Analysing ground temperatures and geomechanical mapping of the 2008 Signaldalen rock slide. A case study from Northern Norway

R. Frauenfelder (1), K. Isaksen (2), J. Noetzli (3), M.J. Lato (4), H.C. Smebye (1)
(1) Norwegian Geotechnical Institute, Oslo, Norway
(2) R&D Department, Norwegian Meteorological Institute, Oslo, Norway
(3) Department of Geography, University of Zurich, Zurich, Switzerland
(4) RockSense GeoSolutions Inc., Ottawa ON, Canada

ABSTRACT
In June 2008 a rock slide with an estimated volume of 500,000 m^3 detached from the NE-slope of Polvartinden, a mountain in the Signal valley, Northern Norway. Ground surface temperature measurements were initiated in 2009. Several locations along the NNW-ridge of Polvartinden and in the valley ground were instrumented with miniature temperature data loggers. In the autumns of 2010, 2011 and 2013, the slide detachment zone was imaged with a terrestrial LiDAR. The temperature measurements and the 3D subsurface temperature modelling indicate warm/marginal permafrost, and yield an estimated mean lower limit of permafrost at around 600-650 m a.s.l. This altitude coincides with the upper limit of the detachment zone. The depth to the actual failure surface was found to range from 40 m at the back to 0 m at the toe. Considering that temperature penetration to, e.g., 15-20 m depth in frozen rock typically takes one year it is likely that changing rock-/ice-temperatures due to the general warming and in response to an extreme warm year previous to the event played an important role in the detaching of the slide.

RÉSUMÉ
En juin 2008, un glissement de terrain de l'ordre de 500 000 m^3 s'est produit le long du versant NE du mont Polvartinden, situé dans la vallée de Signal, dans le Nord de la Norvège. Le relevé des températures de surface a débuté en 2009. Des enregistreurs de données miniatures ont été installés à plusieurs endroits le long de la crête NNW du Polvartinden et dans la vallée. Au cours de l'automne 2010, 2011 et 2013, le glissement de terrain a été imagé au moyen d'un LiDAR terrestre. Les mesures de température ainsi que la modélisation 3D des températures du sous-sol indiquent la présence d'un permafrost marginal, avec une limite inférieure située à environ 600-650 m d'altitude. Cette altitude coïncide avec celle de la limite supérieure du glissement de terrain. La surface de rupture a été estimée à une profondeur variant entre 40 et 0 m (respectivement à l'arrière et au pied du glissement de terrain). Etant donné que l'avancée d'un front thermique dans la roche gelée jusqu'à des profondeurs de l'ordre de 15-20 m prend généralement un an, il est probable que l'évolution des températures en réponse au réchauffement climatique et à la suite des températures particulièrement élevées de l'année précédente ont joué un rôle primordial dans le déclenchement du glissement du terrain.

1 INTRODUCTION

In the morning of June 26th, 2008 a rock slide detached from the northeast facing slope of Polvartinden at 16.18N/19.95E, a 1275 m high mountain in the Signal valley, Troms county, Northern Norway (Figure 1). The rock slide endangered two farms and several recreation cabins, and it permanently destroyed a considerable amount of livestock pastures (Figure 2).

Visible in situ ice was observed in the detachment zone just after the rock slide event (Figure 3). This observation led to the hypothesis that warming or degrading of permafrost could have played a role in the timing and the magnitude of the event. Therefore, a temporary temperature monitoring system was put in place and repeated surveying of the detachment zone and the adjacent slopes was carried out between 2009 and 2013.

Here, we report on the now available temperature series from the installed loggers, as well as on the subsequent simulation of the subsurface temperature regime and on the LiDAR based volume calculation and change detection results.

