Lessons learned from the 2015 Soerkjosen shoreline landslide in Norway

Leçons à retenir suite au glissement côtier de Soerkjosen en Norvège

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ABSTRACT: Soft and partly sensitive clays along the fjords of northern Norway pose a challenge for infrastructure. Learning from failures is essential in providing guidelines for future geotechnical work in such areas. A shoreline landslide with a volume up to 1.4 million m^3 took place close to Soerkjosen in northern Norway during the night from the 9th to the 10th of May 2015. The shoreline slumped into the sea over a distance of more than 1 km and parts of a harbor were destroyed. No persons were killed, but after the slide the traffic had to take a 700 km detour through Finland to pass the site. The slide took place in a fjord with steep mountainsides and a large river delta. There was ongoing road construction prior to the event, including rock blasting. The authors of this paper took part in the investigation group that concluded that the stability was lowered to a critical level already in November 2014 when a breakwater / embankment was widened by filling crushed rock into the sea for a road crossing. The actual slide was, however, finally triggered by heavy rain and snow melt half a year later. The lesson learned is to do sufficient ground investigations in such settings. In this case a rather deep, weak clay layer was missed and not taken properly into account in geotechnical design.

RÉSUMÉ : Les argiles molles et sensibles constituent un défi d'envergure pour la construction infrastructures routières le long des fjords Norvégiens. L'étude de glissement historique permet d'apprendre de nos erreurs et est essentiel afin de fournir des lignes directrices pour les travaux en géotechniques. Dans la nuit du 9 au 10 mai 2015, un glissement côtier est survenu près du village Soerkjosen dans le Nord de la Norvège. Près de 1.4 million m^3 de sol s'est rapidement effondré le long du fjord sur une distance de plus de 1 km. Le glissement a détruit une partie du port de mer. Aucune personne n'a été blessée, mais suite au glissement, les trafiquants ont dû faire un détour de 700 km en Finlande. Le glissement a eu lieu dans un fjord aux pentes escarpées et près d'un delta. Il y avait de la construction en cours avant le glissement, incluant du dynamitage. Le groupe d'enquête a conclu que la stabilité de la pente était déjà à un niveau critique en Novembre 2014 quand un brise-lames a été élargi. L'élément déclencheur est relié aux fortes pluies et à la fonte des neiges 6 mois plus tard. La leçon à tirer est de faire suffisamment de sondages sur le chantier. Dans ce cas, une couche d'argile n'a malheureusement pas été prise en compte dans la conception géotechnique.

KEYWORDS: Slide, soft clay, failure, slope stability, near-shore, fjord, case record, soil investigation, geotechnical design.

1 LEARNING FROM FAILURES

Landslides along Norwegian fjords occur periodically and are a threat to coastal communities. Analysis of past landslide events gives important information on factors contributing to and initiating failure, mass propagation as well as tsunamigenic potential. The aim is to reduce the risk for new landsides.

A shoreline landslide of between 1,1 and 1.4 million m^3 took place close to the village of Soerkjosen in Northern Norway during the night of the 9th to the 10th May 2015 (see location in Fig. 1). The shoreline was destroyed over a distance of more than one kilometer. In the north a warehouse slumped into the sea whereas in the south a pier sank in the fjord, destroying a harbor. A small tsunami was triggered in the fjord. No casualties were encountered, but the landslide closed the main road, E6, connecting North and South in Norway. After the landslide the traffic had to take a 700 km detour through Finland to get across. The landslide occured in a fjord-marine deposit dominated by loose to medium dense sand and silt covering clay and silty clay on moraine and bedrock. The failure occured to the west of a large river delta. Road construction was ongoing and included blasting. After the slide an investigation group was appointed by the Norwegian Public Roads Administration (NPRA), the Norwegian Coastal Administration and the Energy Directorate of Norway in order to identify the cause(s) and the mechanisms of the landslide.

