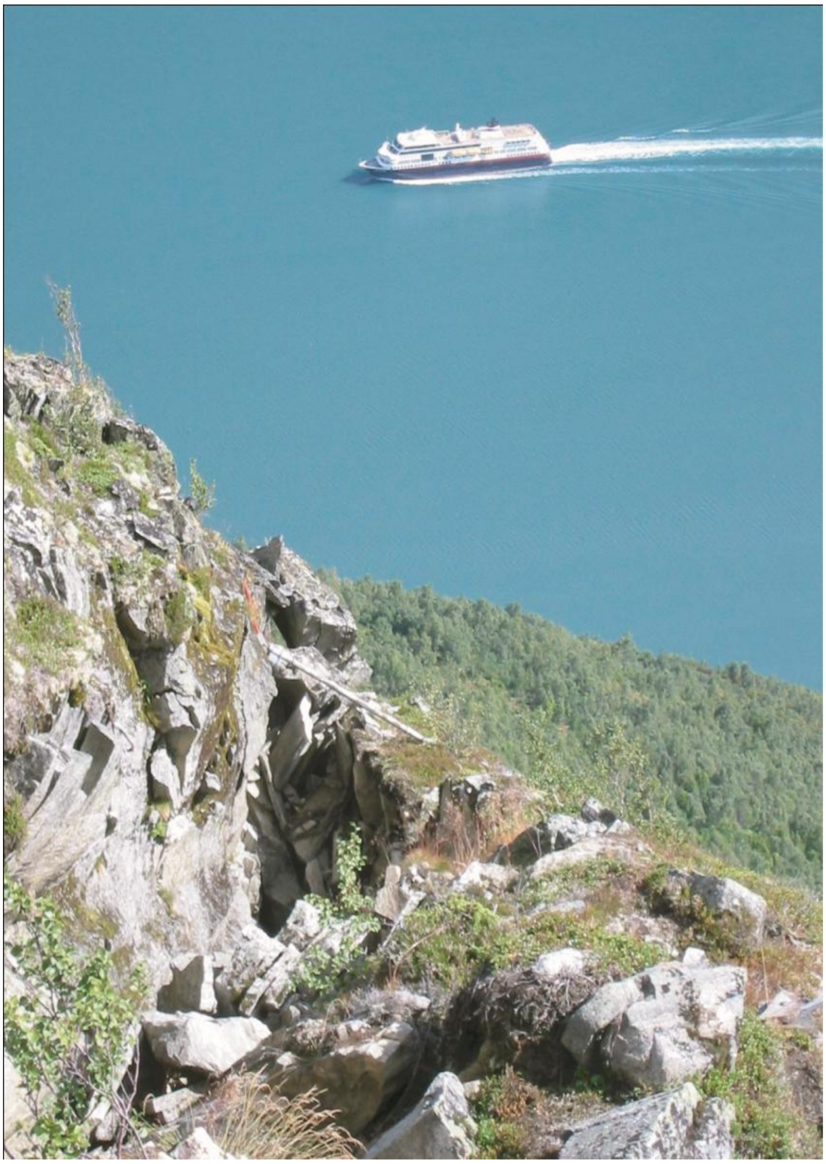
Åknes report 02 2010

Åknes: State of instrumentation and data analysis



Summary

Report number	Åknes 02.2010
Title	Åknes: State of instrumentation and data analysis
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Report date	08.12 2010
Pages	43

Summary:

Documentation, analysis and interpretation of data are an important part of the quality routines for Åknes/Tafjord Early Warning Centre. Numerous instruments measure the movement in the Åknes rockslide. In addition to the continuous monitoring measurements presented here, the mountain side is monitored during summertime with a ground-based radar and periodic laser scanning. The extensive multi-sensor instrumentation at Åknes has been established on the basis of need of redundancy, the large consequences of failure and the regulations in Norwegian building codes. Especially important is the need of having enough knowledge to provide a safe early warning to the public. Raising a false alarm may also decrease the Åknes Centre's credibility and should be avoided if possible.