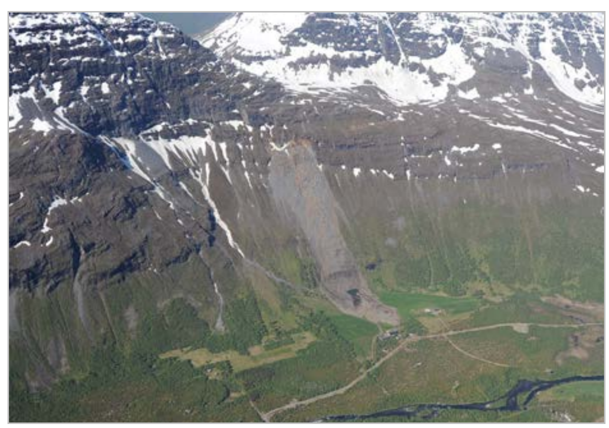

Figure 1. Signaldalen rock slide as seen from helicopter on 28.7.2009 (Photograph by courtesy of G. Kristiansen, NVE region nord).

Figure 2. Runout area of the Signaldalen rock slide (Photograph by courtesy of G. Kaiser).

Figure 3. Visible in situ ice (white and greyish spots in centre of image) observed in the rock slide detachment zone on June 26th, 2008.This photo was taken a few hours after the event (Photograph: K. Brattlien, NGI).

2 METHODS

Ground surface temperatures were measured with miniature temperature data loggers of the type M-Log5W (GeoPrecision GmbH, Germany), redesigned UTL-1 (University of Bern and University of Zurich, Switzerland) and UTL-3 (GEOTEST and WSL Institute for Snow and Avalanche Research SLF, Switzerland). The loggers were installed to measure temperatures at 10 cm depth at several locations along the NNW-ridge of Polvartinden and in the valley ground. Measurements were ongoing from September 2009 to August 2013.

Nine temperature loggers (type M-Log5W and redesigned UTL-1) were installed in vertical rock faces on rock outcrops and along small cliffs with different aspects (Figure 4), while five loggers (UTL-1, UTL-3) were placed directly into the soil material (Figure 5). One additional logger was installed in the valley floor in order to monitor air temperature (Figure 5).

The past and present temperature field pattern in the subsurface of the detachment zone was further studied by combining these data with climatological data and with a basic three-dimensional transient heat conduction model (Noetzli and Gruber, 2009).

In the autumns of 2010, 2011 and 2013, the slide detachment zone was imaged with an Optech 3D Ilris terrestrial LiDAR (Optech Incorporated, Canada). In addition, the detachment zone and its surroundings were imaged with a Giga-Pan in autumn 2013.

Figure 4. Logger installation in rock outcrop.

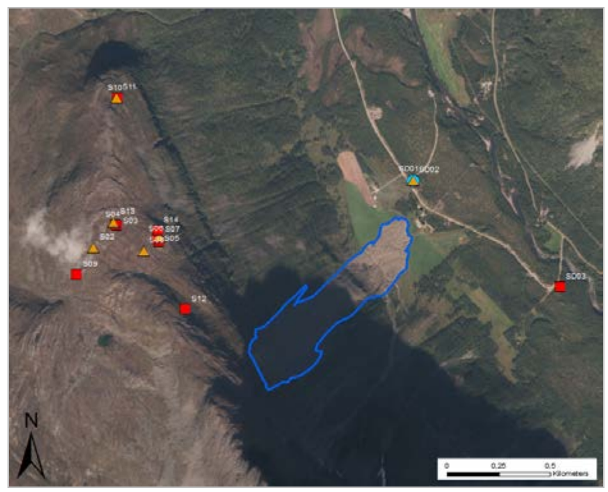

Figure 5. Temperature measurement locations in vertical rock faces (red squares), within soil material (yellow triangles) and within a stone cairn (one blue circle in the valley bottom). Slide outline in blue. Background: Aerial photograph (© by Norwegian Mapping Authority/Statens kartverk).

2 RESULTS

2.1 Ground temperatures

Temperatures measured during 2009–2011 show mean annual ground surface temperatures (MAGST) between -1.4°C (coldest) and +1.7°C (warmest) in 2009/2010, and between -0.3°C (coldest) and +2.5°C (warmest) in 2010/2011. Temperature recordings in all loggers were considerably higher during 2010/2011 than in

2009/2010. For the vertical rock face sites, the lowest MAGST was recorded at the north facing site in 2009/2010 (Figure 6).

