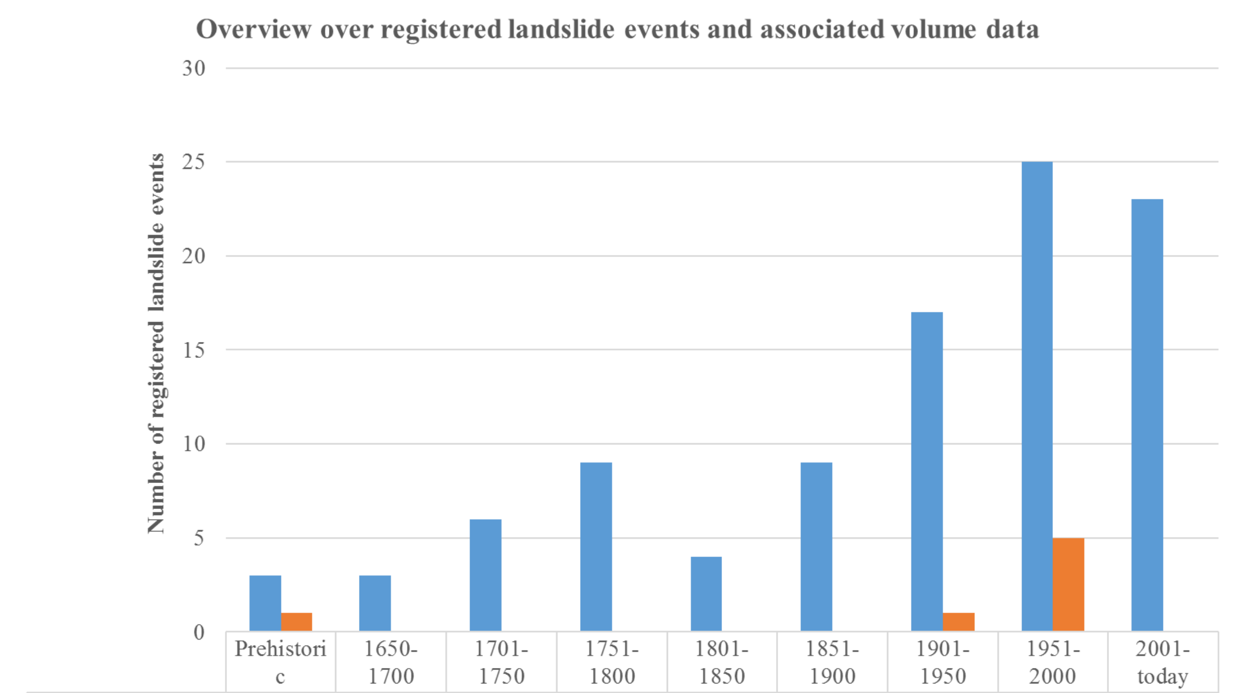


Figure 5.7: Overview of registered landslide events in Buskerud gathered from the database in Appendix C by the author.

The diagram shows that some decades have more registered events than others. The trend of the data shows an increase in registered events the last century. The earliest registrations are most likely larger events, in comparison to the data from the 1950's until today when more sophisticated registration tools are available.

This accumulation of historical data allows us to somehow specify the statistical likelihood in space and time. Most information is gathered concerning the timing of these landslides, but some contain spatial information. Figure 5.8 shows in which 50 year period the spatial data was collected and the how many registrations contain this of data.



	Prehistoric	1650-1700	1701-1750	1751-1800	1801-1850	1851-1900	1901-1950	1951-2000	2001-today
Number of events	3	3	6	9	4	9	17	25	23
Volume data	1	0	0	0	0	0	1	5	0

Figure 5.8: Overview of number of events and amount of volume data. The data is collected from the database in Appendix C.

The restricted data of area and volume (7 slides, 7%) results in an approximate estimation. However, the area ranges between 8500 and 190000 m^3 with an average of 76200 m^3. The volume ranges between 4000 and 2850000 m^3 with an average of 541150 m^3. These ranges are given as guideline purposes only. The average area and volume estimate due not fulfill the definition of large quick clay slides (area: 80-100 000 m^2, volume: 0,5-1 000 000 m^3) proposed by Aas (1981), however some of the individual slides are defined as large. The large variations in area and volume reflects the difference in topography, climatic and geological environments, data amounts and slide mechanisms.

Interpretation of results

The technical reports and literature are considered to be expert knowledge. There is some uncertainty connected to the registrations in the national database. This is due to the fact that the public often register the location of damage by the slides and not the location of the slide initiation, and larger slides may be double registered as they cause damages at multiple locations.

The quality level of the registrations is better for the new data than the old. The reason for this is more sophisticated tool for registration of landslide events, but also the realization that historical data are important for a landslide risk analysis. Another problem is that the historical records often don't extend adequately back in time for a statistically reliable and robust relationship to be established. This especially the case for the low frequency, large events. It is important that all landslides are included in the analysis, whether they are high frequency, small slides or low frequency, larger events. The risk in nature is often dominated by these smaller events of higher frequency (Lacasse et al., 2012). However, the historical records are often dominated by the larger events of lower frequency, as they have caused the greatest damages. Hence, the records may result in overestimated area and volume values, and underestimated occurrences in time. A more detailed estimate with respect to area and volume cannot be made due to lack of sufficient data. To better describe the risk, the historical data should be supplemented by geological data and expert judgement.

Frequency estimate

The method of calculating recurrence intervals, or return periods, can be used to estimate the landslide frequency in Buskerud. The two methods presented in chapter 4 by Sciencing.com (2017) are used for calculating the recurrence interval:

3) ***Simple recurrence interval***:
   For the sake of this calculation the prehistoric events are not included. Following, the recurrence interval becomes:

   $$\boldsymbol{RI} = \frac{\mathbf{(2017-1671)}\boldsymbol{years}}{\mathbf{99}\ \boldsymbol{events}} = \frac{\mathbf{346}\ \boldsymbol{years}}{\mathbf{99}\ \boldsymbol{events}} = \mathbf{3,49} \approx \mathbf{3,5}\ \text{years/event}$$

   This result means that, based on the database, the average time between landslide event in Buskerud is 3,5 years.

4) ***Detailed recurrence interval***: is calculated using the number of events per decade and their ranking. The decades are ranked after number of events, where the decade with most events is ranked 1 and the higher the ranking the less severe is the event. The probability of occurrence and recurrence period are calculated in Table 5.4 using Equation 4.3 and Equation 4.4 from Sciencing.com (2017) and plotted in Figure 5.9.

Table 5.4: Shows the numbers and method used to calculate probability and return period.

Year intervals	Number of events	Rank	Probability	Return period
2011-2020	17	1	2.70	37.0
1931-1940	11	2	5.41	18.5
1951-1960	9	3	8.11	12.3
1991-2000	9	4	10.81	9.3
1781-1790	7	5	13.51	7.4
2001-2010	6	6	16.22	6.2
1971-1980	5	7	18.92	5.3
1851-1860	4	8	21.62	4.6
1901-1910	4	9	24.32	4.1
Prehistoric	3	10	27.03	3.7
1701-1710	3	11	29.73	3.4
1871-1880	3	12	32.43	3.1
1670-1680	2	13	35.14	2.8
1711-1720	2	14	37.84	2.6
1761-1770	2	15	40.54	2.5
1821-1830	2	16	43.24	2.3
1861-1870	2	17	45.95	2.2
1921-1930	2	18	48.65	2.1
1981-1990	2	19	51.35	1.9
1691-1700	1	20	54.05	1.9
1731-1740	1	21	56.76	1.8
1811-1820	1	22	59.46	1.7
1841-1850	1	23	62.16	1.6
1911-1920	1	24	64.86	1.5
1961-1970	1	25	67.57	1.5
1681-1690	0	26	70.27	1.4
1721-1730	0	27	72.97	1.4
1741-1750	0	28	75.68	1.3
1751-1760	0	29	78.38	1.3
1771-1780	0	30	81.08	1.2
1791-1800	0	31	83.78	1.2
1801-1810	0	32	86.49	1.2
1831-1840	0	33	89.19	1.1
1881-1890	0	34	91.89	1.1
1891-1900	0	35	94.59	1.1
1941-1950	0	36	97.30	1.0

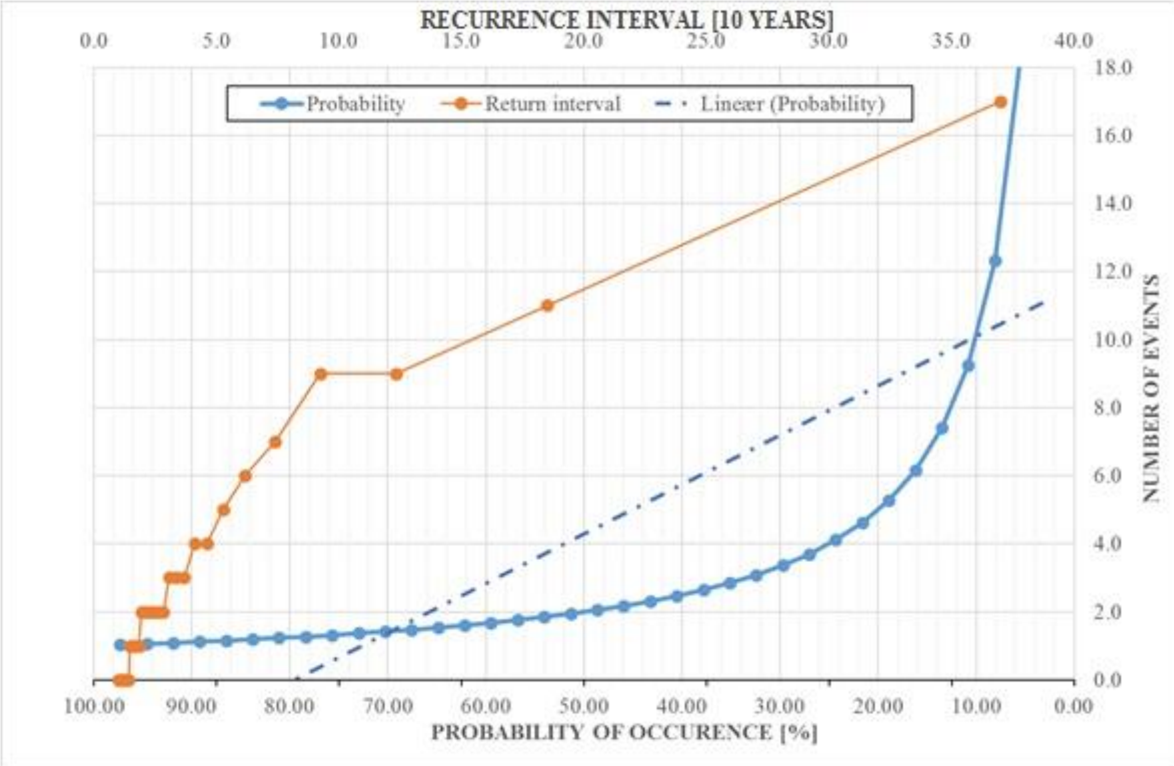


Figure 5.9: Shows the calculated probability with associated trendline and the calculated recurrence interval given in decades. The numbers are based on the results in Appendix C, and is created by the author.

The result of the detailed recurrence analysis is shown in Figure 5.9, where the probability of occurrence and recurrence interval is plotted. The probability functions increase as the number of events is reduced, and flattens out towards zero event. The line shows the linear trendline of the probability function, which is declining as the number of event decreases. The recurrence function increases with increasing number of landslide events, which seems reasonable as 17 landslide events in a decade is less common than 2 landslides.

Interpretation of results

Prediction of temporal frequency of quick clay landslides in the future is dependent on estimation of return periods, and this understanding is largely based on distributions of historical landslides through time. It is important that the return period or recurrence interval is not used for forecasting future landslide events! The interval, however, provides an estimate of how often landslide events have occur in a defined area, but does not say anything about the future. The recurrence interval assumes that the variable included are random variables. Geological events, such as landslides, are generally assumed to be random variables. Hence, the future landslide events are not dependent of the past events. This fact is not always true, as they more often reoccur close to previous slide locations.

The result from the simple recurrence interval calculation is that the average time between quick clay landslide events in Buskerud is 3,5 years. This number will now be tried to put in a context using other estimates of landslide frequency:

- According to Furseth (2006) the large quick clay slides in Norway have a frequency of 2-3 per hundred years, but the smaller slides occur more often.
- According to Bjerrum (1971), Norway have experienced 1 or 2 larger quick clay slides every year the last century.
- Aas (1981) proposed that quick clay landslides involving many million m^3 occur with an interval of 4 years.
- According to Karlsrud (2008), landslides with volume of 1 million m^3 or greater occurs every 4^{th} year on average, whereas slides of volumes around 100 000 m^3 occur on average every year.

These estimates are made for Norway, and not Buskerud county. No estimates have been carried out for Buskerud alone. Therefore, in a susceptible area for quick clay landslides, such as Buskerud, the recurrence interval of 3,5 years/landslide event seems reasonable. Most of these slides will be high frequency, smaller slides causing less damages than those included in Furseth, Bjerrum, Karlsrud and Aas studies. If the recurrence interval was based only on the newest registrations, the recurrence interval would have been considerably lower, as they have occurred more often than previous in the history. For example, if the period between 1851 until today was chosen, the recurrence interval is calculated to 2,24 years/event. Further, these intervals are calculated for Buskerud county. Hence, the probability of a slide occurring in the Hvittingfoss area, or the Haugen quick clay zone more specifically, would be much lower.

