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Analysis of landslide triggers in a complex soil stratigraphy prone to water induced erosion

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ABSTRACT

The valley along the Ångermanälven river in the northeastern part of Sweden is known for its high and steep riverbanks (nipa) with complex glacial and postglacial sediments (silt, sand, clay) that over millennia have been reworked and redeposited as the river has gradually cut its way into the landscape due to land uplift. Land erosion processes caused by heavy rainfall, snow melting, surface runoff, infiltration of excessive amounts of water during prolonged rain, and frozen ground conditions are examples of present-day landslide triggers in this area., Thus, the landslide triggers are not so much caused by the river itself. A municipal documentation of historical landslide events in the area inspired to an analysis of the trigger factors. A database was created and analyzed in respect to different types of soil movements in the area. The results played an important role as in-depth knowledge for the parallel ongoing slope stability and landslide probability analyses for a landslide risk mapping project. The landslide risk and climate impact mapping identified areas with high, moderate, and low risk for landslides, and areas sensitive to climate change.

INTRODUCTION

Background

Since 2009, SGI (Swedish Geotechnical Institute) has received funds from government appropriation 1:10 Climate Change Adaptation for climate adaptation initiatives in our area of responsibility through investigation, mapping and method development that reduces the risk of landslides and erosion and contributes to sustainable settlements in a changing climate.

The landslide risk mapping along prioritized watercourses is a part of this initiative and is intended to provide comprehensive documentation along these watercourses. The documentation can be used at a general planning level to facilitate priority-setting in the ongoing work of municipalities and county councils to adapt society to climate change. The investigation along the Ångermanälven river began in 2015 and was completed in May 2022. The landslide risk mapping along the Ångermanälven river has resulted in a comprehensive overview of the risk of landslides in the current climate and in the climate of the future, for built-up and undeveloped land and for areas with critical infrastructure. The results and conclusions of the investigation are presented in SGI Guidance 5 "Landslide risks in a changing climate – Ångermanälven river valley", consisting of three parts, see for example SGI, 2022a and SGI, 2022b.

High landslide risk occurs to a small extent in the Ångermanälven river valley, within about 1.5% of the land surface of the investigation area. Moderate landslide risk occurs in 20% of the land surface. Moderate and high landslide risk, as well as a substantial and high probability of landslides, occurs mainly on the steep slopes towards the river and in larger ravines. Most of the area, approximately 70% of the land surface, has a low risk level. The landslide risk maps show the location of sensitive areas requiring more detailed investigation in terms of clarifying the geotechnical conditions and the consequences of a landslide. The maps also provide an indication of which areas, in the long term, may be the most vulnerable to a changing climate due to deteriorating stability conditions.

The river has since the 1940s been subject to large scale hydropower generation, which has had a large effect on the water levels and erosion processes in the riverbed. The river and bank erosion has been modelled for a time frame until the year 2100 (SGI, 2022d). The results show that in this area the river erosion is small due to the regulated water conditions and the decreased sediment transport. Therefore, the river erosion has minor impact on the slope stability.

The geology in the area along the Ångermanälven river, with layered clayey, silty and sandy soil, differ from the previously investigated areas, with mainly clay deposits. For the earlier investigated river valleys, the main trigger for landslides was assessed to be erosion of the riverbed (SGI, 2012a, 2012b, 2017, Bergdahl and Odén, 2015, Bergdahl et al, 2016). However, for the Ångermanälven river, other factors were considered to have a more significant impact on the slope stability. Therefore, as a part of the landslide risk mapping a more in-depth understanding of the landslide triggering processes including other types of erosion than from the river, in this challenging area was needed for a better understanding of the key factors of the slope stability. This paper describes other erosion and landslide triggering processes than from the direct influence by the river flow.

Scope and limitations

The landslide risk mapped area extends from the outlet of the Faxälven river upstream in the north-west to Överlännäs downstream in the south-east (Figure 1) covering about 25 km, corresponding to 50 km of the riparian shoreline of the Ångermanälven river within the municipality of Sollefteå (SGI, 2022a). The width of the investigation area extends about 300 m from the riparian shoreline. The river is the third largest in Sweden with an average outflow of 490 m^3/s into the Baltic Sea.

The area covering the content in the used database is larger than the risk mapped area. The database covers the whole municipality of Sollefteå including other parts of Ångermanälven and tributaries.