This report presents data from various instruments that monitor movement of the Åknes rockslide. The instruments are diverse and do in many cases not cover the same time intervals. Some instruments provide data in 3D coordinates (DGPS and total station) while other measure a distance (lasers, radar, crack- and extensometers). Other instruments measure derived properties of movement such as seismic activity and tilt of vertical cliffs or boreholes.

The new data from the deep monitoring at upper borehole may indicate that movements can occur deeper than earlier expected (below 130 m deep). The need for deeper instrumentation needs to be evaluated. Threshold values for SMS messages have been proposed here, but we still need more focus on evaluating the levels of movement that trigger SMS messages for individual sensors, in addition to threshold values for alarm levels.

Content

Introduction

Documentation, analysis and interpretation of data are an important part of the quality routines for operative early-warning systems.

This report presents data mainly from 2007 and to the end of 2009, but the data series are not exactly overlapping in time. It includes various instruments at Åknes that monitor movement of the rockslide. The instruments are diverse and while some instruments provide data in 3D coordinates (DGPS and total station), other measure a distance in 1D (lasers, radar, crack- and extensometers). The distance should ideally be measured parallel to the direction of movement, but this may not always be the case. Other instruments measure derived properties of movement such as seismic activity and tilt of vertical cliffs or boreholes. For these reason it may be difficult directly to compare the measurements of the different instruments.

Data-series from each instrument is presented, followed by a brief assessment of the expected performance in the case of increased or accelerated velocity of the landslide. This analysis is essential in order to have proper warnings when an acceleration of movements occurs. In addition to the daily inspection of all data, warning will be sent by automatic SMS messages to the person on duty. In order not to receive excessive amounts of false warnings, the alarms are placed on the most reliable instruments with low noise level and few error readings. The person on duty is checking data from all instruments daily to observe the landslide activity.

This report is an important base for the established advisory group for the Åknes/Tafjord Early Warning Centre.

Background

The Åknes rockslide is located at the western side of Sunnylvsfjorden in Storfjorden, Stranda municipality (Figure 1).

FIGURE 1: THE LOCATION OF ÅKNES IN THE INNER PART OF STORFJORDEN

The upper boundary of the landslide is characterized by a zone of tension cracks at 900 m asl and a lower compressional toe at about 100 m asl (Blikra, 2008; Ganerød *et al.*, 2008). The average slope is 30-35°. Today no one is living below the landslide, but the landslide is located directly above the fjord. The danger today is due to a major tsunami, which will generate when the rock avalanche fall into the fjord, with devastating effects to the towns and villages along the fjord margins. This has happened on several occasions in Storfjorden and similar Norwegian fjords in historic and prehistoric time (Blikra *et al.*, 2006).

Geology

The Åknes rockslide is situated within the Western Gneiss Region, dominated by gneiss of Proterozoic age (Braathen *et al.*, 2004). The gneisses at Åknes varies, but the dominating types are a medium grained granitic gneiss and a dark gray biotite bearing granodiorite gneiss (Ganerød *et al.*, 2008).

Morphology

The morphological investigations show several characteristic features (Figure 2):

- An about 500m more or less continuous back crack (Upper tension fracture).
- A large depression in the upper western corner of the rockslide, developed as a graben structure. The total vertical displacement is from 20-30 m.
- A series of tension fractures from the upper to the middle part of the slope.
- Prominent slide scars along the southwestern canyon. Historical data indicates a slide in the upper part in the late 1800, and slides also in 1940 and 1960.
- Small slide scars in the lower part of the rockslide.
- Large blocks or parts of the rocks is “coming out” of the slope at two particular areas, one in the middle part and one area in the lowermost part.
- Distinct water springs at the lowermost part of the slope at about 100 masl. However, there are also smaller springs in the middle part of the slide area.