5.2.4. Consequence analysis

The consequence analysis consists of an evaluation of consequence level and vulnerability analysis. Loss of life is the main focus of the consequence analysis, but considerations concerning damage of structures and properties are also included.

Evaluation of consequence level

The method of evaluating the consequence level of a potential hazardous landslide area is used for the Haugen quick clay zone. Table 5.5 presents the factors (elements at risk) that should be included in an evaluation, but also which type of data/tool is used to obtain the relevant information. In cases of insufficient information, a conservative assumption should be made. The basis of each factor will be explained before a decision of score is made; hence the judgement will be more transparent.

Table 5.5: Parameters that should be included in an evaluation of consequence level onshore and where this information is found.

Factor of consequences	NVE maps	SSB maps	Statens vegvesen register	Jernbaneverket register	Effect on humans
Number of dwellings	X	X			Direct
Industry buildings	X	X			
Roads (traffic density)			X		May effect humans
Railways (importance)				X	Indirect
Power lines	X				
Buildings, value	X	X			
Flooding impact	X				May effect humans

This consequence evaluation is based on information gathered from map services by NVE and SSB, and registers from Statens vegvesen and Jernbaneverket. The obtained results are based on the proposed method of consequence evaluation which is based on the existing practice described by (Gregersen, 2001). The consequence evaluation of the Haugen quick clay zone is evaluated based on:

Number of dwellings: This factor comprises settlement of permanent residents, and includes property both inside the zone and in the probable run-out area of the quick clay masses. Detached houses, town houses, apartment buildings and nursing homes are included (Gregersen, 2001). Based on maps from NVE, Google Maps and SSB we can see that the Haugen zone has a high number of dwelling, including a nursing home. The residential area has dwellings closely spaced, resulting in larger consequences compared to widely spaced areas. Therefore, the highest consequence score was assigned. Hence, the consequence score of 4(weight) * 3(score)=12 points.

Industry buildings, people: This factor comprises buildings were the occupancy varies, and is dependent on the time of the day and the month of the year (temporal probability). There will be more occupants during the day, and most likely no one during the night. There will also be less number of occupants during the summer and vacation times. This includes schools, industry buildings, office spaces and other public buildings. Based on the maps from SSB and NVE there are no industry buildings in the area. Therefore, the lowest consequence score is assigned. Hence, a score of 0 points is assigned.

Roads (traffic density), ÅDT: Breaches of the road network will have consequences for the society nationally, regionally and/or locally. It can result in danger for loss of life or injury to people. The traffic density is decided by Statens vegvesen's traffic registration from Buskerud county (Statens vegvesen, 2017). Fv 40 is located at the border of the Haugen zone, and has an average ÅDT (Årsdøgntrafikk) of 2300-2400 (Figure D. 1). The traffic density in the Haugen zone is assumed to be the same as where the registration was carried out. Hence, the consequence score of 2(weight) * 2(score)=4 points.

Railways (importance): Breaches of the railways will have consequences for the society nationally, regionally and/or locally. It may result in danger for life/injury of humans. The classification is based on Jernbaneverket's railway priority. However, as there are no railways in the Haugen zone a score of 0 points are assigned.

Powerlines: Breaches of the powerlines will have consequences for the society nationally, regionally and/or locally. However, breaches will most likely not result in any danger of human lives/injuries. Hence, a weight of 1 is assigned. Based on the map from NVE's map catalogue, as shown in Figure D. 2, the powerlines have regional consequences if breached. Hence, the consequence score of 1(weight) * 2(score)=2 points.

Buildings, value: This factor comprises settlements with no permanent resident, but with great importance for the society. This can include historical, religious or cultural buildings. The weight of 1 is assigned as people most likely will not be involved/affected if a landslide occurs. Based on the maps from NVE and SSB, no cultural or historical buildings are located in the Haugen quick clay zone. Hence, a consequence score of 0 is assigned.

Flooding impact: This factor includes damages which can occur along the river as a result of a tsunami triggered by the landslide moving into the water masses. Whether the landslide masses will form a tsunami is hard to predict. How the landslide will develop in size and how the masses will move, is a result of a complex interaction between numerous factors. Just as difficult is it to predict the damages a possible tsunami may result in. Figure D. 3 presents a map of the areas with danger of flooding and associated consequences. The map shows that these areas are located along Lågen and not inside the quick clay zone. Therefore, a consequence score of 1 (small impact) is assigned, which gives a score of 2(weight) * 1(score)=2 points.

The results from the consequence level evaluation gives a total score of 20, which responds to a severe consequence level (44% of the maximum score) as shows in Table 5.6.

Table 5.6: Results from the consequence evaluation is plotted in the table modified from Gregersen (2001). The hazard scores are colored after their weight; the red color represents the highest weight and green the lowest weight.

Loss	Weight	Score for consequences				Points
		3	2	1	0	
HUMAN LIFE AND HEALTH						
Number of dwellings[I]	4	> 5 (close)	> 5 (wide)	< 5 (wide)	0	12
Industry buildings, people	3	> 50	10-50	< 10	0	0
INFRASTRUCTURE						
Roads (traffic density), ÅDT	2	>5000	1001-5000	100-1000	<100	4
Railways (importance)	2	Main	Required	Level	None	0
Power lines	1	Main	Regional	Network	Local	2
PROPERTY						
Buildings, value[II]	1	High	Significant	Limited	0	0
Flooding impact[III]	2	Critical	Medium	Small	None	2
MAXIMUM SCORE		45	30	15	0	20
% of maximum score		100%	67%	33%	0%	44.00%

[I]: Permanent residents in sliding area (close means closely spaced. Wide means widely spaced).
[II]: Normally no one on premises, but building(s) have historic or cultural value.
[III]: Sliding may cause water blockage or even dam overflow, flooding may cause new slides; need time for evacuation; losses depend on interaction of several factors.

Interpretation of results

A score of 20 was determined, which was classified as a severe consequence level. This level was consistent with the expectations. The definition of a severe consequence level included danger of loss of human life, property, social loss or extensive economical losses. The definition fits the Haugen zone as it is highly populated, with roads and powerlines. However, the zone is not classified as extremely severe due to the lack of industry buildings, railways and building of value.

The limitation of this method is that a lot of the information is dependent on the assessors' interpretation of the maps and the registers. These sources of information are considered to be trustworthy. However, building of value may be a subjective matter, and not all the residents may agree that there are none in the Haugen zone. Conservative estimations are used in the evaluation, which may lead to an overestimated consequence level.

Vulnerability analysis

The physical vulnerability of structures will be determined using the method by Lacasse and Nadim (2011). This calculated vulnerability also includes the people inside the structures. The Haugen study area is shown in Figure 5.10. A potential landslide with a predicted run-out distance from the slope towards the urban area of Haugen is drawn in yellow. The system boundary (A_t) in blue and area of "structures" (A_i) in red is used to find the spatial impact ratio (K_s). The ratio is defined as the ratio A_i/A_t. The size of these areas is found by using the drawing tools in the NVE Atlas. The results are shown in Figure 5.11.

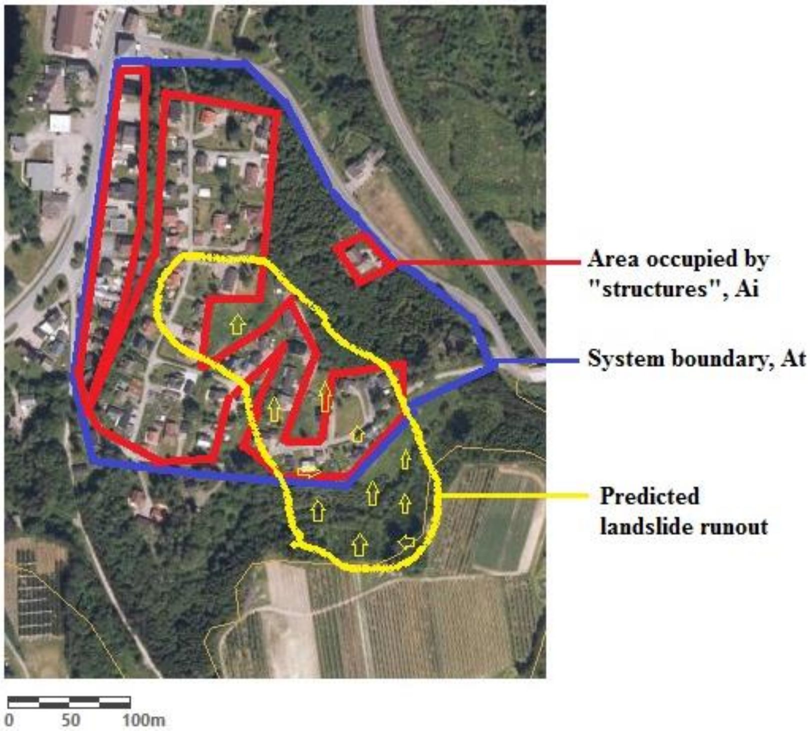


Figure 5.10: Shows a potential landslide with predicted run out distance, system boundary and area of "structures".

The relevance factors are collected from row 2 in Table 4.3 as the vulnerability analysis focuses on the structures and a quick clay slide is classified as a rapid landslide. Hence, r_D=0,9 and r_G=0,1. The intensity components have been assigned with my best knowledge to be: I_D=0,9 and I_G=0,1. The landslide intensity is then calculated using Equation 4.6:

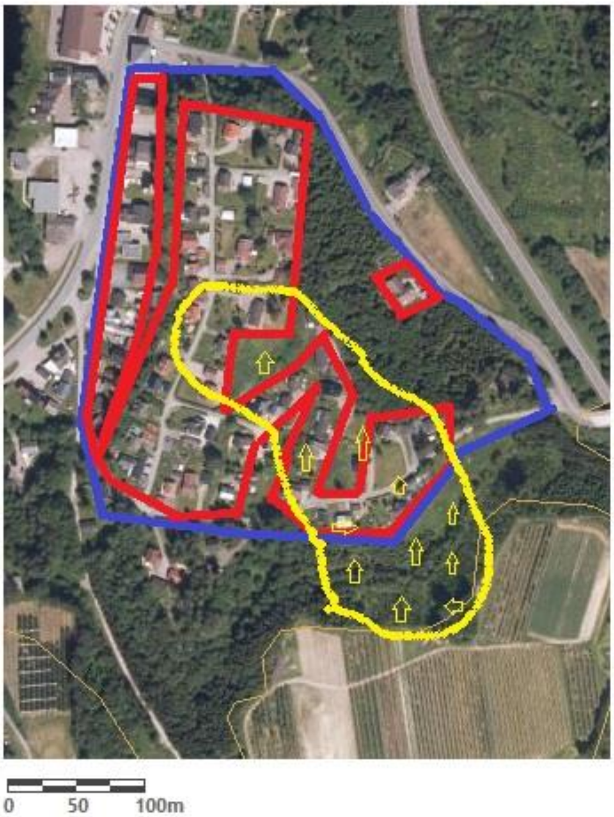
$$\boldsymbol{I = K_s * [r_G * I_G + r_D * I_D] = 0,56 * [0,9 * 0,9 + 0,1 * 0,6] = 0,487 \approx 0,49}$$

The susceptibility, S, is found using the numbers from Table 4.5. From the map on NVE and Google maps the Haugen study area composes approximately 97 structures, where 68 are timber structures (70%), 20 reinforced concrete structures (20%) and 9 light structures (10%). Of these structures 30% are assumed to be of poor state and 70% are of good state. The susceptibility is calculated using Equation 4.5 and the values found in Table 4.5:

$$\boldsymbol{S_{STR} = 1 - (1 - \varepsilon_{\overline{STY}})(1 - \varepsilon_{\overline{SMN}}) = 1 - (1 - 0,64)(1 - 0,19) = 0,708 \approx 0},71$$

This result gives a vulnerability for structures in the Haugen area, and is shown in Figure 5.11.

$$\underline{\boldsymbol{V = I * S = 0,49 * 0,71 = 0,348 \approx 0,35}}$$



V = I * S = 0,49*0,71 = 0,35

C = 2-5 m/sec
At = 77 000 m^2
Ai = 43 000 m^2

Intensity, I
Ks = Ai/At = 0,56
r_D = 0,9
r_G = 0,1
I_D = 0,9
I_G = 0,6

I = 0,49

Susceptibility, S
97 structures (68 timber, 20 reinforced concrete, 9 light; 30% poor state, 70% good state)
S = 0,71

Figure 5.11: Shows the result of the vulnerability analysis for the structures in the Haugen quick clay zone.

The obtained vulnerability factor indicates low to medium losses if a quick clay slide should occur. The value of the spatial ratio has a large effect on the vulnerability factor. The same landslide would have had a considerably higher vulnerability value if a smaller system area (blue) had been chosen, as the K_s ratio would have been higher and closer to 1. Therefore, the choice of study area is crucial for this analysis and this limitation must be considered carefully.

A similar study should be carried out for people outside and in vehicles. However, due to all the unknowns, including the number of people, their ages, income and the population density, this analysis will not be carried out in this thesis. However, it is highly recommended that such a vulnerability analysis is carried out in the future, when more information on the residents and their habits are gathered. Information on how many people are likely to be in vehicles and outside at all times in the area potentially affected by a landslide is also needed, which can be created using a probability distribution. The probability is temporal as these elements are mobile and varies according to time of the day, month or year, which complicates the analysis.