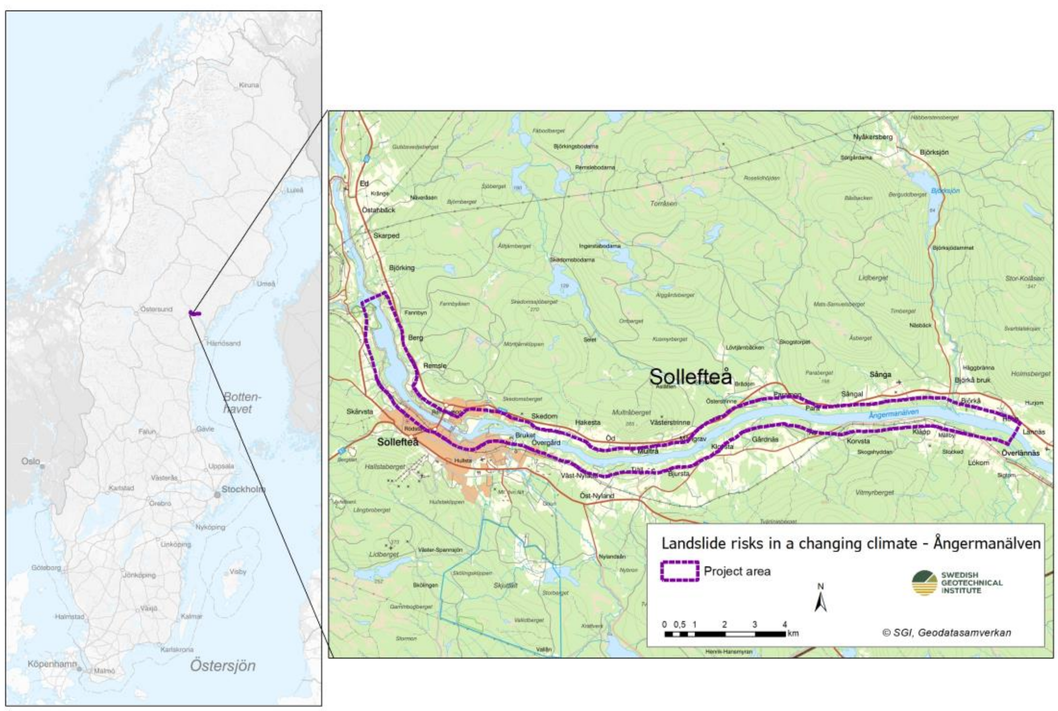

Figure 1. The geographical extent of the landslide risk mapped area along the Ångermanälven river.

Geology

The last ice age glaciation had a large impact on the geological features in the study area (SGI, 2022b, Smith and Mikko, 2016). During the glaciation phase mainly tills and glacio-fluvials were deposited beneath and in front of the ice margin, while clay and more fine-grained sediments were deposited in water in front of the ice, primarily during the deglaciation. Delta plains were also formed along the river. In this area the deglaciation was fast, with a large land lift due to the decompression from the weight of the ice sheet, which caused the river to successively erode and redeposit the previously accumulated sediments. The result today is a complex stratigraphy with remnants of ancient terraces and riverbeds, often high above the present riverbank.

Scars from landslides and mud flows are abundant in the area, as well as ravine formations. Some of the geological layers are very sensitive to high ground water levels and pore water pressure that can reduce the shear strength, but also induce erosion if discharged from permeable layers in the slope wall. This study focuses on the type of landslides that often occur in the upper part of the high and steep terraces, leaving sometimes almost vertical slopes with the landslide debris accumulated at the toe. An example is shown in Figure 2. This type of landslide can also cause flooding as a secondary effect if it is large enough.

Figure 2. A typical landslide in the study area, 12 years after the event. Photo Karin Bergdahl, SGI.

METHOD

The municipality of Sollefteå has since the year 1999 kept a landslide logbook for documentation of reported soil movements, and the measures taken in each case (Gullersbo, 2017). In the beginning, the documentation was quite sparse, consisting of a map with location of the reported event and notes about type of movement, date, and eventual actions to be taken. But soon a template was developed to be used for the reporting. In the template the following information should be filled in:

- Property designation and owner of the property with address
- Description of the location
- Time and date for reporting of event
- Extent of the event
- Decisions taken and the person responsible for making the decisions
- Documentation of the event in a map
- Photo documentation
- Name of the person documenting the event and time for documentation

The Municipality has also documented the location of each soil movement in a GIS layer. For the time 1999 to 2017, when SGI received the landslide logbook, the GIS layer consists of 165 events in total, of which 133 events within the area of the SGI landslide risk mapping for Ångermanälven river. SGI has further developed the GIS layer by connecting the geographical location of each event to a folder containing all documentation of the event, so it easily can be opened through the map in GIS (Figure 3).