This paper summarizes the work of the investigation group and is based on available information about the construction work, eyewitness testimonies, meteorological data, interpretation of soil surveys, multiple bathymetric surveys, photos, orthophotos and slope stability evaluations in selected sections of the landslide.

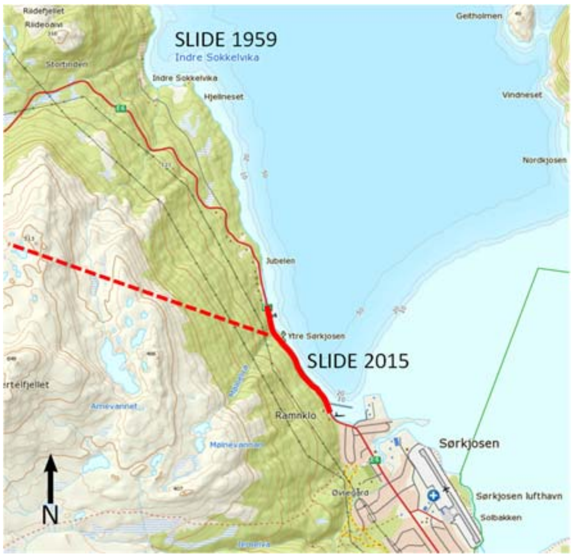

Figure 1. Soerkjosen is 75 km east of the city of Tromsoe in Norway. The 2015 slide sent the shoreline marked by a solid line into the fjord. The dotted line is a rock tunnel under construction. The site of a disastrous landslide in 1959 in Sokkelvik that killed 9 persons is marked.

2 BACKGROUND AND SEQUENCE OF EVENTS

Road construction along the fjord started in January 2014 and consisted of widening the road along the shoreline where the landslide later happened. The work was based on detailed planning including geotechnical investigations and design. Measures were taken to remove soft clay deposits where this was found in the road-line and substitute the clay with competent material. The widening was mainly made into the mountainside by blasting and the blasted rock was moved out of the area except for mass used to extending a fill into the sea in the southern part of the area. At the time of the landslide most of the construction work in the area had been completed. There had been no rock blasting for more than a month.

The Soerkjosen landslide happened between 2 and 3 am in the morning, Sunday, 10th of May 2015. Located almost at latitude 70 degrees north it was daylight and eye witnesses were soon aware of what was going on. Several photos were taken, and the time stamps on the photos show that the whole kilometer of shoreline slumped into the fjord within only a few minutes. The witnesses could not tell where along the shoreline the slide actually started. A moderate height tsunami was seen travelling across the fjord towards east.

3 BATHYMETRY

Detailed bathymetric surveys were performed in the fjord outside Soerkjosen at two occasions before the landslide (i.e. 2006 and 2011), and subsequent to the landslide in 2015. This data set provided an excellent opportunity to study the seabed morphology prior to, and after the landslide. Figure 2 presents a detailed image of the seafloor at Soerkjosen prior to the landslide in 2006. A bathymetric image of the same area after the landslide is shown in Fig. 3.

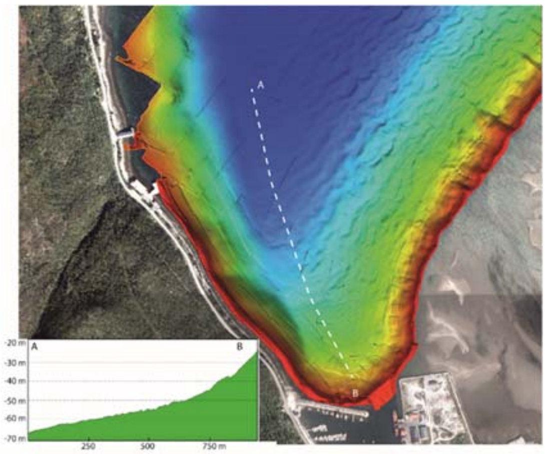

Figure 2. Bathymetry image prior to the landslide showing a smooth seafloor with no traces of previous slides. The wave pattern is related to sedimentation of sand (i.e. sand waves) and is normal in delta areas. Data courtesy of the Geological Survey of Norway (NGU).