Geological model and shear zone of the landslide

Numerous geological, geophysical and geotechnical studies were made on the Åknes rockslide to better understand its mechanism and to locate sliding surfaces, e.g. Rønning *et. al* (2006), Blikra (2008) and Ganerød *et. al* (2008). The geology of the rockslide is not totally understood, but the instability is clearly controlled by the structural pattern of the gneissic rocks, with the step back fracture following a sharp fold, and the sliding zones being parallel to the foliation planes further down slope. In a geological model of the rockslide (Figure 3), Ganerød *et. al* (2008) proposed to divide the rockslide into several subdomains. In general, the upper part of the rockslide is characterized by tension, while several parts in the lower area show compression features (Figure 3 and Figure 4). However the geometry and subsurface deformation is more complex than this general pattern (e.g. Jaboyedoff *et. al* (2011)). The rockslide is composed of several individual blocks with different surface movement directions, and also differential movement at different depths.

Borehole measurements show distinct sliding surfaces at 34-50 m depth, in addition to several areas of movement down to below 120 m depth. Failure planes at depth down to 120 m depth will give potential rockslide with volumes up to 55 mill m^3. Modelling by Kveldsvik *et. al* (2008) showed that failure at a deep level may be more realistic than a more shallow failure provided the given levels of shear strengths of the rock. A correct interpretation of a potential sliding plane is important, because it determines the rock avalanche volume. A Norwegian summary of different scenarios and their modelled tsunamis can be seen in Blikra *et. al* (2010).

