Impact of climate change and human activity on quick clay landslide occurrence in Norway

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ABSTRACT
Landslides in sensitive clays represent a major hazard in many northern countries of the world. Past and recent examples of catastrophic landslides illustrate the extreme mobility of sensitive clays and their hazardous retrogressive potential. This paper uses a new database of landslide in sensitive clays in Norway to assess the influence of weather conditions and human activity on the triggering of quick clay landslides. The paper is a contribution to "what to expect in the future" with climate change. The data suggest that fewer landslides will occur during the dryer summer months in the future, whereas there will be an increase in landslide activity in the spring and fall seasons due to an increase in precipitation and an increase in heavy, sometimes intense, rainfall events. A peak in landslide occurrence is observed in the spring. This peak will likely occur sooner in the year in the future due to higher temperatures, earlier arrival of the spring season and changes in the spring flood patterns. Besides the impact of climate change, the database in itself speaks clearly to geotechnical engineers and policy-makers: in the last decade, 90% of the slope failures link to human activities! Either our knowledge on the behavior of this material is insufficient or, we have not learned from earlier landslide events.

1 INTRODUCTION
Increased landslide frequency is commonly listed as an impact of climate change. This is true for many type of rapidly-moving landslides such as for example earth flows, debris flows and flow slides (e.g. Evans and Clague 1994, Geertsema et al. 2006, Jædicke et al. 2008). However, the relationship between increased precipitation due to climate change and rapid flow-like landslide in sensitive clays, or quick clay, is not fully understood.

Landslides in sensitive clays represent a major hazard in the northern countries of the world. Past and recent examples of catastrophic landslides have illustrated the extreme mobility of sensitive clays and their hazardous retrogressive potential. In Norway, important changes in annual temperature, precipitation, heavy rainfall events and flood frequency are anticipated by the end of the 21st century. The question is how will these changes affect the occurrence of landslides in sensitive clays?

Over the years, the Norwegian Geotechnical Institute (NGI) has assembled a large database of landslides in sensitive clays. The database includes over 550 Norwegian landslide events, with essential information on pre-conditioning and triggering factors for landslide in sensitive clays. A short overview of some of the results from the database is presented in this paper to illustrate the influence of weather conditions and human activity on the triggering of quick clay landslides in Norway. The aim of the paper is to bring a contribution to "what to expect in the future" based on anticipated climate changes.

2 IMPACT OF CLIMATE CHANGE ON HYDROMETEOROLOGICAL FACTORS IN NORWAY
Table 1 summarizes the result of a study by Hanssen-Bauer et al. (2017). By year 2100, temperatures are expected to rise by an average of 4.5 °C, and annual precipitation will increase by about 18%, and there will be more frequent intense rainfalls in Norway than before. These expected changes in climate were used in the the GeoExtreme project to study the changing geohazard pattern in Norway in the upcoming years (Jaedicke et al. 2008).
Table 1: Anticipated changes in temperature, precipitation, heavy rainfall, floods and sea-level rise in Norway up to year 2100 based on IPCC scenario RCP8.5 (after Hanssen-Bauer et al. 2017).

<table>
<thead>
<tr>
<th>Hydrometeorological factor</th>
<th>Anticipated change up to year 2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Annual temperature will increase by about 4.5 ºC (interval: 3.3 to 6.4 ºC)</td>
</tr>
<tr>
<td>Precipitation</td>
<td>Annual precipitation will increase by about 18 % (interval: 7 to 23 %). This increase is forecasted to be higher in the spring and lowest in the summer.</td>
</tr>
<tr>
<td>Intense rainfall</td>
<td>Rainfall will be more intense and occur more frequently. Some regions, especially in the southeastern part of Norway might experience summer drought.</td>
</tr>
<tr>
<td>Floods</td>
<td>Floods induced by rainfall will increase in magnitude and occur more frequently. Floods caused by snowmelt will decrease in magnitude and frequency.</td>
</tr>
<tr>
<td>Sea-level</td>
<td>Mean sea level will increase by 15 - 55 cm depending on location along the Norwegian coast</td>
</tr>
</tbody>
</table>

3 WHAT IS QUICK CLAY

In Norway, the classification of a clay material as quick is based on a threshold value for the remoulded shear strength ($c_{rr}$). Clays are classified as quick when the remoulded shear strength is less than 0.5 kPa. Quick clay occurs within unconsolidated, marine clay deposits in the low-land areas of the country. The distribution of such deposits is closely linked to the postglacial and Holocene landscape development. The marine clays accumulated in the sea and fjords following the last ice-age and emerged subsequently above sea level, up to 220 m.a.s.l., due to the relative fall of sea-level since deglaciation.

The high sensitivity of Norwegian quick clays is attributed to the leaching by fresh groundwater of the salts within the grain structure (Rosenqvist 1953). Fresh water percolating downwards through the marine deposits due to surface run-off, or up-wards due to artesian pressures, removes the salt ions and leaves behind a metastable, sensitive structure made up of flocculated clay minerals. Upon remoulding, this unstable structure is destroyed and the surface water which is liberated give rise to a fluid material. This liquefaction when subjected to loading is one of the main agents governing the post-failure behaviour of quick clays.