Interpretation of results

This method is assumed to be appropriate for all types of landslides, which is reasonable as long as the factors included in the analysis is specified to fit quick clay landslides. This method allows the vulnerability to be estimated quantitively. It focuses on several elements at risk and operates at a lower level, which is seen as an advantage, as the estimate is more accessible and easier to understand.

The vulnerability study was carried out for the structures and the people inside them. The analysis gave a vulnerability of 0,35. There are uncertainty associated with this estimate, as several of the values, such as the maintenance level and the intensity components, were assumed and are based on my best knowledge. This knowledge is considered to be of medium strength. Consequently, the vulnerability estimate is only approximate, as the values used in the calculations may be subjective. The results must therefore be used with care, based on the problem statement and the chosen reference area. The choice of study area has a large effect on the spatial impact ratio and the final result. The smaller reference area the higher the intensity factor and vulnerability estimate. However, the estimate can be useful in ranking other vulnerable categories and their associated consequences, but also to prioritize the need for mitigation measures to be implemented.

5.2.5. Risk estimation

The qualitative risk or semi-qualitative estimation is based on the hazard level, H_{WS}, and the consequence level, $C_{WS.}$ The risk score is calculated using the relationship established in Equation 4.10 for the individual zones. The results from the evaluation of the hazard level gave a score of 24% of the maximum score (low hazard), whereas the consequence level gave a score of 44% of the maximum score (severe consequences). The risk is calculated:

$$\boldsymbol{R_S = 0,24 * 0,44 * maximum\ score = 0,1056 * max.score = 0,1056 * 10000 = 1056}$$

The score of 1056 puts the Haugen in risk class 3, with medium risk. The Haugen zone with the risk class is shown in Figure 5.12. Risk mitigation measures will be discussed in sub-chapter 5.4.

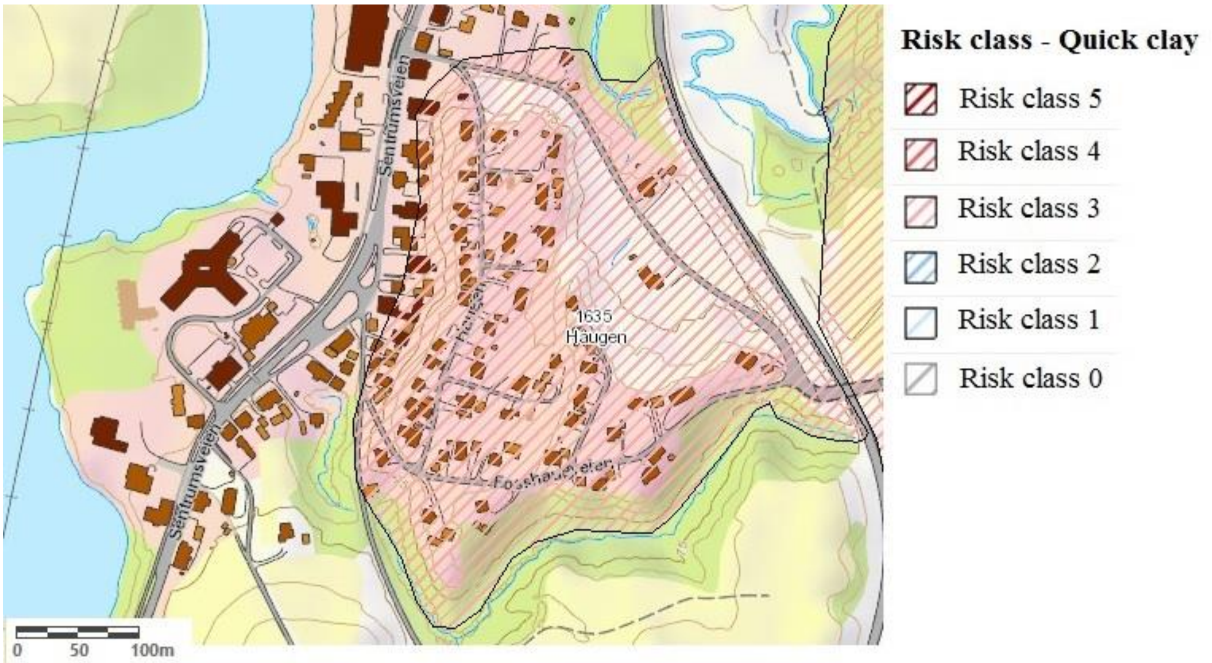


Figure 5.12: Shows the risk level of the Haugen zone (NVE, 2017a).

Interpretation of results

Medium risk was expected based on the low hazard level and severe consequence level. If one, or both, of these estimates are inaccurate this will have an effect on the risk estimation. Therefore, to discover the uncertainties in this estimate, the quality of the hazard and consequence level must be evaluated. The estimate will give an indication of the risk level in the Haugen zone, and can provide assistance in decision making. The risk class is used to decide whether the risk is acceptable and decides the priority of the risk mitigation measures to be implemented. The estimates are approximate and relative; however, they will help preventing catastrophic quick clay events.

The risk estimation is qualitative or semi-qualitative as there is an inadequate amount of numerical data. In this case a quantitative analysis would have been misleading and biased, therefore, a qualitative analysis is chosen.

5.2.6. Judgement and knowledge

One of the limitations in the risk analyses is the amount of judgement going into the individual analysis. This may result in aleatory uncertainty connected to the risk estimates. For example, if the hazards are not sufficiently recognized the risk may be underestimated. The more understanding and experience a practitioner has of the processes the more reliable the analysis will be. It is therefor, assumed that the scientists behind the reports and literature on the subject, and the geotechnical staff behind the soil investigations are experts and their knowledge base is considered strong. However, the result of an analysis will always be different depending on the practitioner knowledge base and experience. If the landslide risk in one area is studied using various approaches, the result will be significantly different, especially if the analyses are performed by different practitioners.

As established, the inputs of some risk analyses are highly judgmental. It is important to defend the judgements and assessments, and explain the logic behind them, but it is also recommended to clarify associated limitations and uncertainties. This is especially useful when a qualitative approach is chosen. The "defensibility" of the analysis can be seen as a quality measure of the information used in the analysis. The quality also depends on the experience and knowledge of the practitioner. The defensibility is also useful for the decision makers'; this is because their perspective in not conditional of the assessors' knowledge. The decision may change as deviation from the assumptions occur. The estimates presented to the decision maker should be unbiased, which is hard to achieve when dealing with insufficient data, even for practitioners with a lot of experience.

5.3. Risk assessment

A risk estimate has a limited value on its own. To serve as a decision tool, the estimate must be compared with an established acceptance criteria or other risk estimates.

5.3.1. Individual risk

In Norway, there does not exist an established risk acceptance criteria for loss of life due to quick clay landslides. However, some considerations of the tolerable and acceptable risk related to landslides and slopes are:

- Tolerable levels of risk are thought to be higher for naturally occurring landslides than those occurring in engineered slopes.
- If a slope is subjected to monitoring, or measures to reduce the risk have been executed, the tolerable risk is reduced.
- The tolerable risk depends on the historic exposure to hazards for landslides.

These considerations are quantified in Figure 5.13 by (AGS, 2000), and tolerable levels for loss of life are suggested. Values are given for existing and natural slopes, both for the average person at risk and the individual most at risk.

Situation	Suggested Tolerable Risk for Loss of Life
Existing Slopes	10^{-4} person most at risk 10^{-5} average of persons at risk
New Slopes	10^{-5} person most at risk 10^{-6} average of persons at risk

Figure 5.13: Shows the suggested tolerable risk levels for loss of life of existing and new slopes (AGS, 2000). These values are for landslides in general, and may be different for quick clay landslides.

The acceptable risks are usually considered to be lower than the tolerable risk, often reduced by one order of magnitude. The risk is accepted if the calculated risk is less than the risk acceptance criteria. If not, the risk is seen as unacceptable risk mitigation measures must be implemented and further investigations carried out. However, the final decision of the risk acceptance criteria must be decided by the those at risk, together with the regulator and owner.

Interpretation of results

When considering these risk criteria, it is important to remember that the values are not absolute. Variations in the risk value up to one magnitude may be acceptable in some cases. Judgements are needed to decide whether the risk should be accepted or not. The tolerable risk criteria are only mathematical expressions trying to showcase the society’s opinion of risk. In some cases, risk values over the upper limit may be accepted according to the ALARP principle, as the risk is not practicable to be further reduced. In a risk assessment, the owners, regulators and society considers social, legal and political issues in addition to the risk estimate. Hence, the risk estimate is one of the inputs into an assessment process.

5.3.2. Societal risk

When dealing with societal risk a qualitative method is most practical. Therefore, a qualitative risk assessment is carried out for the Haugen case. The risk matrix created for this thesis is presented in Table 5.7. The defined hazard, consequence and risk classes are used for constructing the risk matrix.

Table 5.7: Shows the defined risk assessment matrix. The black circle shows the risk of the Haugen quick clay zone.

Likelihood of occurrence	Severity of consequences		
	Extremely severe	Severe	Not severe
High	Very high	High	Medium
Medium	High	Medium	Intermediate
Low	Medium	Intermediate	Low

The risk classes are defined as very high, high, medium intermediate and low, which are shown in the risk matrix. This categorization helps in prioritizing the risk and mitigation measures, which is discussed for the risk classes below in Table 5.8.

Table 5.8: Description of risk categories.

Risk category	Description
Very high High	The risk is unacceptable and should be assigned high priority. The risk will result in a large number of fatalities and damages to structures. Immediate risk reducing measures must be taken. Rehabilitation and rebuilding may take a long time, up to several years.
Medium	The risk may be acceptable over a short term. This risk will result in fewer fatalities and damages to structures. This risk can be dealt with, especially with good planning and do not necessarily require extensive resources. Risk reduction plans must be included in the future strategies and budget plans.
Intermediate Low	The risk is acceptable. The risk will result in no fatalities and only minor damages. Hence, do not pose a significant threat and can be ignored. Measures for futher reduction must be implemented in conjuction with other security and mitigation upgrades.

From the risk estimation in the risk analysis, a medium risk level was calculated. Table 5.8 defines the medium risk as acceptable in a short-term perspective. Based on this, the societal risk is defined as tolerable risk, located between the acceptable and unacceptable region, in the F-N curve by GEO (1998) presented in Figure 4.4. This zone is by Diamantidis et al. (2006)

this area is defined as the ALARP zone, where the ALARP principle apply. This principle says that the risk of the hazard should be reduced, whenever reasonably practicable. Generally, a cost-benefit analysis determines what is perceived as reasonably practicable, and consequently what types of risk reducing measures should be implemented. All risk reducing measures should be implemented unless it can be documented that there is disproportion between the costs and the benefit (Aven, 2008). This process is shown in a flowchart in Figure 5.14.

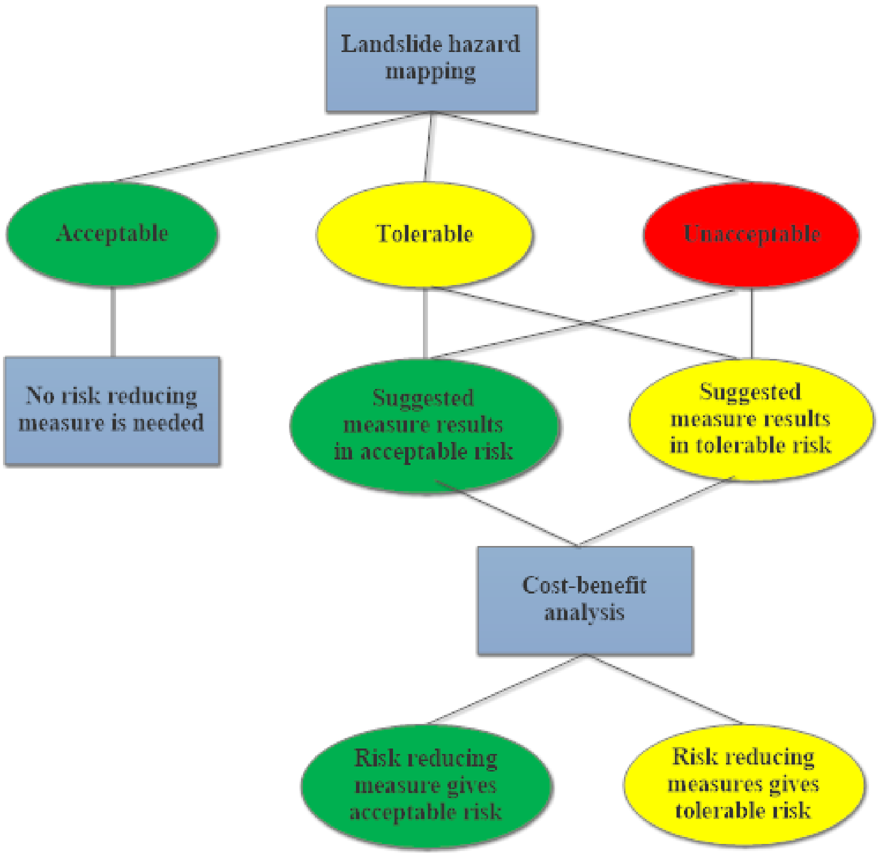


Figure 5.14: Flowchart showing the decision process from hazard mapping to making a choice of accept level.