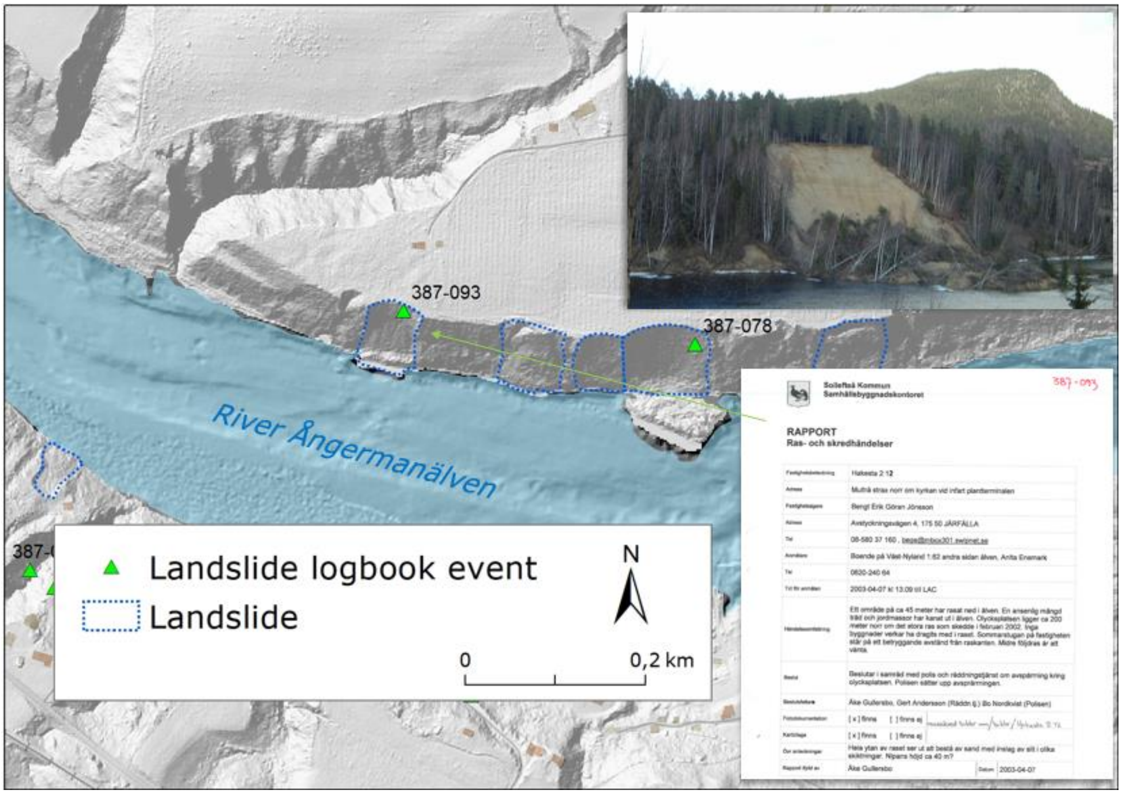

Figure 3. Example of the content in the Landslide logbook (Gullersbo, 2017) illustrated in a topographical map. Map content © SGI, Geodatasamverkan.

ANALYSIS

The documented soil movements in the landslide logbook were used to analyze possible landslide triggering factors and a spread sheet was used for the analysis (SGI, 2022c). The report in the logbook often contains a description of the event with photos, which makes it possible to draw conclusions of the factors that could have triggered that specific soil movement. Based on general knowledge and the reports in the logbook, a list of possible triggering factors, grouped into four categories; climate factors, drainage systems, loads and other factors, was proposed (Table 1). The cause is not always possible to assess and often more than one triggering factor is present in each of the documented events. Later the list of triggering factors was complemented with forestry measures, as clearcutting, which could have an influence on the runoff in the area.

Table 1. Identified possible triggering factors for soil movements.

Main group	Possible triggering factors	Comment, clarification
Climate factors	Snow melting	
	Thawing	
	Surface water	E.g. from intense precipitation, standing water
	Groundwater, porewater pressure	
	Snow storage	Both meltwater and load
Drainage systems	Pipes	E.g. drainage, sewage
	Private sewage	E.g. infiltration, three-chamber well
Loads	Storage	E.g. storage of soil, garden waste
	Excavation work	E.g. set-up of machines, vibrations
Other factors	Water level	High or low level in river
	Clearcutting	

For all events where it was possible to identify one or more triggering factors from the information in the landslide logbook, this was documented. In addition, the type of movement for each of the events were specified where it was possible. The following types were characterised:

- Shallow landslide (0-3 m depth)
- Deep landslide (deeper than 3 m)
- Debris flow (where the sand/silt material flow out and create a ravine or extend an existing ravine)
- Settlement (the ground has subsided, but a landslide has not developed, cracks)

It was also considered interesting to identify where in the slope the main soil movement occurred for the events, as it could depend on the type of triggering factor.