The large inter-annual variability found between 2009/2010 and 2010/2011 is in congruence with general climate conditions in Troms and is confirmed by measurements in nearby mountain slopes (Isaksen et al. 2011a). For the monitoring periods 2009/2010 and 2010/2011, mean annual air temperatures (MAAT) at the nearby Skibotn meteorological station (10 km to the NNW from Signaldalen) were 0.6°C below and 0.2°C above the MAAT for the reference period of 1961–1990.

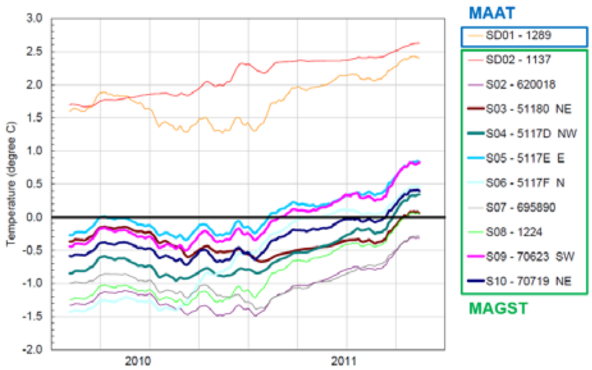

Figure 6: MAGST (respectively MAAT for SD01) for 2009–2011 calculated by a 365-day moving average filter showing, among others, the high correlation of rock (near) surface temperature with air temperature.

During 2010/2011 some of the sites were clearly influenced by a snow cover. Based on an analysis of wind direction, wind speed and total snow accumulation at nearby weather stations (among others Skibotn), we assume this difference in snow cover between 2009/2010 and 2010/2011 to be caused by inter-annual differences in prevailing wind direction and preferential snow deposition.

The correlation between the air temperature measurements (2009–2011) in the valley bottom and data covering the same period from Skibotn met.station is very high (R^2 = 0.97). This will allow for using the Skibotn data for modelling of the potential permafrost distribution and recent ground temperature changes in Signaldalen by coupling our in-situ surface temperature data with regional and large-scale climate data.

The MAGST between 2009–2011 (Figure 6) indicate warm/marginal permafrost at several of the sites, and yield an estimated mean lower limit of permafrost at around 600-650 m a.s.l., an altitude which coincides with the upper limit of the detachment zone.

Regional climate data since 1948 and nearby borehole data suggest a general warming and that the highest mean near surface temperatures on record occurred the year before the Signaldalen rock slide detached.

A 3D transient heat conduction model was set up with idealized and homogeneous surface and sub-surface conditions and an upper boundary condition based on an extrapolation of MAGST based on aspect, elevation and deviation to the long term MAAT (Figure 7). Since two loggers with southern orientations stopped working during the observation period, these aspects are missing in the base data. The resulting curve shown in Figure 7 is, therefore, just a first estimate.

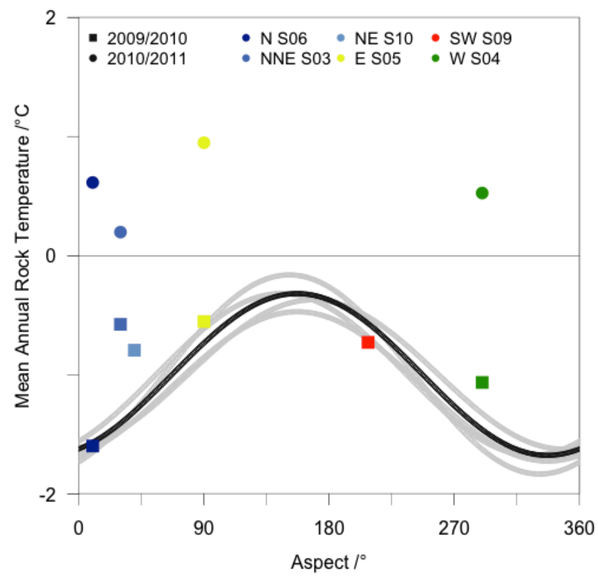

Figure 7. Aspect dependency as derived from the logger data.