From the landslide hazard mapping process, a tolerable risk was assigned to the Haugen quick clay zone. According to the ALARP principle, the tolerable and unacceptable risks should be reduced. Therefore, the suggested risk reducing measures should result in a lower risk level. The cost-benefit analysis is used as the decision tool, and if the costs of the measure are in proportion to the benefits, the measure should be implemented.

Interpretation of results

A risk matrix is a useful tool for describing the risk level, and works as a presentation tool for communication with stakeholders. The matrix can help making recommendations concerning risk, and more importantly how to prioritize risk and mitigation measures. The risk matrix requires thorough knowledge of the hazard and consequences of the study area. Hence, the assessors' strength of knowledge should be indicated in the matrix.

To obtain a high level of safety, additional methods other than RAC must be implemented. Consequently, the combination of the ALARP principle and the cost-benefit analysis is used. This is especially important when studying phenomena or processes with large uncertainties that may cause fatalities, such as quick clay landslides. The combination will result in a drive toward risk reductions and improvements.

It is argued that the traditional cost-benefit analysis as a tool for choosing the best risk-reducing measures is not sufficient. The cost-benefit analysis is based on expected values, which is only one number. The result will be misleading for the extreme events with low likelihood of occurring and high consequences. The estimates based on expected values are strongly determined by assumptions. The analysis does not adequately account for the risk and uncertainty associated with quick clay landslides. Consequently, the analysis is not suitable for showing the usefulness of safety measures. Therefore, a broader and more detailed evaluation process is needed.

When dealing with landslide risk the cautionary principle should also apply. This principle should be used by the politicians responsible for assigning weights/prioritize the various risks to justify the need of a measure.

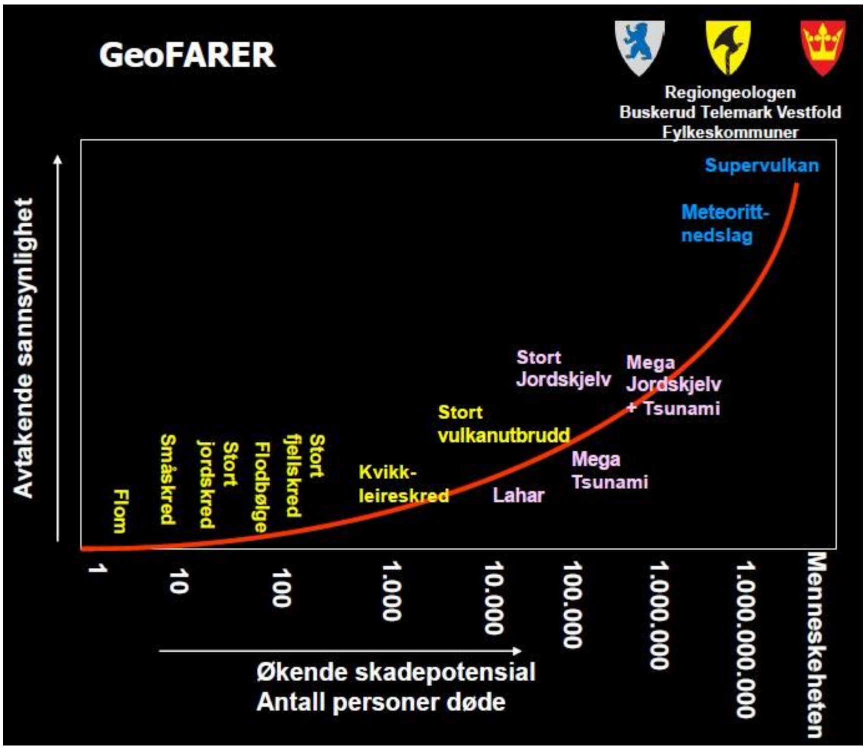


Figure 5.15: F-N curves for various geohazards. Kvikkleireskred=Quick clay landslide (Dahlgren, 2012).

This curve shows that the probability of quick clay landslides is lower than the probability of large rock avalanches, tsunamis, large clay landslides and floods, but higher than large volcanic eruption, Lahar (volcanic mudflow), mega tsunamis, large earthquakes, meteorite impact and super volcanoes. The consequences, expressed by number of fatalities, is set to approximately 1000 fatalities. The reason for the high number of fatalities is several densely populated areas in the risk areas where human intervention activities are many and occurs all the time.

Interpretation of results

The F-N curve presented by the regional geologist is useful for presenting the societal risk of quick clay landslides. The curve represents the local and current situation in the region. However, the assumption behind the curve, the defined study area, and the definition of large quick clay landslide is not stated. Hence, a sensitivity analysis can be useful for evaluating the effect changes in the assumptions may have.

5.4. Risk management

As mentioned before, the risk management for quick clay landslides can be carried out by reducing the likelihood and severity of the landslide events through structural measures, or by reducing the exposure and vulnerability through non-structural measures. Risk mitigation measures in the Haugen quick clay zone will address both these types of events:

- For the events of low likelihood (frequency) and high consequences, the consequences should be reduced by implementing risk mitigation measures. These events are typically larger quick clay landslides, and are located in the upper, left corner in the F-N plot. The consequences can be reduced by improving the awareness, response and preparedness efforts. The use of non-structural measures is most appropriate to reduce this risk.
- For the events of high likelihood (frequency) and lower consequences, the vulnerability and hazard should be reduced by the use of structural and non-structural techniques. These events are typically smaller landslide events, and are located in the lower, right corner of the F-N plot. Reducing the hazards may be a difficult task as there are high amounts of associated uncertainty, and by reducing one hazard another may arise. It may however be useful to take steps in reducing the triggering factors, that may lower the likelihood of occurrence somewhat.

5.4.1. Structural measures

Table 5.9 provides recommendations on what activities should be carried out and the need for remediation, and is dependent on the assigned qualitative risk class. Risk classes can be used as the basis for prioritizing the quick clay areas where risk mitigation measures are most required.

Table 5.9: Activity matrix which shows what measures should be taken as a function of the defined risk classes. Modified from Lacasse et al. (2012).

Activity	**Risk classes**			
	12	**3**	**4**	**5**
	Low and intermediate	**Medium risk**	**High risk**	**Very high risk**
Soil investigations	None	Consider additional *in situ test* and pore pressure measurements	Require additional *in situ* tests and pore pressure measurements	Require additional *in situ* tests, pore pressure measurements and lab tests
Stability analyses	None	None	Consider doing	Required
Remediation[1]	None	None	Consider doing	Required
[1]: E.g. erosion protection, stabilizing berm, unloading, soil stabilization, moving of residents				

NGI recommends supplementary soil investigations in the quick clay zones of high and very high risk (Lacasse et al., 2012). The Haugen zone is assigned to risk class 3 with medium risk, however, since the consequences are categorized as severe, the Haugen zone should be evaluated further. Consequently, additional *in situ* tests including pore pressures should be carried out according to the activity matrix. The supplementary investigations can give an improved evaluation of the hazard level, thus give reason for executing a stability analyses so that the need for potential safety measures can be decided. The hazard evaluation is often based on insufficient information concerning the soil conditions, hence conservative assumptions are made. This may result in a larger defined hazard zone than actual area of landslide hazard, or a too high hazard level estimate. According to NVE (2006a) the supplementary investigations of quick clay zones often result in lower hazard levels and further limitation of hazard extent.

Supplementary stability analyses have been carried out in 4 slope profiles in the Haugen quick clay zone; profile 4A, 4B, 4D and 4E. The basics of stability analyses and the two main analyses, ADP and AFI, was explained in Appendix B. In the analyses carried out by Rambøll, the stabilizing measures must fulfill the demanded percentage improvement of the stability according to NVEs guidelines for measures in quick clay zones (NVE, 2011). The demands specified in the guidelines is a safety factor (Fs) ≥ 1,4. The results obtained from the ADP and AFI analysis was collected in Table 5.10. The calculated stability in the drained situation is better than for the undrained situation.

Table 5.10: Summarized safety factors of the current situation from the ADP and AFI-analyses (Rambøll: Tveit et al., 2016).

ADP-analysis:		
Profile	**Safety factor, SF**	**Demanded FS (% improvement)**
4A-CS	1.62	
4B-CS	1.05	1.14
4D-CS	1.34	1.36
4E-CS	1.18	1.24
AFI-analysis:		
Profile	**Safety factor, SF**	**Demanded FS (% improvement)**
4A-CS	1.87	
4B-CS	1.1	1.18
4D-CS	1.46	
4E-CS	1.43	

Based on the safety factors obtained in the stability analyses, cost-benefit considerations (according to the flowchart in Figure 5.14) and landslide risk assessments, the following actions are proposed:

- ***Profile 4A (north in zone):*** The stability is good and the FS is satisfactory, hence no improvements are needed. The likelihood of a larger slide in this profile is very low.
- ***Profile 4B (south in zone):*** The FS is not satisfactory for the undrained or drained situations; hence immediate interventions are needed. Landslides may be triggered by erosion of the slope base or by excessive loading on top of the slope. The height of the slope is between 14 and 18 m and has an inclination of 35˚ (Rambøll: Tveit et al., 2016). There is potential for smaller slides in the overlying sand layer which will affect the houses situated on the top of the slope. To achieve the demanded percentage improvement drastic measures, such as closing of the stream or demolition/moving of apartment buildings, are required. These are high cost alterations, and therefore disproportionate to the gained benefits. Consequently, terrain inventions resulting in less drastic measures that partly improves the stability should be considered. A protection barrier (stabilizing fill) should be implemented to keep the stability in the sand layer and controls on the erosion of the river toward the slope should be further investigated.
- ***Profile 4D (west in zone):*** The FS is close to the demanded FS for the undrained case, and lower than the required 1.40. An intervention of the terrain to increase the safety factor from 1,34 to the demanded 1,36 in the profile should not be carried out as the cost of the intervention will be disproportionate to the benefits gained. The height of the slope is approximately 12 m and is relatively steep with an inclination of 35˚ (Rambøll: Tveit et al., 2016). The likelihood of a larger, natural landslide in the quick clay is relatively low. However, the overlying sandstone layer may slide out during periods of prolonged heavy rain.
- ***Profile 4E (northeast in zone):*** The safety factor is not satisfactory in the undrained case, but satisfactory in the drained case. The demanded undrained safety factor is achieved by implementing a protection barrier (stabilizing fill) at the base of the slope. The slope consists mainly of sand, thus the likelihood of large quick clay slides towards the river is low. However, the erosional conditions on the slope base should be more thoroughly investigated.

Interpretation of results

For the structural mitigation measures the ALARP principle, with the cost-benefit analysis, may provide a base for choosing the most effective measure for reducing or modifying the risk. First we need alternatives for risk reduction. Then these alternatives can be analyzed and evaluated, and finally a decision can be made on which measure to implement.

5.4.2. Non-structural measure

Most of these measures, such as public awareness and land-use plans, are responsibility of the authorities, county and municipality. Statens vegvesen, Jernbaneverket, NGI and NVE have several guidelines to ensure sound construction and building practices in quick clay zones. These are established through collaboration between the agencies and with the authorities. An example is *The Building and Planning Act* which were put into force in 1966 (Nadim and Lacasse, 2009). Consequently, the early warning systems will be the focus in the Haugen quick clay zone. As previously mentioned, NVE in collaboration with other agencies have created a tool to monitor, forecast and prepare the people in landslide the run-out area. Xgeo includes data for landslides in soil, however not data for quick clay landslides. Quick clay slides are the landslides causing most fatalities and damage in Norway and should be included. This type of landslides is difficult to forecast. Regardless, some ideas will now be proposed on types of data needed, where to collect data and reliability. The propositions include:

- Gathering of data from weather radars. This information is already available in xgeo. However, install a weather radar in the Haugen zone. This data would allow for an increased understanding of the hydrological conditions, including water capacity, groundwater conditions, amount of precipitation and rainfall.
- Measuring and monitoring slope displacement. This can be carried out by a remote sensing tool called InSAR which detects movements in the masses on a mm scale in “real-time”. This would allow for a direct measure of the possible instability both in the quick clay and potential overlying deposits. The strengths of this method are the size of the survey area, the affordability, resistant equipment and mapping of rapid movements are possible (NGU, 2015a).
- Monitor earthquake activities and registrations in the NORSAR map database (NORSAR, 2017).
- Measure and monitoring changes in shear strength (sensitivity), pore pressure and salt content of porewater. Changes in these parameters may lead to failure of slopes. The

measurement must be collected from the quick clay layer, hence subsurface. Consequently, the equipment must be resist the stress and still give reliable results. According to Clague et al. (2012) these parameters cannot reliably and easily be determined with today’s technology, hence further research is required.

Nonetheless, from an economic perspective not all zone subjected to landslide hazard can be systematically monitored. The priority is therefore set to urban areas, and surrounding areas, where most damage can occur. Hence, a sensor network with the aim of monitoring triggering events for landslides should be installed. The sensors should be geographically distributed throughout the Haugen zone, wireless and connected to satellites so that the results easily and quickly can be shared. The early warning systems can give out a warning or alert in time for corrective actions can be taken to reduce the impact of the landslide by moving the elements at risk. The time between a triggering event and the quick clay slide may be sufficient to execute prompt measures to reduce the risk of property and loss of life. The social element of the warning system should also be taken into consideration. These are as important as the technology, because without people taking decisions, communicating the warning to the population, creating emergency plans and implementing them there is no value in the warning signals. Lack of response and communication may even be more drastic than the failure of the technology. To maintain the systems credibility false signals should be avoided (Lacasse et al., 2012).