RESULTS

Type and location of soil movements

It was possible to identify triggering factors for 46 of the soil movements that are presented in the landslide logbook (SGI, 2022c). For these events it has been possible to characterize the type for 32 soil movements. These are divided as follows:

- Eleven shallow landslides
- Five deep landslides
- Ten debris flows
- Four ground settlements

Two of the soil movements were assessed as erosion.

Where in the slope the soil movements occurred was possible to assess for 26 of the 46 soil movements. These are divided as follows:

- Sixteen have occurred in the upper part of the slope
- Four have occurred in the middle of the slope
- Two have occurred in the lower part of the slope
- Four included the whole slope

Triggering factors

It was estimated that more than one triggering factor was present for almost half of the 46 analyzed soil movements (SGI, 2022c). The distribution of the different triggering factors is presented in Figure 4. The triggering factors surface water and snow melting were assessed to contribute to most soil movements (in 17 respective 16 events). Also, pipes were assessed to contribute to a large amount of soil movements (in 14 events). This could be due to for example leakage or rupture of a pipe. It was assessed that storage, thawing and groundwater/porewater pressure contributed to the soil movements in several cases, whereas the other identified triggering factors only contributed occasionally. Clearcutting in the vicinity of the soil movement has been noted in four of the analyzed cases. In three of these, it has been noted that clearcutting has been carried out above the slope and in one case in the slope.

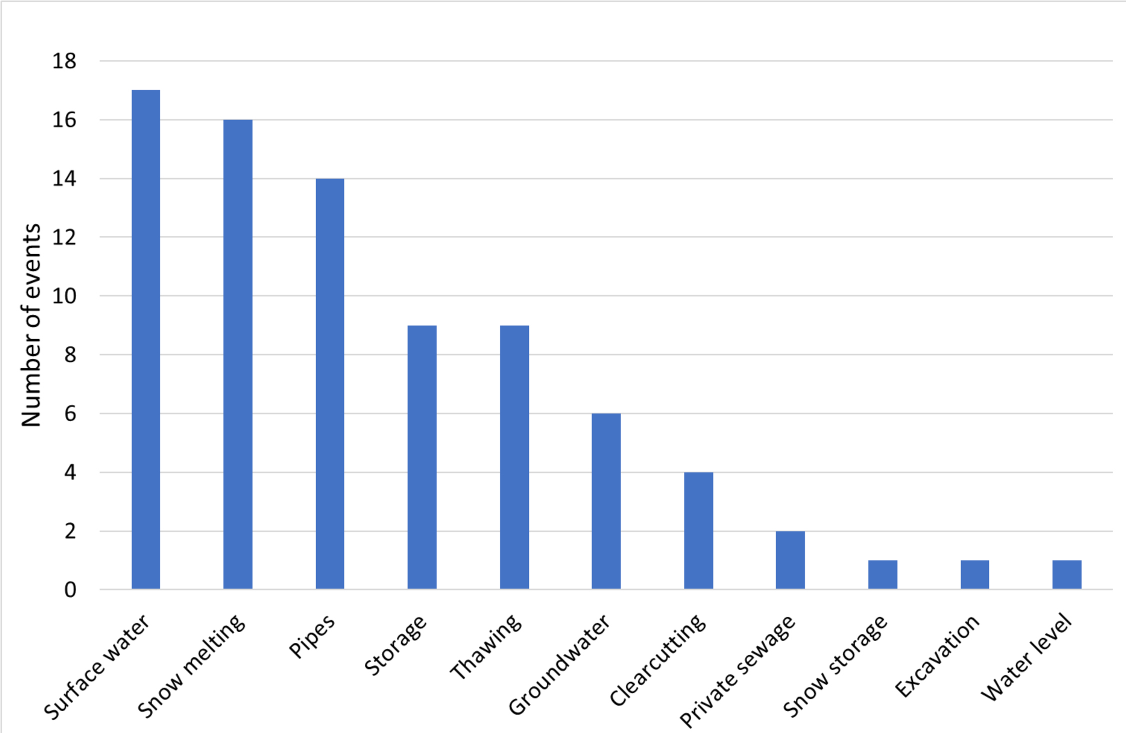

Figure 4. Assessed triggering factors for analyzed soil movements.