Results of the 3D transient heat conduction modelling show an aspect dependency with a slightly lower permafrost limit in northern exposition as opposed to slopes exposed to the South (Figure 8).

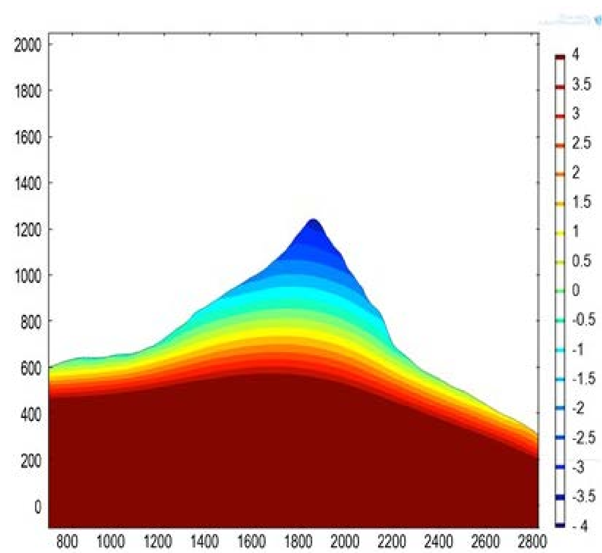

Figure 8. 3D transient heat modelling of the subsurface temperature field. Figure shows a slice from South (left) to North (right).

2.2 Geomechanical mapping

Based on the LiDAR results, the volume of the rock slide can be estimated to be approximately 500,000 m^3. These results confirm earlier estimates by NGI (2008), suggested during the emergency response work initiated directly after the event.

The depth to the actual failure surface was found to range from 40 m at the back to 0 m at the toe, with the source zone being a complex wedge with increasing depth of the plane of failure from the front to the back (Figure 8).

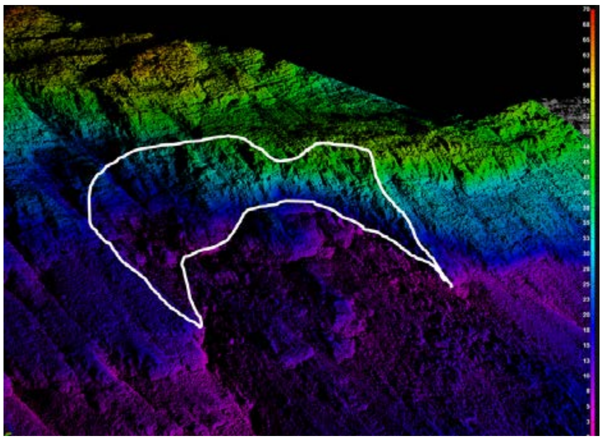

Figure 8. The source zone, outlined in white, is a complex wedge much deeper to the plane of failure at the back than at the front.

Understating the principle mechanism behind the failure involves a kinematic evaluation of the failure scarp. Figure 9 illustrates an equal area stereonet. Plotted on the stereonet are the poles to the bedding surface.

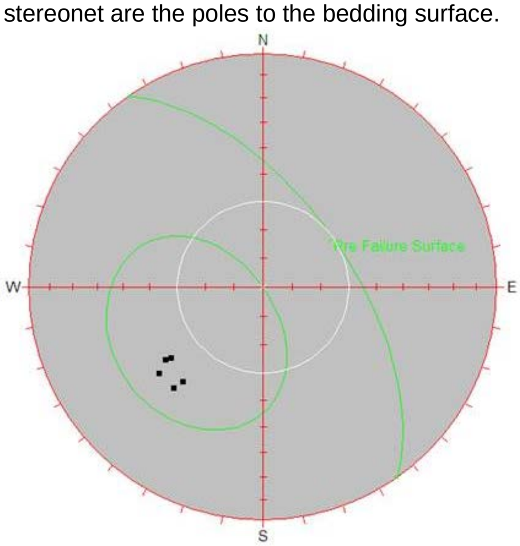

Figure 9. Kinematic analysis of bedding planes for sliding failure. The white circle represents an estimated friction cone of 30º and the green cone represents the sliding daylight window for the associated pre failure surface.