Interpretation of results

Should the early warning system for quick clay landslides be installed? This depends highly on the government and politicians approach and attitude toward uncertainties and risk. If the government uses the cautionary principle the cost of a EWS can be justified, even if a cost-benefit analysis does not justify the installation of such a system. This shows that when dealing with the risk of loss of life it is necessary to see beyond the expected values and probabilities. However, there are hidden uncertainties in such an installation, such as reliability of the tools and equipment deterioration, which is assumed to be fixed by the maintenance cost.

This chapter have presented a demonstration of the risk analysis framework on the Haugen quick clay zone. the next chapter will discuss the usefulness of this analysis generally and more specifically for the residents in the Haugen zone.

6. Discussion

This discussion focuses on the larger perspective when addressing the validity, expectations and usefulness of the results. The strength and weaknesses of the individual methods, along with the interpretation of the results, were discussed in the previous chapter. This chapter is divided into two parts: risk analysis framework and empirical example.

6.1. Risk analysis framework

The motivation of this research was the need for a complete risk analysis framework for quick clay landslides in Norway. Until now, there have been partial analyses and guidelines published which focuses on single parts of the risk analysis process. The *Landslide Risk Management* framework compiled by the Australian Geomechanics Society (AGS) was used as a base for the process. However, this framework was highly modified to fit the Norwegian practice and quick clay landslides. This developed framework encourages a uniform and systematic method to perform risk analyses, in addition to promoting an increased understanding of the hazard and consequences. This framework enables an increase in communication between the risk practitioners and stakeholder, but also across agencies and disciplines. This is especially important, because according to Lacasse et al. (2012) a broad consensus is not jet been established of the principles and fundamental concepts in risk management, despite several mature methods.

The value of this framework is a complete method for analyzing the hazard, consequences, frequency and risk of quick clay landslides in a chosen study area. The use of such a framework will hopefully result in reduction of the socio-economic consequences of landslide events, due to the increased knowledge and understanding of the mechanisms involved. It has lately been recognized that a proactive approach is required to deal with quick clay landslide risk; hence, this risk analysis framework can be used as a tool in this process.

This study met the expectations specified in the problem statement; a complete risk analysis framework was established and an empirically case study was performed on the Haugen quick clay zone. The risk analysis methods for hazard, consequence and risk evaluation of quick clay found in the literature was more technical than expected. Consequently, the whole risk framework became more technical with respect to geotechnics than initially expected. Hence, more information from the onsite soil investigation was used as input in the analyses. The risk analysis framework focused on the potential of loss of life and property as a result of a quick clay landslide, which matches the framework drawn in the introduction. Due to the limitations of this study, such data and time constraints, the focus was on the risk analysis part of the framework. An ideal distribution would be if the time was evenly shared between the risk analysis, risk assessment and risk management.

The previous focus of risk associated with quick clay landslides have been mapping of quick clay zones. There are several studies covering the mapping process and classification of hazard, consequence and risk level. However, they lack discussions of how to assess and deal with this risk, hence they do not include the whole risk process. There is no value in identifying zones of landslide risk if nothing is done to treat or mitigate the risk. This study covers the whole process from identification of quick clay zones to the proposition of mitigation measures to treat the classified risk; hence it adds value to the current practice. The study also provides guidance of which types of analyses that should be carried out to reach this goal. These guidelines also have an important role in communicating and explaining the process, achieved results and limitations to the public, legal profession, authorities and regulators.

The main challenge is that the risk analysis framework must be simple, but also explain complicated connections as correctly as possible. Quick clay landslides are complex systems with a variety of variables with associated uncertainties. In addition, the risk changes with time, due to changes in development and natural processes. The variables are not fully understood in the scientific community, and especially not the combination of processes and variables. Consequently, simplifications are needed to model the reality without losing the complexity of the quick clay slides. This poses an eternal challenge and no definite answers exist on how solve this challenge. The risk analysis should systemize expertise and knowledge on the landslide hazard and consequences, but also include influences of climate. The risk analysis framework must focus on improvements and be continuously updated as more information is gathered. This is important as each step of the process allows for an increased understanding of the quick clay slide hazard, and associated risk.

The hazard mapping has until now been limited to identification of potential areas without considering landslide mechanisms after the initial slide. Due to the increased social awareness, there is a great need for mapping the run-out areas and landslide extents in the future. This is because these processes cause the most losses and damages when a slide occur. A better understanding of the post-failure mechanisms can be used to improve the hazard mapping and evaluation, but also result in better land-use planning and placement of geotechnical investigations. The post-failure behavior should include run-out distance, velocity and retrogression potential, which are not currently considered. However, the quick clay maps are still useful. The usefulness is the visual form that easily allows the public to identify areas of potential hazard and thus, be extra careful.

Implementing and executing a complete risk analysis framework for all the mapped quick clay zone would be a costly affair. However, the system is easy and relatively low labor intensive. NVE should be in charge of this process as they have the overall responsibility of risk posed by landslides and floods on a nationwide level. However, the implementation requires communication and collaboration between NVE and the municipalities, regions and agencies. There is a need for prioritization of the quick clay zones. The current prioritization in NVE of the highest risk classes with high consequences located in urban areas should be used. The risk management will focus on the structural mitigation measures as these are quicker to implement, and the fact that there exist experience, procedures and equipment for such implementations. The implementation of early warning system for quick clay requires further research, new technology, procedures and must be approved by the government.

The result from the risk analysis framework must be easily accessible for the public and other interested parties. The main results with simple explanations should be presented in the NVE Atlas with the other quick clay information. The full risk analysis should be gathered in an open database on NVE’s homepages for the authorities, developers and agencies performing land-use planning and construction work. New knowledge and experiences should be shared between the agencies and NVE, but also with the various municipalities. This is because lack of knowledge results in lack of understanding of the consequences. Therefore, there is a need to gather all this knowledge and experience in a system that is available for all the interested parties. This knowledge can again be used to update the risk reducing measures as it currently attaches great attention to. The scientific community should also contribute by expanding the knowledge of the mechanisms to be able to assist the authorities with up-to-date techniques, including investigation methods, hazard assessments, planning and mitigation measures.

The empirical study on the Haugen quick clay zone will enlighten the value of the risk analysis method.

6.2. Empirical example: Haugen quick clay zone

This exemplification of the risk analysis framework has contributed in a better understanding of the risk the residents are exposed to on a daily basis, and what can be done to reduce this risk. The value of the risk analysis results for the Haugen quick clay zone is knowledge of the local conditions which can be used to avoid potential quick clay landslide in the future. The value of these results is a local understanding of hazard, consequences, risk level, but also landslide extent and run-out distance, vulnerability and typical return periods of quick clay landslides in the region. The need for further mapping, detailed investigations and safety measures are based on these estimates and evaluations. Hence, if the risk is categorized as high or very high safety measures with be implemented. The risk in the Haugen zone was established as medium, thus not an immediate priority for NVE. However, the zone is densely populated so it will be prioritized among other zones of the same risk class. If the zone had been extended down to Lågen and the flooding impact was further investigated the risk may have been classified differently.

The quick clay maps contribute in educating the public of the hazard and risk level their neighborhood is exposed to. All the resident should be enlightened of the presence of the quick clay maps and the existence of the NVE Atlas. The municipality should also provide information about how to live and deal with the quick clay risk, especially to new residents settling on high and very high risk zones, which exist in other parts of the Hvittingfoss area. If the municipality, developers and landowners have the necessary knowledge of risk associated with quick clay landslides the possibility of human induced landslides would be reduced. This given that the knowledge is shared with the right people. If construction work or terrain interventions are planned in the Haugen zone, the municipality should perform a detailed investigation of the slope stability. This is done to be sure that the requirements for satisfactory safety factors can be achieved. The *Quick Clay Guidelines* by NVE prepared in collaboration with the geotechnical industry should be followed systematically (NVE, 2014). However, the natural triggering events are the most common, and these should be monitored by the weather station on xgeo.no.

A typical issue in decision making is that a reliable decision needs to made. The longer the time horizon and the more uncertainties associated to global changes in climate and demography the more complex the decision process becomes. Due to the epistemic and aleatory uncertainties in the elements of quick clay landslide risk, such as hazard, exposure, consequences and vulnerability, the risk management process is definitely decision making under uncertainty. There is also uncertainty associated with the various risk analysis and how they may affect the closing decision. Consequently, there is a need for consistent rules concerning the decision making with respect to risk and cost. A general framework for risk assessment and management is required. The risk assessment is based on simple tools, including risk matrix, F-N curves and ALARP principle, to provide assistance in making important decisions of acceptable or tolerable risk levels. But, also on how to prioritize these measures. The risk and hazard of quick clay slides change with time. Hence, the risk assessment model should be easy to use and transparent, without compromising the reliability and value of the assessment.

The risk assessment process is used chose the “best” solutions, in an economic perspective, to reduce the risk. The effect can be documented through a cost-benefit analysis. However, this risk framework recommends to use the ALARP principle in addition to the cost-benefit analysis. In the future, technical feasibility and uncertainty assessments should also be included in the risk assessment process to select the most appropriate mitigation strategies. It is recommended that more data is gathered and included in the analysis. Increased amounts of quantification are highly recommended as lives are believed to be at stake.

Risk mitigation measures for the Haugen zone can be recommended based on the execution of the risk analysis framework. The risk mitigation measures should be focused of the stability conditions toward the river in the south of the zone. The focus should primarily be on the potential natural triggering events, which in this case is erosion at the slope base. Consequently, further investigation should be carried out of the erosional and hydrological conditions. Secondary, a stabilizing fill should be considered along the river to increase the safety factor to some degree. Along the whole Haugen zone steep and high slopes are present, which may be potential sliding surfaces. Stabilization measures should focus of increasing the stability in the quick clay but also in the overlying sand layer.

7. Conclusion

A complete risk analysis framework for quick clay landslides in Norway has been established in this thesis. This framework is based on the *Landslide Risk Management* framework by AGS, but was modified to fit the Norwegian practice for quick clay landslides. A thorough document analysis was performed to gather the information on the partial analyses and guidelines previously published. Some of the analyses applies for landslides and was therefore modified to fit the quick clay mechanisms.

An empirical exemplification of the risk framework was performed on the Haugen quick clay zone in Kongsberg. The Haugen zone was confirmed as a quick clay zone based on Quaternary geological and marine limit maps, which matched the expectations from the quick clay map in the NVE Atlas. The hazard level was categorized as low based on a semi-qualitative hazard evaluation. From the fault tree analysis, it was identified that three factors are required for a quick clay landslide to occur: a triggering event, fulfilled topographical criteria *and* favorable properties of the slide area. Quick clay slides are most often triggered by natural events, where intense rainfall, floods and river erosion are the most common triggers. The maximal run-out distance for the quick clay masses was estimated to 0,9 km and a velocity of 18 km/hour was assigned. From the created landslide database of historical quick clay events in Buskerud, a return period (frequency) of 3,5 years/event was calculated. Based on these numbers, a potential landslide poses a great threat to human lives and will result in economic losses. The consequence level was categorized as severe, because the zone is highly populated, with roads and powerlines. The vulnerability was calculated to 0,35 for the structures in the Haugen zone, which means low to medium degree of loss if a landslide occurs. From the hazard and consequence scores, the risk was classified as medium. Based on the risk matrix, the risk is acceptable in a short-term perspective, but should be reduced if possible. The measures that gives the greatest socio-economic benefits relative to the costs should be implemented. Therefore, the risk mitigation measures should be focused of the stability conditions toward the river in the south of the zone. The focus should primarily be on the potential natural triggering events. Secondary, a stabilizing fill should be considered along the river to increase the safety factor to some degree. Further research should be performed on the Early Warning System for monitoring of the quick clay slopes and triggering events.

8. Recommendations for further work

To improve the quick clay mapping practice, I would recommend to:

- Quality check all the registered landslide events in the area when the new quality requirements are established by NVE. All the registrations should be flagged with a quality level to improve the quality of the database. Routines are under development.
- Continuous updating of information of the quick clay zones after mapping by NVE. Increase the implementation of the mapping process if possible.
- Areas under 10 acres in extent and areas located in the shoreline should be included in the mapping. The guidelines by L'Heureux et al. (2014) should be used for mapping the areas in the shoreline.
- Combine all the quick clay detections, observations and registrations in one database available to the public. This requires collaboration between all the different agencies, such as NVE, Jernbaneverket, Statens vegvesen, NGI, NGU, SWECO and private consultant.
- Include the data from quick clay mapping carried out by the individual municipalities.

To improve the evaluation of hazard and consequences the following analyses are recommended:

- Include aerial photographs, which can be used to confirm locality and extent of landslides, but also indicate slide mechanisms. The photographs can be used to detect signs of previous slides not included in the landslide database.
- Use GIS analysis to create a quick overview of areas with potential danger for quick clay slides. The preliminary analysis should be used for selection of potential areas. The selection should be based on the most populated area or areas with most dense settlements.
- Include LiDAR data if available, or collect data from airplanes or stations on the ground. For more details refer to Ottesen et al. (2016).
- Include geophysical measurements with the purpose of creating more realistic geological models, stability calculations and a more complete understanding of great value for the mapping of landslides.