A morphological analysis of the seafloor showed that the landslide started in south (lower end) at the harbour, where the fill placed in November 2014 slid into the fjord. This initial slide moved about 200.000 m^3 of soil dominated by loose to medium dense silts and sands. The slide rapidly transformed into a debris flow as it accelerated northwards on the seabed due to the large elevation differences (more than 50 meter). The erosive force of the debris flow is thought to have removed the toe of the slopes along the western shoreline which then became unstable and subsequently failed. While the initial slide was deep, the secondary slides (3 – 5 in Fig. 3) were rather shallow. Bathymetry data shows that the soil mass from slide 3 to 5 is flowing over the mass from the initial slide, marked 1 on Fig. 3.

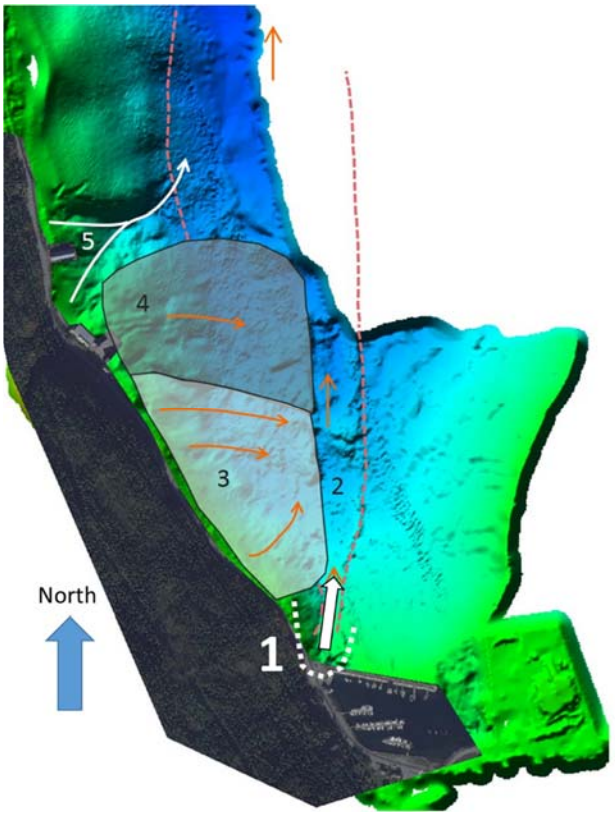

Figure 3. High resolution bathymetry with aerial photo after the slide. The interpreted sequence of event based on morphological analysis of the seafloor is shown with arrows and indicated by the numbering.

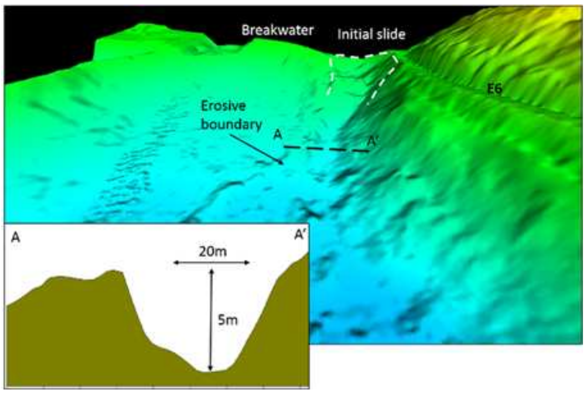

Figure 4. The initial slide left a scar and an erosion channel along the foot of the mountainside slopes when the mass accelerated downslope and changed into a disintegrated debris flow.