The bedding planes have been identified as the failure surface from the LiDAR data and photographic interpretation. The extraction of the orientation of the bedding surface and the orientation of the natural slope ("Pre Failure Surface") are determined directly through measurements using the LiDAR data.

The green line in Figure 9 represents the orientation of the natural slope surface, and the green circle represents the corresponding daylight window. The white cone depicts an estimated friction surface of 30º's. Poles that are contained outside of the white circle but within the green circle are kinematically unstable and represent potential sliding failure planes. This stereonet demonstrates that the bedding surface orientation is steeper than the estimated friction angle but shallow enough to daylight with respect to the slope face. Thus meeting the kinematic requirements of sliding failure and posing a potential rockfall hazard (see e.g., Hasler et al., 2012).

Gigapixel photography technique enables a detailed visualization of the rockmass as illustrated in the inset photo of Figure 10. This image displays the basal sliding surface of the 2008 failure. The surficial change of the exposed rockmass between 2011 and 2013 is mapped through the comparison of LiDAR data collected at different points in time. The lower right image of Figure 10 is a change detection map. The blue and green colours identify rock blocks that have been released from the rockmass between scans, the black sections of the image represent occluded zones that were not imaged due to a narrow angle between the scanner and the surface normal. The size of blocks released between 2011 and 2013 range from 1 m^3 to 10 m^3. In summary, the repeated LiDAR measurements between 2009, 2011 and 2013 show little to no activity in the 2008 detachment zone, as well as in the adjacent rock slopes.

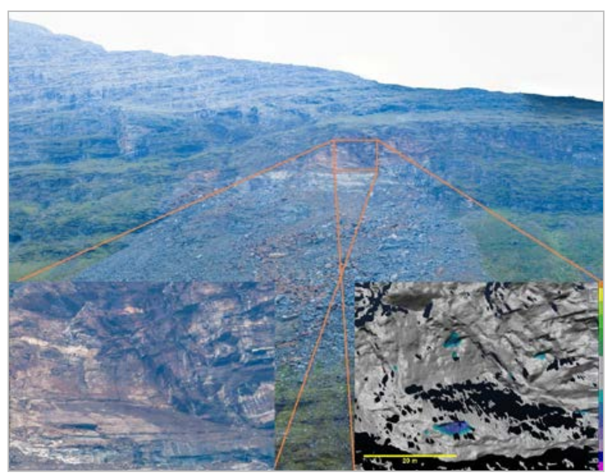

Figure 10. Lower left: basal sliding surface of the 2008 failure as depicted by Gigapixel photography. Lower right: surficial change of exposed rockmass between 2011 and 2013 as derived from multi-temporal LiDAR data. Blue and green colours = rock blocks released from the rockmass between 2011 and 2013, black sections = occluded zones that could not be imaged.

3 DISCUSSION

Based on our findings we expect a regional lower limit of permafrost at around 600-650 m a.s.l.; this is in agreement with earlier estimates in the inner fjord- and valley areas of Troms (Isaksen et al. 2011a).

In Scandinavia, the amount of direct observations about the influence of solar radiation on near surface temperatures in different aspects of steep mountain walls is limited so far. Generally, the influence of direct solar radiation is less pronounced at high latitudes than in mid-latitude mountain ranges, which can be observed in our modelling results of the subsurface temperature field.

Our results indicate an altitudinal difference of several tens of meters between northerly and southerly aspect, as compared to several hundred meters in, e.g., the Swiss Alps (cf. Gruber et al., 2004). Due to our small sample size these results should be seen as tentative estimates. Yet, Hipp et al. (2014) recently reported comparably small aspect dependencies of the lower permafrost limit for a location in Southern Norway, thus supporting our findings.