To include all the hazard aspects of the Haugen site, the following is recommended:

- Further investigate the effect a tsunami would have in the area around Lågen. The hazard and consequence level should be updated based on the results.
- Include several consequence analyses, and various scenarios. This require collecting more information about the population density and the socio-economic characteristics of the population.
- Further investigations of the early warning system proposal.

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Appendix

A: Landslide and risk terminology

The purpose of this appendix is to establish a uniform risk and landslide terminology, which will be used throughout this thesis. The risk terminology is consistent with the core terminology found in AGS (2000), Fell et al. (2005), Aven (2008), Cardona et al. (2012), Clague et al. (2012), Lacasse et al. (2012) and Aven et al. (2013). Landslide terminology is also included in agreement with the problem statement (Varnes, 1978, IAEG, 1990, WP/WLI, 1993, Cruden and Varnes, 1996, AGS, 2000, Lacasse et al., 2012, NGU, 2012, NIFS, 2014). Geotechnical terms are found in Janbu (1989) and NVE reports.

Geohazards are defined as natural processes and human activities which can trigger natural disasters with danger for the environment, human lives and infrastructure (NGU, 2012, NGU, 2016a). In this thesis, geohazards are understood as natural processes occurring on Earth, including volcanic eruptions, earthquakes, tsunamis, storms, floods and landslides, which the society must adapt to. In addition, processes such as human activity and erosion is included.

Consequence is in risk analysis understood as the result or outcome of a particular hazard that occurs (Fell et al., 2005).

Danger or ***threat*** is defined as a phenomenon that may result in damages, and is described by its characteristics. The descriptions do not involve any forecasting. The danger can describe an existing or potential future danger (Lacasse et al., 2012).

Element at risk involves infrastructure (roads, communication etc.), population, services (water supply, electrical supply etc.), environmental features, buildings and all other economics activities of an area affected by and exposed to a hazard (Fell et al., 2005).

Exposure is defined as an overlap in time and space between a dangerous process and elements at risk (Clague et al., 2012).

Frequency is defined as a measure of the likelihood, and is often expressed as the number of realized events within a given number of trials or within a given time period (Fell et al., 2005).

Hazard is defined as the probability of a specified damaging event (threat) occurring within a specified area within a specific period of time (Lacasse et al., 2012). The damaging events are natural events which affects human activities, such as droughts, hurricanes, diseases, floods, earthquakes, volcanic eruptions and landslides. The various hazards have differing degrees of severity and intensity, and can partly be specified by human intervention and environmental degradation of the natural ecosystems (Cardona et al., 2012). The risk description varies with the nature of hazard and the extent of the consequences.

Disaster is defined as the risk people involved is exposed to, and is a combination of hazard and vulnerability. An interaction of both results in a disaster; one cannot occur without the other (Wisner et al., 2003).

Landslide intensity is a set of parameters which is related to the damaging power of quick clay landslides. These parameters are described qualitatively or quantitatively, and often includes maximum velocity of the landslide, total displacement, depth of the slide, differential displacement etc. (AGS, 2000).

Likelihood is defined as the conditional probability of a result or outcome given a specific set of information, data and assumptions. Likelihood is used to describe frequency or conditional probability in a qualitative way (Fell et al., 2005).

Probability is defined as a measure of degree of certainty. The probability is expressed by a number from 0 to 1, where 0 is impossible and 1 total certainty. It is estimates of the likelihood of future events occurring, or the size of the quantity associated with the uncertainty (Fell et al., 2005). There are two different interpretations of probability associated with risk:

1) Frequentist probability (P_f) is built on classical statistics, where the probability is defined as a fraction or frequency, which means the proportion of times the outcome occurs (for example dice shows 5) given an infinite number of trials. Given this understanding, a "true" probably is established, by the use of analyses and experiments (Aven, 2008).
2) Knowledge-based probability (P), also referred to as judgmental or subjective probability, is a quantification of the degree of belief, judgements and confidence with respect to an outcome. The probability is obtained by considering all the available information with a minimum amount of bias. This probability will be affected by the

degree of background knowledge the assessor possesses, and changes over time when the amount of knowledge changes (Fell et al., 2005, Aven, 2008).

Temporal (spatial) probability is the probability that a specific element at risk is located in the area of the treat at the time when it occurs (Fell et al., 2005).

Risk: According to Aven (2008): “Risk is related to future events A and their consequences C. Today, we do not know if these events will occur or not, and if they occur, what the consequences will be. In other words, there is an uncertainty U associated with both A and C. How likely it is that an event A will occur and that specific consequences will result, can be expressed by means of probabilities P, based on our knowledge (background knowledge), K” (Aven, 2008, p.15). Risk can be described by (C, C*, U, P, K), where C* is a prediction of C.

Risk concept: Risk can be generated anywhere a potential source of loss or damage exists. In the geohazard case, the source of the hazard (landslide, flood etc.) and the target of the hazard is the environment, assets and the people (Aven et al., 2013). shows the basic concept of risk.

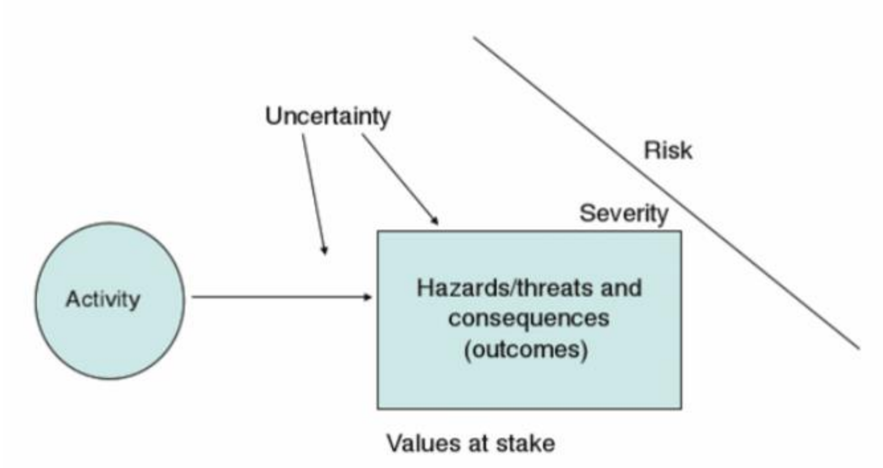


Figure A. 1: Risk concept which reflects hazards, treats and consequences with the associated uncertainties (Aven et al., 2013).

The figure illustrates the development from an activity to the resulting hazard and the following consequences. There are uncertainties concerning the activity with respect to the possible consequences. Understanding of these uncertainties is crucial. Risk and consequences are often only focusing on the adverse effects and undesirable events, however positive outcomes (opportunities) also occurs. If no hazard exposure, there is no risk for the values and people. The risk will depend on the groups exposed to the hazard (Mun, 2004).

Risk for landslides is quantitatively expressed as: Hazard × Potential value of loss (Lacasse et al., 2012).

Risk analysis is used to estimate the appropriate risk to property, populations or individuals, or the environment, from potential hazards based on the available information. To be able to understand the risk posed by quick clay landslides, the hazards must be identified, its frequency, elements at risk, vulnerable elements, and the assets at risk (see Figure 4.1 for the risk analyses steps). The risk analysis systemizes the knowledge and will try to answer questions, such as (AGS, 2000):

- What may happen?
- What is the probability of it occurring?
- What are the consequences?
- How large damage or how many injuries will the event result in?
- What can be done to prevent it?

Qualitative risk analysis is based on words to form numerical and descriptive scales for rating of the potential magnitude of consequences and the likelihood that these may occur (Fell et al., 2005).

Quantitative risk analysis is based on numerical values of the probability, consequences and vulnerability, a results in a numerical value for the estimate of risk (Fell et al., 2005).

Acceptable risk is a level of risk people are ready to accept without any reductions. The society do not justify spending money on reducing the level of such a risk (AGS, 2000).

Tolerable risk is a level of risk the society is prepared to live with as long as certain net benefits are secured. This risk range is seen as non-negligible and is needed to be continuously kept under review and reduced whenever possible. In some cases the risk is tolerated by individuals facing the risk, but only because they cannot afford to reduce the risk they have recognized is not sufficiently controlled (AGS, 2000, Fell et al., 2005).

Risk assessment provides judgements concerning uncertainties and likelihoods, whereas the risk evaluation compares the acceptable and tolerable risk levels and further assesses the options and priorities (Aven, 2008). The main objective is to decide whether the risk should be accepted or treated, and to set the desired priorities.

Risk evaluation judges the estimated risk in form of acceptability and significance. This process might involve comparisons to other assessed risks or acceptance criteria associated with financial losses, loss of life or other values (Lacasse et al., 2012). In some situations, this value judgment can easily be made if the client is the only affected party of the risk. However, if this is not the case, environmental effects, politics, public reaction and business must be considered before making the decision whether the risk is acceptable. The process is often iterative, and requires assessments of the sensitivity of the assumptions and calculations, but also development modifications and revision of measures to mitigate risk (AGS, 2000).

Risk control covers the enforcement and implementation of actions with the goal of controlling the risk, but also to re-evaluate the efficiency of these measures on a periodic basis (Fell et al., 2005).

Risk management is defined as the complete process from risk assessment to risk control (as seen in Figure 4.1).

Risk mitigation: The application of selective, but appropriate management techniques and principles for reducing the consequences or likelihood of an occurrence, or both (Fell et al., 2005).

Individual risk is defined as the probability of loss of life for a particular person. The risk can also be seen as the amount of risk imposed on a specific person from the existence of a particular hazard (Aven, 2008).

Societal risk is the risk of several injuries or fatalities in the society when seen as a unit. The society carries the burden if a landslide is realized and causes fatalities, injuries or environmental, financial or other losses. Too high consequences may provoke political response (Fell et al., 2005).

Severity is defined as the size, extension and intensity of something that effects human values (money, lives, environment, etc.) (Aven, 2008). Severity and uncertainty is associated with the consequences of a specific activity, losses and gains, and are a way of characterizing them (for example by loss of life or momentary value).

Vulnerability is in this thesis divided into social and physical vulnerability. The physical vulnerability is defined as the degree of loss expected within a system from a particular threat. This vulnerability is quantified with a number between 0 and 1, where 0 is no loss and 1 is total loss (Rollins and Zekkos, 2012). The social vulnerability is by Wisner et al. (2003) defined as: “By vulnerability we mean the characteristics of a person or group and their situation that influence their capacity to anticipate, cope with, resist and recover from the impact of a natural hazard (an extreme natural event or process)” (Wisner et al., 2003, p.11). Vulnerability is a combination of factors which determines to what degree someone’s livelihood, life, assets and property are exposed to risk by a specific event (Clague et al., 2012).

Uncertainty is defined as situations without total certainty, and probability distributions can be used to describe the uncertainty. The cause of uncertainty is lack of sufficient knowledge (incomplete data) or natural variations. In the safety context, uncertainty is either epistemic (insufficient knowledge of parameters included and the relationship between them) or aleatory (natural variability in events and properties) (Fell et al., 2005).

Cost-benefit analysis estimates the momentary value of the cost and benefits of a measure or project to the society, and decides whether the cost is worth it (Aven, 2008)

Susceptibility is defined as the tendency for circumstances to exist that favors new landslide developments. Susceptibility is a measure of this tendency, and do not include information concerning return period or temporal frequency (Quinn et al., 2011).

Safety factor is defined as the ratio for the maximum stress a material or structural part can endure to the stress it was designed to endure (Dictionary.com, 2017). The safety factor is in this thesis used to decide if the stability of a slope is sufficient.

Pore pressure is defined as the pressure of water or other fluids within a reservoir or formation. Hydrostatic pore pressure state is when fluids are at rest, which means that all the stresses are vanished in a system (Schlumberger, 2017).

Overconsolidation ratio (OCR) is defined as the ratio between the maximum effective stress the soil has experienced (preconsolidation stress) and the effective stress in the current state (Janbu, 1989).

Retrogression is defined as a backward movement (Janbu, 1989). In some quick clay landslides, the masses located behind the triggering point is involved in the slide, hence the movement is regressive.

Run-out distance is defined as the total length the landslide masses travel from the toe of the slope until the masses comes to a stop (L'Heureux and Solberg, 2012).

B: Landslide classification and stability analysis

Description of First Movement

Rate	Water Content	Material	Type
Extremely rapid	Dry	Rock	Fall
Very rapid	Moist	Earth	Topple
Rapid	Wet	Debris	Slide
Moderate	Very Wet		Spread
Slow			Flow
Very slow			
Extremely slow			

Figure B. 1: Glossary for creation of landslide names (Cruden and Varnes, 1996).

Velocity Class	Description	Velocity (mm/sec)	Typical Velocity	Probable Destructive Significance
7	Extremely Rapid			Catastrophe of major violence; buildings destroyed by impact of displaced material; many deaths; escape unlikely
		5×10^{3}	5 m/sec	
6	Very Rapid			Some lives lost; velocity too great to permit all persons to escape
		5×10^{1}	3 m/min	
5	Rapid			Escape evacuation possible; structures; possessions, and equipment destroyed
		5×10^{-1}	1.8 m/hr	
4	Moderate			Some temporary and insensitive structures can be temporarily maintained
		5×10^{-3}	13 m/month	
3	Slow			Remedial construction can be undertaken during movement; insensitive structures can be maintained with frequent maintenance work if total movement is not large during a particular acceleration phase
		5×10^{-5}	1.6 m/year	
2	Very Slow			Some permanent structures undamaged by movement
		5×10^{-7}	15 mm/year	
	Extremely SLOW			Imperceptible without instruments; construction POSSIBLE WITH PRECAUTIONS

Figure B. 2: Proposed velocity scale and accordingly probable destructive significance (Cruden and Varnes, 1996).