4 SOIL CONDITIONS

Soil investigations were carried out prior to and after the landslide both on- and off-shore. The investigations included total soundings, cone penetration tests (CPTU), piezometers, soil sampling and laboratory investigations. Results show that soil deposits are dominated by loose to medium dense sand and silt over clay and silty clay on a discontinuous layer of moraine upon bedrock. The clay was partly sensitive. The investigations conducted after the landslide were in good agreement with the former, but also revealed a layer of soft clay in the southend of the area that was missed in the original investigations. The soft clay layer is rather shallow behind the backscarp of the initial slide, but is found deeper towards the north under thick layers of silt and sand (up to 20 m). This may explain why the clay layer was missed in the original investigation. The original investigations did not go sufficiently deep in this area to encounter the clay layer. Figure 5 presents undrained shear strength interpretations in the clay based on CPTU results and laboratory investigations. The sounding on Fig. 5 was carried out in the fjord inside the evacuated landslide scar near the pier at a water depth of 7 m. Before the landslide, this location was covered by 14 m of sand and rock fill up to an elevation of +4 m.a.s.l. In the sounding on Fig. 5 the top of the clay has an undrained shear strength varying between 25 to 30 kPa and is covered by sand and debris from the landslide.

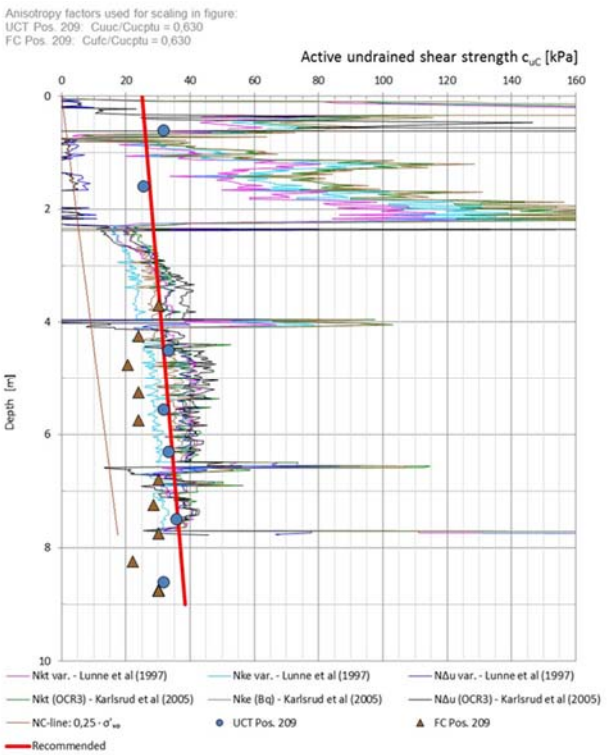

Figure 5. Undrained active shear strength results from soil investigations performed after the slide within the evacuated scar. The failure surface corresponds to the top of the clay layer now covered by sand and landslide debris.

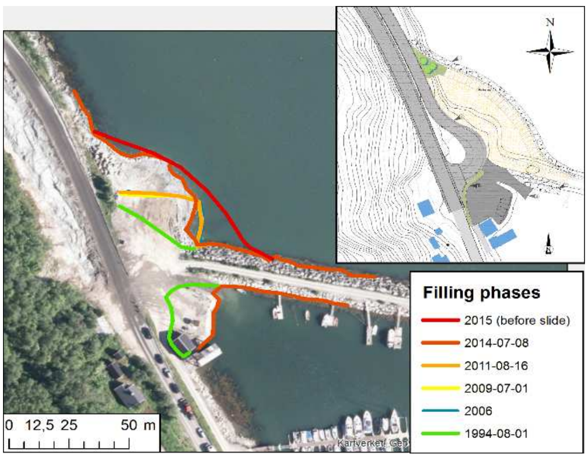

Figure 6. Map showing the widening of the breakwater and road crossing since 1994. The 2015 landslide started in this area. The area sunk and moved north into the sea. The extent of the fill has been defined from available aerial photography and satellite imagery.

5 LOADING OVER TIME

The breakwater at Soerkjosen was first constructed in 1977. Satellite imagery and aerial photography also show that there has been filling in several phases between 2006-2014 (Figs. 6-7).