According to a study by Fischer et al. (2012) on potential triggering factors at 56 historical rock slide and rock fall events in the Alps, it seems to be the marginal permafrost zone where most of the recent changes concerning ice content and hydrology have taken place; parameters that are seen as having an important influence on slope stability.

In southern Norway, permafrost degradation has been observed on gentle mountain slopes (Isaksen et al. 2011b). The same study also showed that the greatest temperature increases at 5-10 m depth were found at sites with present mean annual ground temperatures (MAGT) slightly above 0°C. This may be caused by a gradual vanishing of ice due to recent permafrost degradation, leading to a drier near-surface layer and, thus, changes in the near-surface heat exchange. In addition, heat advection during the opening up of talik/water systems could have been an additional factor.

Considering that temperature penetration to, e.g., 15-20 m depth in frozen rock typically takes one year it is likely that changing rock-/ice-temperatures due to the general warming and in response to the extreme warm previous year played an important role in the detaching of the Signaldalen slide.

4 CONCLUSIONS

Analyses based on data from available four-year ground surface temperature series and a 3D-transient heat model suggest warm/marginal permafrost at several of the sites, and yield an estimated mean lower limit of permafrost at around 600-650 m a.s.l., an altitude which coincides with the upper limit of the detachment zone. Regional climate data since 1948 and nearby borehole data suggest a general warming and that the highest mean near surface temperatures on record occurred the year before the Signaldalen rock slide detached. A LiDAR based volume calculation show that the depth to the actual failure surface was found to range from 40 m at the back to 0 m at the toe. The repeated LiDAR measurements between 2009 and 2013 show little to no activity in both the 2008 detachment zone and the adjacent rock slopes. Considering that temperature penetration to, e.g., 15-20 m depth in frozen rock typically takes one year it is likely that changing rock-/ice-temperatures due to the general warming and in response to the extreme warm previous year played an important role in the detaching of the slide in Signaldalen.

REFERENCES

Fischer, L., Purves, R.S., Huggel, C., Noetzli, J. and Haeberli, W. 2012. On the influence of topographic, geological and cryospheric factors on rock avalanches and rockfalls in high-mountain areas. *Natural Hazards and Earth System Sciences* 12: 241–254.

Gruber, S., Hoelzle, M. and Haeberli, W. 2004. Rock wall temperatures in the Alps – modelling their topographic distribution and regional differences, *Permafrost and Periglacial Processes* 15(3): 299–307.

Hasler, A., Gruber, S., Beutel, J. 2012. Kinematics of steep bedrock permafrost. *Journal of Geophysical Research* 117: F01016, DOI:10.1029/2011JF001981.

Hipp, T., Etzelmüller, B., Westermann, S. 2014. Permafrost in Alpine Rock Faces from Jotunheimen and Hurrungane, Southern Norway. *Permafrost and Periglacial Processes*. DOI: 10.1002/ppp.1799.

Isaksen, K., Blikra, L.H. and Eiken, T. 2011a. The existence of warm permafrost in unstable rock slopes in western and northern Norway. *Geophysical Research Abstracts* 13, EGU2011-10942, EGU General Assembly.

Isaksen, K., Ødegård, R.S., Etzelmüller, B., Hilbich, C., Hauck, C., Farbrot, H., Eiken, T., Hygen, H.O. and Hipp, T.F. 2011b. Degrading mountain permafrost in southern Norway: Spatial and temporal variability of mean ground temperatures, 1999-2009. *Permafrost and Periglacial Processes*. DOI: 10.1002/ppp.728.

Noetzli, J., and Gruber, S. 2009. Transient thermal effects in Alpine permafrost. *The Cryosphere* 3: 85-99.

Acknowledgements

This study was funded by the Norwegian Research Council (through their funding of NGI's Strategic Institute Program no. 12, and Strategic Project no. 3). We would like to thank L. Skogli (Signaldalen) who let us install loggers on his property and helped with the logistics during the LiDAR measurements, as well as Steinar Engsted (Storfjord municipality), Håkon Pedersen and Andrea Taurisano (both from NVE region nord) for their interest in our work. We would also like to acknowledge Scott McDougall for his careful review.