Stability analyses

Stability analyses are carried out to decide the shear strength of the material of interest. The shear strength is a materials ability to resist fracturing. As shown on Figure B. 3 the shear strength (τ_f) works in the opposite direction of the shear stress due to loading (τ). When $\tau_f > \tau$ the slope is stable. If the opposite occurs the slope detaches and forms a landslide.

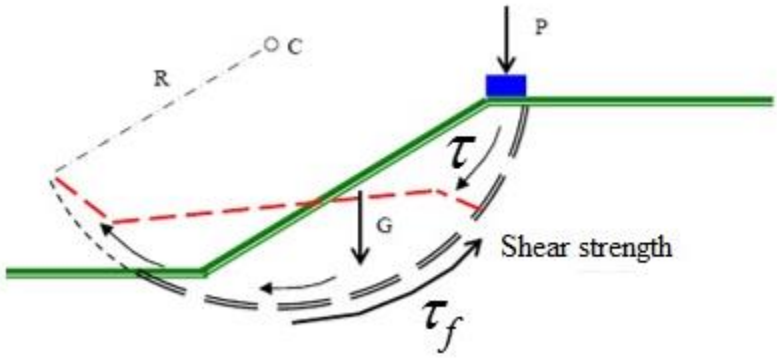


Figure B. 3: Sketch of a slope showing the fracture plane due to increased loading on the top of the slope (Thakur et al., 2014).

There are two main stability analyses, ADP and AFI (Thakur et al., 2014):

- ADP analysis is used to a large extent in stability analysis of the undrained state in geotechnical projecting. Undrained state means that the water inside the pores are unable to escape out of the soil during the analysis. This results in an increased pore pressure due to the loading.
- AFI analysis is used to a large extent in stability analysis of the drained state in geotechnical projecting. Drained state means that the water inside the pores can escape the soil easily. This results in no change in the pore pressure due to the loading.

C: Landslide database of Buskerud

Table C. 1: Shows the landslide database of landslide event going back to prehistoric times. See methodology for the sources of the data.

Number	Locality	Date	County	Fatalities	Triggering factor	Damages	Area (m^2)	Volume (m^3)	Reference
1	Drammenfjorden, Gullaug 2	Prehistoric	Buskerud	?			190000	2850000	L'Heureux and Solberg (2012)
2	Frygne	Prehistoric	Buskerud	Several					Furseth (2006)
3	Kveta Nordre og Søre	Prehistoric	Buskerud	?					Furseth (2006)
4	Rudi og Grønneflåta	1671	Buskerud	0					Furseth (2006)
5	Murugarden	1679	Buskerud	0					Furseth (2006)
6	Rotneim, Gol	1700	Buskerud	1		A village of houses			Furseth (2006)
7	Ulstad og Søre Fetjan (2 slides)	6.1702	Buskerud	0		Houses and soil			Furseth (2006)
8	Torpo	1706	Buskerud	0					Furseth (2006)
9	Huseby Nordre	1713	Buskerud	0		Half the village			Furseth (2006)
10	Kveta Nordre og Søre	1720	Buskerud	0					Furseth (2006)
11	Søre Nestegard	1735	Buskerud	0		4 houses			Furseth (2006)
12	Brugard	1760	Buskerud	0		Half the farm			Furseth (2006)
13	Kvernrud	1763	Buskerud	3-4		Several houses and animals			Furseth (2006)
14	Hagaplassen (7 slides)	1789	Buskerud	0					Furseth (2006)

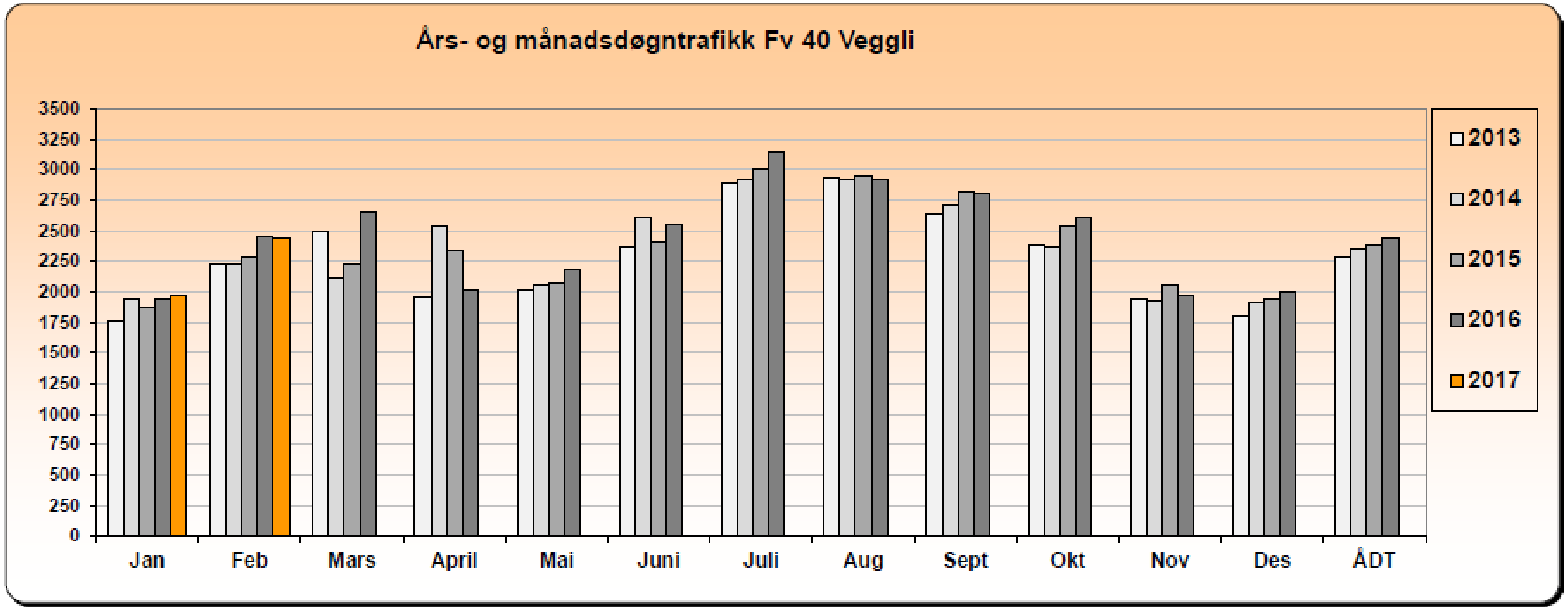
15	Flekken, Gol	1812	Buskerud	0		Houses, animals and soil			Furseth (2006)
16	Dugursnatten	1825	Buskerud	0		Houses			Furseth (2006)
17	Tviten Øvre og Gardar	1827	Buskerud	0					Furseth (2006)
18	Hokksund	1850	Buskerud	0	Spring flood				Furseth (2006)
19	Nordre Langslet	1860	Buskerud	0		soil and forrest			Furseth (2006)
20	Rudi, Land og Bergerud	1860	Buskerud	0		?			Furseth (2006)
21	Sundbakken, Ullern og Lerberg	1860	Buskerud	0					Furseth (2006)
22	Hemsedal, Hol	17.06.1860	Buskerud	?	Rainfall and snow melting			?	Furseth (2006)
23	Ullern	1861	Buskerud	0		Road			Furseth (2006)
24	Ullern	1865	Buskerud	0		Road			Furseth (2006)
25	Øvre Liaberg	1876	Buskerud	0					Furseth (2006)
26	Ål	14.7.1876	Buskerud	3	Local storm	214 animals, 38 houses, 42 farms, roads and railways			Furseth (2006)
27	Kveta Nordre og Søre	1879	Buskerud	0					Furseth (2006)
28	Nord-Husebø	1906	Buskerud			harm			Furseth (2006)
29	Krødshead	2.8.1910	Buskerud	3 (and 4 injured)		Train and railways			Furseth (2006)
30	Krosshaugen	1910	Buskerud	0					Furseth (2006)
31	Sanden og Haga	23.12.1910	Buskerud	0		5 farms, several animals,		230000	Furseth (2006)

						boats (tsunami)			
32	Bakkan	1920	Buskerud	0		1 house			Furseth (2006)
33	Hemsedal	1930	Buskerud	0					Furseth (2006)
34	Krosshaugen	1930	Buskerud	0					Furseth (2006)
35	Renskog	1931	Buskerud	0					Furseth (2006)
36	Skotselv (2 slides)	1931	Buskerud	0					Furseth (2006)
37	Vinnes	1932	Buskerud	0					Furseth (2006)
38	Drammen	8.1.1935	Buskerud	4	River erosion	Quay facility		?	Furseth (2006)
39	Søre Rue	1935	Buskerud	0		Soil, boats and roads			Furseth (2006)
40	Ila	1935	Buskerud	0					Furseth (2006)
41	Fallaksøya	1936	Buskerud	0	River erosion				Furseth (2006)
42	Gråbekkdalen	1937	Buskerud	0		Railways			Furseth (2006)
43	Hval og Norderhov	1937	Buskerud	0		?			Furseth (2006)
44	Djupedal	1937	Buskerud	0					Furseth (2006)
45	Drammen	1955	Buskerud	0					Furseth (2006)
46	Drammen	1955	Buskerud	0					Furseth (2006)
47	Drammen	06.01.1955	Buskerud	0				4000	L'Heureux and Solberg (2012)
48	Viul (5 slides)	5.1958	Buskerud	0					Furseth (2006)
49	Grøndalen, Hemsedal	1959	Buskerud	1 (and 1 injured)	Local storms	Houses and soil			Furseth (2006)
50	Lia-gardene	1966	Buskerud	0		1 farm			Furseth (2006)
51	Drammen	1971	Buskerud	0					Furseth (2006)
52	Drammenfjorden, Gullaug 1	29.11.1974	Buskerud	0	Landfill		30000	100000	L'Heureux (2015)

53	Drammensfjorden, Hyggen	23.01.1978	Buskerud	0	Landfill		8500	500000	L'Heureux (2015)
54	Brekka	1978	Buskerud	0		Several houses			Furseth (2006)
55	Hyggen	1980	Buskerud	0		Several houses		4000	Furseth (2006)
56	Vestfossen	1984	Buskerud	0		Strandajordet sport facility			Furseth (2006)
57	Formo	1992	Buskerud	0		1 house		100000	Furseth (2006)
58	Eikeseter	1996	Buskerud	0					Furseth (2006)
59	Hvalfoss	1997	Buskerud	0					Furseth (2006)
60	Landsverk	1997	Buskerud	0					Furseth (2006)
61	Sellikdalen	1998	Buskerud	0					Furseth (2006)
62	Kongshaug	2000	Buskerud	0		3-4 houses			Furseth (2006)
63	Hellum	2000	Buskerud	0					Furseth (2006)
64	Hvittingfoss	11.7.2000	Buskerud	?	Surficial slide in ravine slope, Marine clay, medium strength, medium sensitive, scour from initial slide				Skrednett.no
65	Svelvikveien 500	11.15.2000	Buskerud	?	Erosion due to clogged culvert				Skrednett.no
66	Hvittingfoss	8.6.2001	Buskerud	?	Surficial slide i partially saturated sand slope				Skrednett.no
67	Sullikroken	4.30.2008	Buskerud	?					Skrednett.no
68	Sullikroken	4.30.2008	Buskerud	?					Skrednett.no
69	Heistadmoen-Sagvollen	4.30.2008	Buskerud	?					Skrednett.no

70	Volden- Berg	4.30.2008	Buskerud	?					Skrednett.no
71	Volden-Berg	8.31.2008	Buskerud	?					Skrednett.no
72	Efleløftveien	8.29.2011	Buskerud	?					Skrednett.no
73	Komnesveien	9.19.2011	Buskerud	?					Skrednett.no
74	Efteløftveien	9.19.2011	Buskerud	?					Skrednett.no
75	Voldenveien	9.19.2011	Buskerud	?					Skrednett.no
76	Voldenveien	9.21.2011	Buskerud	?					Skrednett.no
77	Komnesveien	9.26.2011	Buskerud	?					Skrednett.no
78	Eftekøtveien	9.26.2011	Buskerud	?					Skrednett.no
79	Sommerstad	11.1.2011	Buskerud	?					Skrednett.no
80	Åsen	7.9.2012	Buskerud	?					Skrednett.no
81	Øvre Laurud	7.18.2012	Buskerud	?					Skrednett.no
82	Mossåsen	8.6.2012	Buskerud	?					Skrednett.no
83	Passebekk	8.6.2012	Buskerud	?					Skrednett.no
84	Hostvedt	8.6.2012	Buskerud	?					Skrednett.no
85	Teigen	8.6.2012	Buskerud	?					Skrednett.no
86	Åssiden	8.6.2012	Buskerud	?					Skrednett.no
87	Drammensveien	4.17.2013	Buskerud	?					Skrednett.no
88	Sommerstad	5.16.2013	Buskerud	?					Skrednett.no

D: Consequence analysis



År	Jan	Feb	Mars	April	Mai	Juni	Juli	Aug	Sept	Okt	Nov	Des	ÅDT	ÅDT tunge	% tunge
2007	1665	1915	2057	2305	2089	2439	3058	2944	2628	2366	1875	1695	**2254**	**234**	**10,4 %**
2008	1742	2099	2230	1898	1971	2484	3029	3029	2646	2258	1760	1713	**2242**	**216**	**9,6 %**
2009	1722	2027	1995	2496	2079	2492	3088	2848	2685	2081	1705	1774	**2248**	**213**	**9,5 %**
2010	1677	2019	2186	2101	1943	2378	3016	2831	2604	2349	1781	1701	**2217**	**223**	**10,1 %**
2011	1734	2027	2012	2413	2024	2409	2890	2745	2645	2361	1882	1804	**2246**	**234**	**10,4 %**
2012	1801	2133	2093	2168	2014	2273	2782	2654	2561	2211	1836	1751	**2189**	**230**	**10,5 %**
2013	1767	2233	2492	1961	2011	2372	2887	2935	2639	2388	1950	1806	**2290**	**247**	**10,8 %**
2014	1945	2230	2112	2541	2063	2608	2919	2926	2714	2364	1936	1920	**2356**	**257**	**10,9 %**
2015	1868	2286	2229	2339	2076	2410	3009	2955	2814	2532	2053	1951	**2377**	**258**	**10,9 %**
2016	1938	2459	2650	2020	2191	2555	3141	2920	2801	2610	1975	2002	**2439**	**276**	**11,3 %**
2017	1975	2440													

Kommentar

Figure D. 1: Shows the registrations of the traffic density of Fv 40 (Statens vegvesen, 2017).