4 DATABASE ANALYSIS

4.1 Data and limitations

NGI’s new database of landslides in sensitive clays contains over 550 landslide events dating back to the 14th century. When available, the database includes information about the timing of the events (i.e. date is available for 342 landslides), information on the triggering mechanism and geotechnical properties of the soils. The landslides were selected based on available data found in the literature, historical documents or in geotechnical reports. Unfortunately, the spatial and historical coverage of events is limited. Systematic registration of landslide events started first in the 1970s, with the majority of registrations in the last 30 years. Earlier events back to the 14th century are limited to destructive events with fatalities or loss of property. In this short abstract only a few of the exploitable results from the database are summarized.

4.2 Impact of climate on quick clay landslide occurrence

Figure 1 shows the quick clay landslides registered in the database per month and season. There is a clear trend showing a higher frequency of landslides in the spring and during the fall. During the spring season in Norway, there is a combination of rapid snow melting and rainfall, which lead to floods, increase in water infiltration in the ground, increase in pore pressure, and increase in river erosion. Together, these factors contribute in lowering the margin of safety of slopes, and in some circumstances, in the triggering of landslides. On the other hand, lower landslide activity is clearly seen during the summer months. This period coincides with the driest period of the year when the groundwater levels in the soil and in rivers are lowest, and hence the pore pressure regime in the soil and the erosion potential is characterized with lower pore pressures than in the fall and the spring. During the fall season, there are usually increased rainfall, at times intense rainfalls, and some freeze-thaw cycles, each affecting the pore pressure regime and causing higher landslide frequency.
Figure 1: Registered number of quick clay landslides per month since the 14th century in Norway.

Figure 2: Quick clay landslide frequency per decade in Norway (only larger landslides, i.e. > 50,000 m³).

In Figure 2, the landslide database was filtered to focus exclusively of the triggering of the larger landslides (>50,000 m³). The landslide occurrence is described with the "number of landslides per year". Since 1950, the database shows that at least 1.09 large landslide per year have been registered in sensitive clay in Norway. This frequency changes from decade to decade. The highest landslide frequency corresponds to the 1950-1960 decade with a frequency of 1.70 landslide/year (Fig. 2). The lowest landslide frequencies are registered during the period 1990-2000 and 2000-2010 (0.6 landslide/year). On the other hand, since 2010, the landslide frequency has gone up to 1.25 landslide/year. The landslides in the database have occurred at different localities in Norway and it is not possible over this short period to link the changes in landslide frequency to climate change.

4.3 Impact of human activity on quick clay landslide occurrence in Norway

Natural slopes that have remained stable for many years in sensitive clay terrain may suddenly fail due to natural factors (e.g. erosion), man-made activities (e.g. loading at the top of the slope) or a combination of both. In many cases, natural factors such as intense precipitation and/or erosion can undermine the stability of a slope to a point where a small external trigger can suddenly destabilize a slope (e.g. blasting for road construction, adding a thin fill, small excavation). Therefore, and especially for the older landslides, much uncertainty lies in the cause(s) of failure. As an example, the larger amount of landslides registered during the spring when unfavorable groundwater conditions exist could also be partly influence by human activity, and vice-versa. In fact, due to the harsh winters in Norway, many construction projects wait until the spring before initiating, and several human-induced landslides in the spring are known (e.g. the 1959 Sokkelvik landslide). Similarly, most of the Norwegian construction projects are on hold during the month of July (summer holidays) and this could partly explain the very low landslide activity during the summer, although the drier season is probably a more meaningful factor with respect to landslide triggering during the summer.
The database indicates clearly that the impact of human activities has increased over the years when compared to natural factors (Fig. 3). This is linked to the history of construction in Norway. Following World War II, the Norwegian authorities stimulated the agricultural sector in Norway. This included reshaping and levelling of fertile land areas often underlain by marine deposits and quick clays in Norway. Leveling and reshaping of farmland continued until the late 1970's and can explain the higher landslide frequency from 1950 and until the late 1970's. In the aftermath of the Rissa landslide, a national program for identifying quick clay hazard zone was established in the early 1980's. This program led to mitigation of hazard zones and an enhanced public and governmental awareness of quick clay landslides, and hence a decrease in large slope failures from the early 80's (Fig. 2). In between 1980 and 2010, the landslide frequency decreased from nearly 1.5 landslide/year to 0.6 landslide/year. However, during the past decade (i.e. 2010-2018), the frequency of large landslides has increased again to the level similar to that of the 1970's. So how can this be explained?

As seen on Figure 3, as many as 90% of the landslides between 2010-2018 were triggered by human activity. This is believed to be explained again by historical factors. To cope with the financial crisis of 2008, the Norwegian government increased investments in the construction sector considerably during the period 2010-2018. The total investments in this sector were 3.5 times higher in Norway than those of 2004 and led to development of e.g. several large transportation and infrastructure projects which resulted in an increased opportunities for large slope failures.

5 SUMMARY AND CONCLUSIONS

The data presented in this study show that both climate and human-induced factors affect the timing and occurrence of landslides in sensitive clays. Given the anticipated changes in temperature, precipitation, heavy rainfall and flood patterns in Norway by the end of 2100 due to climate change (Table 1), the following impact on landslide activity in sensitive clay in Norway is expected:

- Fewer landslides during the summer period due to dryer summer months;
- Increased landslide activity during spring and fall due to increased rainfall and increased rainfall intensity;
- The landslide frequency peak seen in the spring today will likely occur sooner in the year due to increased temperatures, shorter winter season and changes in the spring flood patterns.

Besides the impact of climate change, the database in itself speaks clearly to geotechnical engineers and policymakers: in the last decade, 90% of the slope failures have been linked to human activities! Either our knowledge on the behavior of this material is insufficient or, we have not learned enough from earlier landslide events.

REFERENCES