6 RESULTS FROM STABILITY CALCULATIONS

New slope stability calculations were performed by the investigation group on several cross sections along the 1000 meter long slide-affected shoreline. The stability calculations confirmed most of the work done during the original design of the road work, with one exception. The newly discovered clay layer under the breakwater was shown to be critical for the stability of the slope. Calculations were performed using the limit equilibrium package GeoSuite and the finite element code PLAXIS. The two programs gave almost identical results with a safety factor slightly above 1.0 after the last phase of filling in November 2014. Adding the effect of the rain in May 2015 a safety factor of 1.0 was computed.

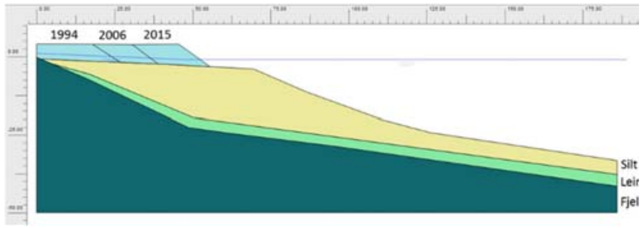

Figure 7. A cross section in NE-SW direction through the harbor pier showing soil layering and the extension of the fill since 1994. The 1994 condition was probably unchanged since 1977, when the pier was first built. The 2015 case includes water saturation and high pore pressures.

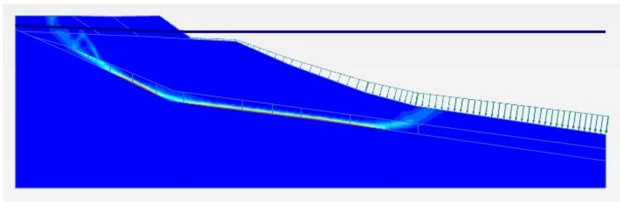

Figure 8. Adding the fill of 2014 and introducing the water and pore-water conditions of May 2015 gave this failure mechanism and a safety factor of 1.0 from PLAXIS. The failure mechanism compares well with the morphology of the landslide and changes in water depth observed from high resolution bathymetry data.

In order to simulate the conditions at the time of the slide in May 2015, the external water level was lowered by 1 meter to fit with the tidal level just before the slide. The unit weight of the fill above the sea level was increased to 19,5 kN/m^3 to simulate full saturation while the pore pressure in the silt and sand was kept at 1 meter excess pressure at depth. The pore pressure changes at depth had almost no effect since here the undrained strength of the clay controlled the problem.

7 TRIGGERING MECHANISM

The regional groundwater regime in near-shore sediments to play an important role in the predisposing of failure. Indeed, a great majority of the historical landslides along Norwegian fjords occur during the thawing season in the spring and during/following intense rainfall (L'Heureux et al. 2013).

It was raining heavily in the afternoon on the 9th of May at Soerkjosen and a significant snowmelt took place during that period of time adding to the amount of water that came down the steep mountansides and filled all ditches and culverts with water. Eye witnesses have described the amount of water as extraordinary.

It is important to note that rain alone normally does not initiate a slide unless it causes significant erosion in the toe of a slope or similar. In this case the area was reshaped and all waterways recently changed as part of the road and road crossing construction. A lot of water from rain and melting snow was taking new routes, partly in the direction of the harbour pier landing.

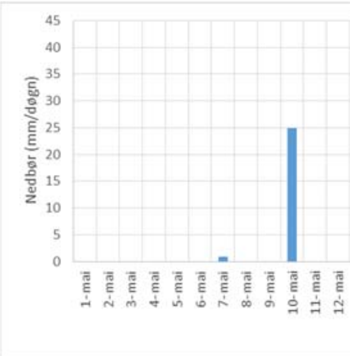

Figure 9. Precipitation in mm in the last 24 hours before 7 am on the 10th of May. Significant snowmelt must be added to understand the effect of this rain.