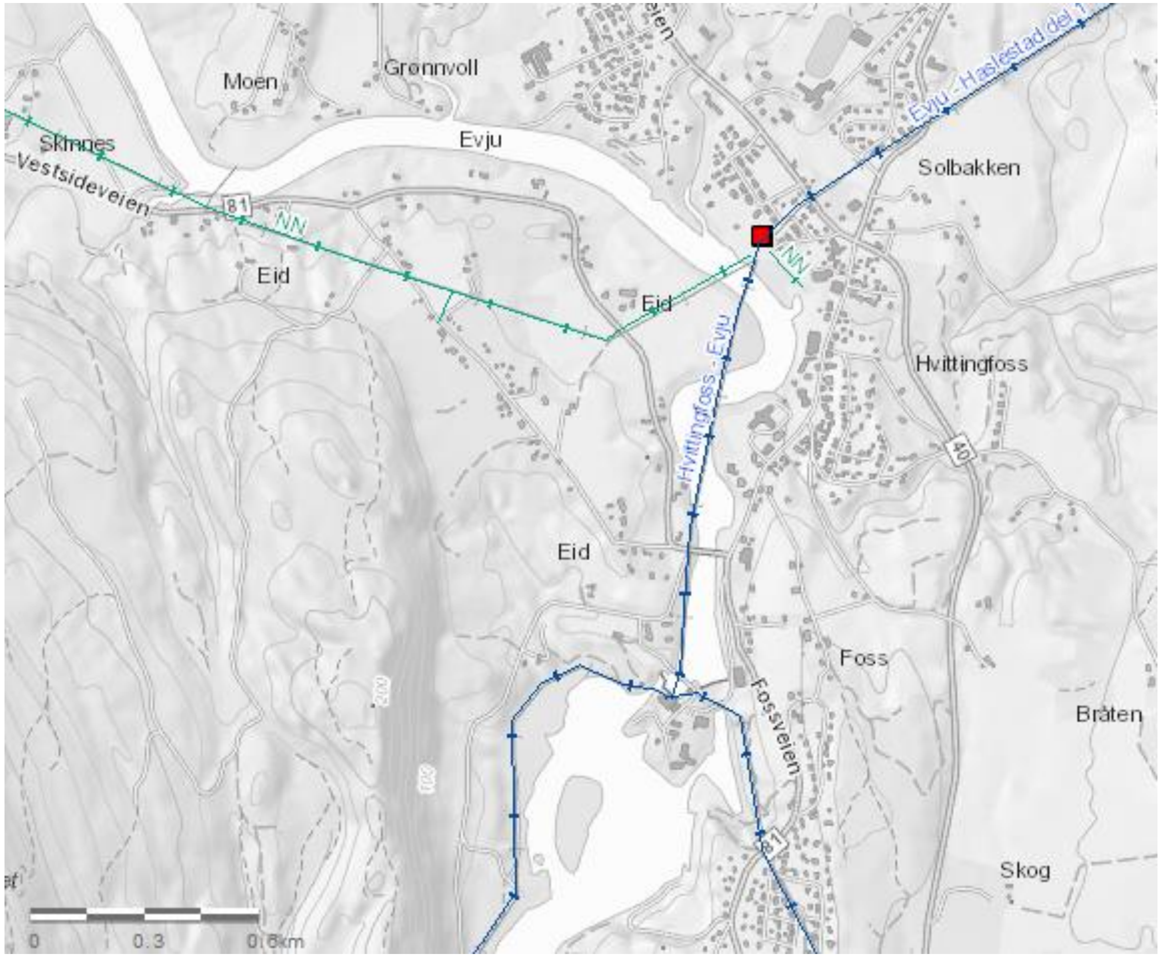


Figure D. 2: Shows the powerlines in the Hvittingfoss area (NVE, 2017a). The red square is a transformer station, and the lines presents the powerlines. The blue are the regional lines and the green the distribution powerlines.

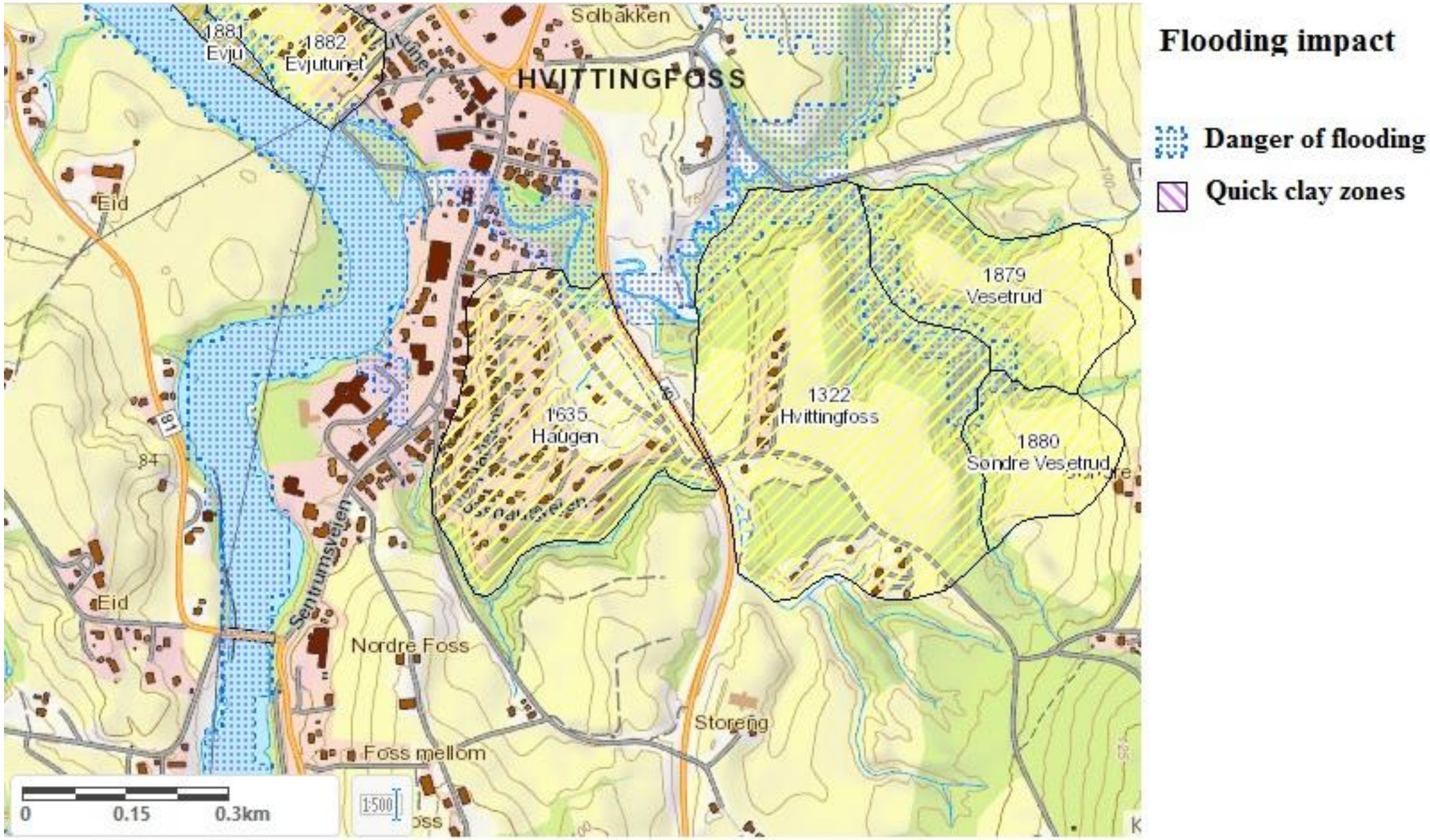


Figure D. 3: Shows the surrounding areas with danger of flooding (NVE, 2017a).

E: Stability analysis

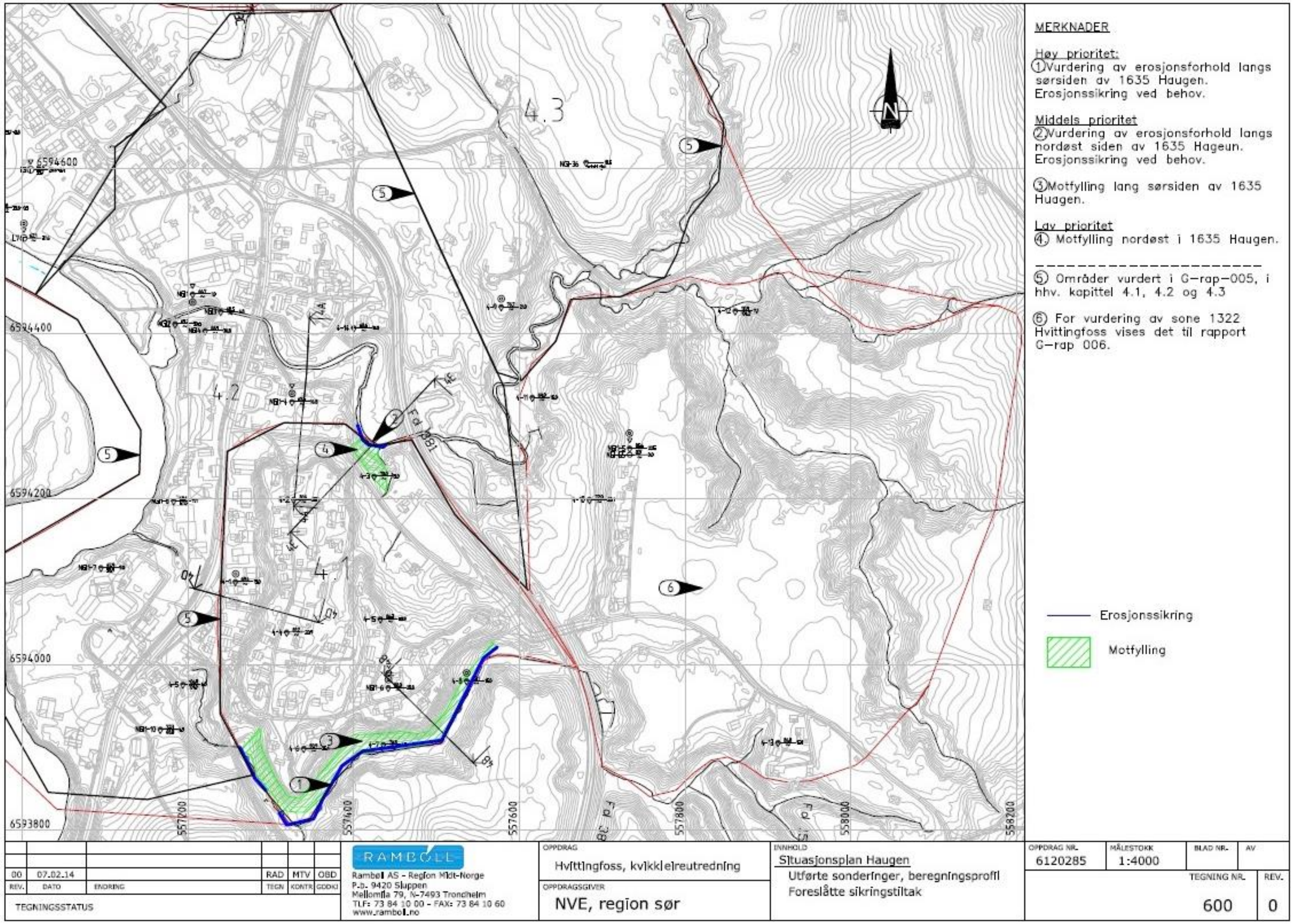


Figure E. 1: Shows the location of the profiles used of the stability analysis (Rambøll: Tveit et al., 2016).