The time of the year when most soil movements occur has also been analyzed. A compilation of all 165 soil movements registered in the landslide logbook from 1999 to 2017 show a clear increase of the number of soil movements during the months April to May, compared to the previous months, Figure 5. This coincides with the time of snow melting in the area. Least number of soil movements occur during the winter months, December to March, when the ground is covered with snow. The rest of the year, the soil movements are quite evenly distributed, with slightly fewer during late autumn (October to November).

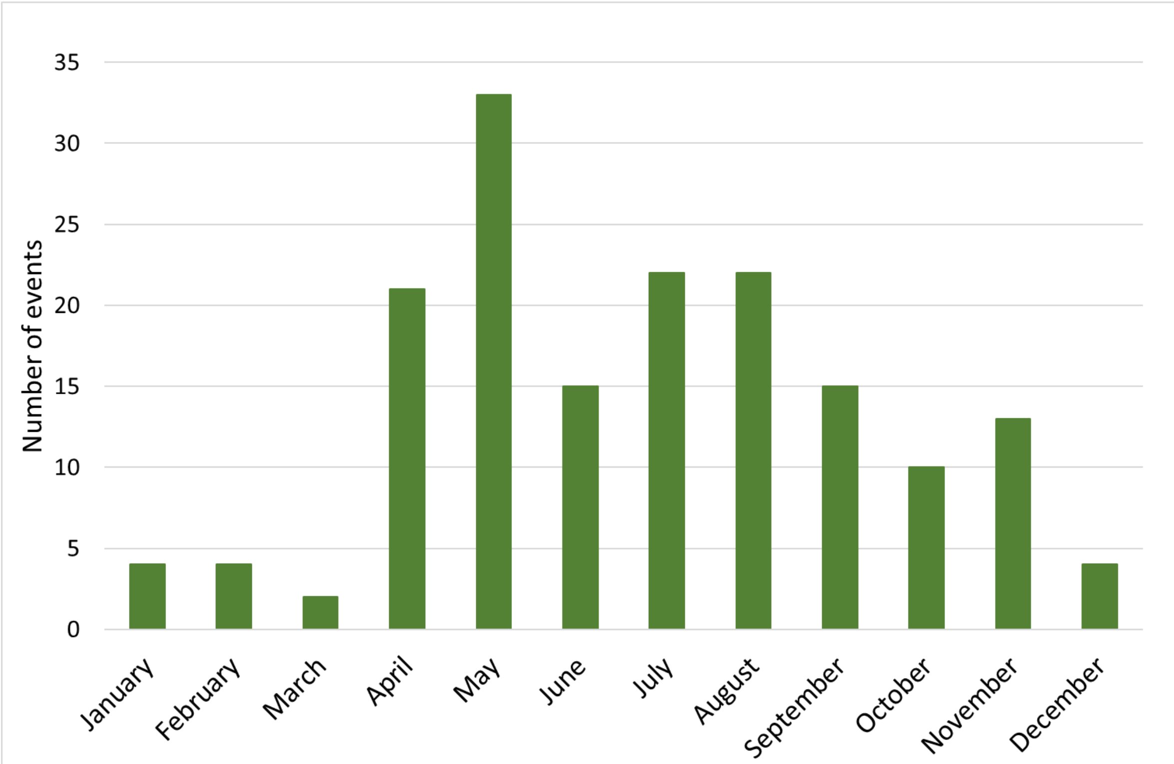

Figure 5. Number of soil movements per months during the period 1999 to 2017.

CONCLUSION

Based on the analysis of the soil movements, the majority are judged to be landslides or debris flows. It is also assessed that there is often more than one triggering factor that cause these soil movements. Surface water, snowmelt and pipes (leakage) are considered to cause most of the soil movements. But also thawing and storage are judged to cause a large number of soil movements. The fact that snowmelt and thawing have a large impact is consistent with the fact that most soil movements occur in April and May in connection with the snowmelt. The least number of soil movements occur during the winter months when the ground is covered with snow. Most of the analyzed landslide movements have occurred in the upper part of the slope, from the crest of the slope. This supports the result of the analysis that it is primarily trigger factors that have an impact on the upper part of the slope that trigger the landslides along Ångermanälven river. The trigger factors that have caused most of the soil movements, i.e. surface water, snow melting and pipes, all are present above she slopes and have an impact in the upper part of the slope.

This survey indicates that along the Ångermanälven river there are mainly other triggering factors for landslides than erosion in the watercourse, which is the main trigger in the previously investigated areas (SGI, 2012a, 2012b, 2017, Bergdahl and Odén, 2015, Bergdahl et al, 2016).

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