Previous studies have shown that near-shore landslides frequently occur during periods of low tide through a mechanism similar to that of the rapid draw-down condition in earth dams. (i.e., the pore pressure in the sub-aerial part of the deposits does not have time to reach steady state conditions for the groundwater flow; Kramer 1988). The support along the slope is minimum at low tides. In the case of Soerkjosen, a combination of low tide, high pore pressures and full saturation of the embankment material is an unfavourable condition. In extreme cases as here, where the embankment had an minimal safety margin after extending it in November 2014 the unfavourable combination is believed to have triggered the landslide. The consequences were large due to existence of sensitive clay and flow susceptible materials.

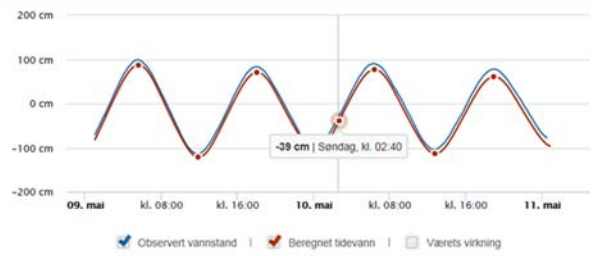

Figure 10. The graph shows the variation in sea level due to tidal variations. The tide was just 39 cm below the mean water level when the slide was observed. Around midnight the sea level was about 1 meter below mean water level.

8 THE SOKKELVIK SLIDE

In 1959 there was a disastrous slide only 3 km north of Soerkjosen in a bay called Sokkelvik (Fig 1). Here, 9 persons were killed in a slide on 7th May 1959, when several houses disappeared into the fjord. Until today, the reason for this slide were linked to low stability in the area due to the presence of sensitive clays, springs (wells) and shoreline wave erosion in addition to heavy rain and melting snow (Brænd 1961). Some minor road construction work was also reported in the area, but was considered to have less significance. From archives in NPRA a MSc student at NTNU was in 2016 able to find the original plans of the old road project. To her surprise the plans contained information on a 5 – 7 meter thick fill placed on the soft soil in one end of the bay to lift the road on to a rocky hill. Site investigations in 2016 showed remains of the fill and confirmed its height. The Sokkelvik slide has since 1959 often been referred to as a catastrophic slide with no clear cause leading to failure. The 2016 stability calculations point to the fill as a very likely cause of failure (L'Heureux et al. 2017). The similarities to Soerkjosen are striking.

9 CONCLUSION

Soft and partly sensitive clays along the fjords of northern Norway pose a challenge for infrastructure. Learning from failures is essential in providing guidelines for future geotechnical work in such areas.

Engineers think in terms of cause and effect. If a slide happens engineers look for an identifiable cause. If a slide might occur without any explanation, it leaves an unidentifiable risk and an unacceptable uncertainty to any activity in the area. Thus all slides of significance should be studied to identify their cause.

In this respect the Soerkjosen slide fall into a category where a reasonable cause is identified. A rather deep, weak clay layer was missed in the original soil investigations and not taken properly into account in geotechnical design. If the clay had been identified, it would have been taken into consideration and an alternative design made. No slide would have happened.

Our study confirms that current state of the art in geotechnical engineering is fully capable of handling the challenge related to building in such an area, but stresses the need for detailed soil investigations.

The cause of a slide and the triggering of a slide may not be the same thing. The cause of the Soerkjosen slide is identified to be the presence of a deep clay layer and the loading by filling crushed rock into the sea for a road crossing. The actual slide was, however, finally triggered by heavy rain and snow melt half a year later.

10 ACKNOWLEDGEMENTS

The investigation reported herein was initiated by the Norwegian Public Roads Administration, the Norwegian Coastal Administration and the Energy Directorate of Norway. The authors are grateful for the opportunity to work on both slides and for all support given in terms of new site investigations. Rigmor Thorsteinsen in NPRA administered the work.MSc student S.W. Austefjord has worked on the Sokkelvik slide.

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