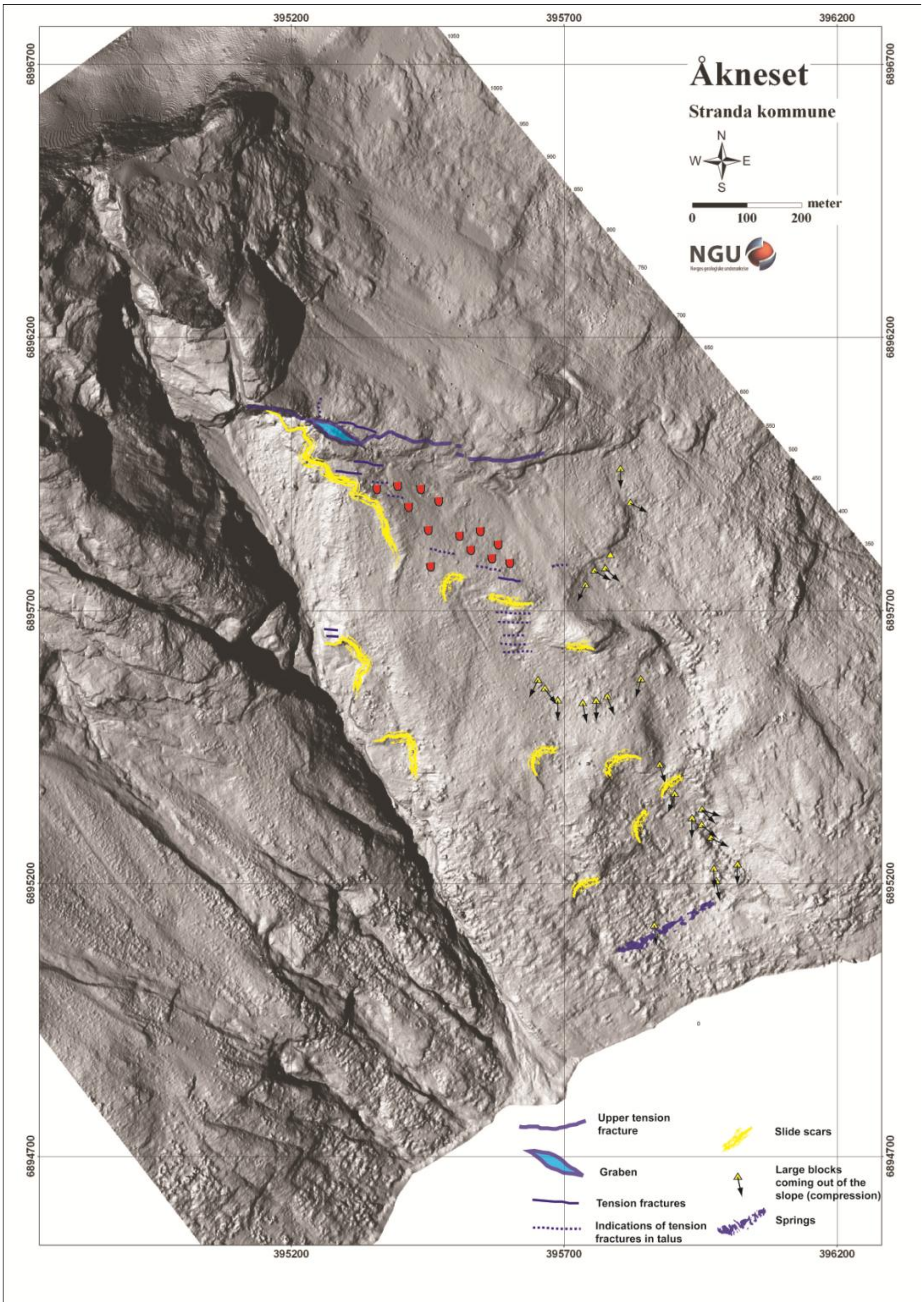


FIGURE 2: MORPHOLOGICAL FEATURES OF THE ÅKNES ROCKSLIDE (BLIKRA, 2008).

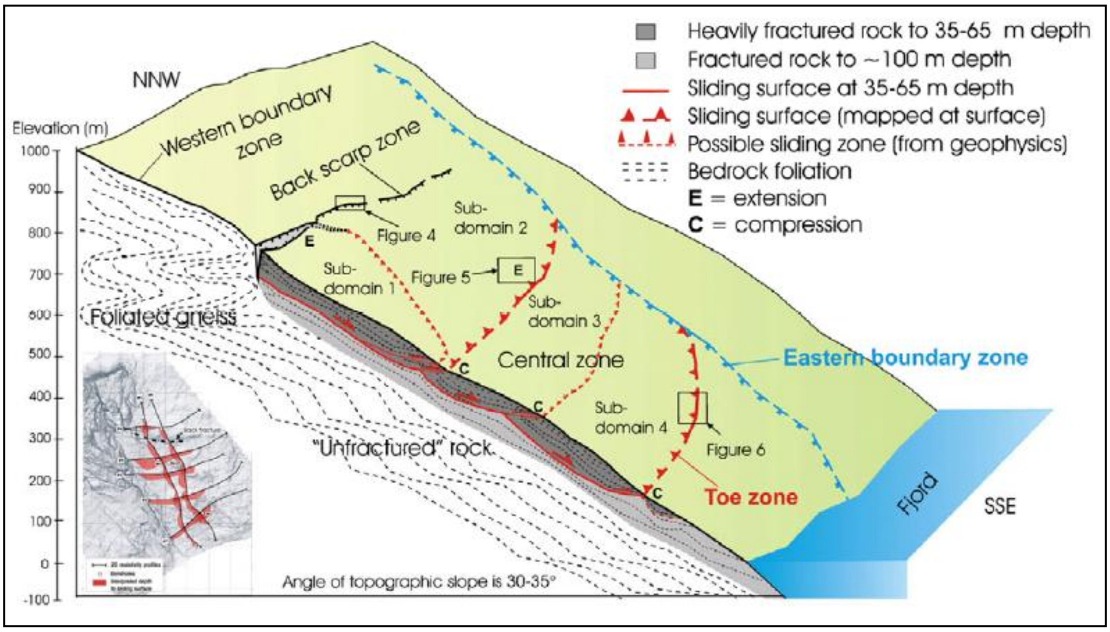


FIGURE 3: ONE OF THE PROPOSED GEOLOGICAL MODELS OF THE ÅKNES ROCKSLIDE WITH DIVISION OF THE ROCKSLIDE INTO SUBDOMAINS (FROM GANERØD *ET. AL* (2008)

Figure 4 show the most probable geological cross profile based on the geophysical data, borehole cores and displacement data.

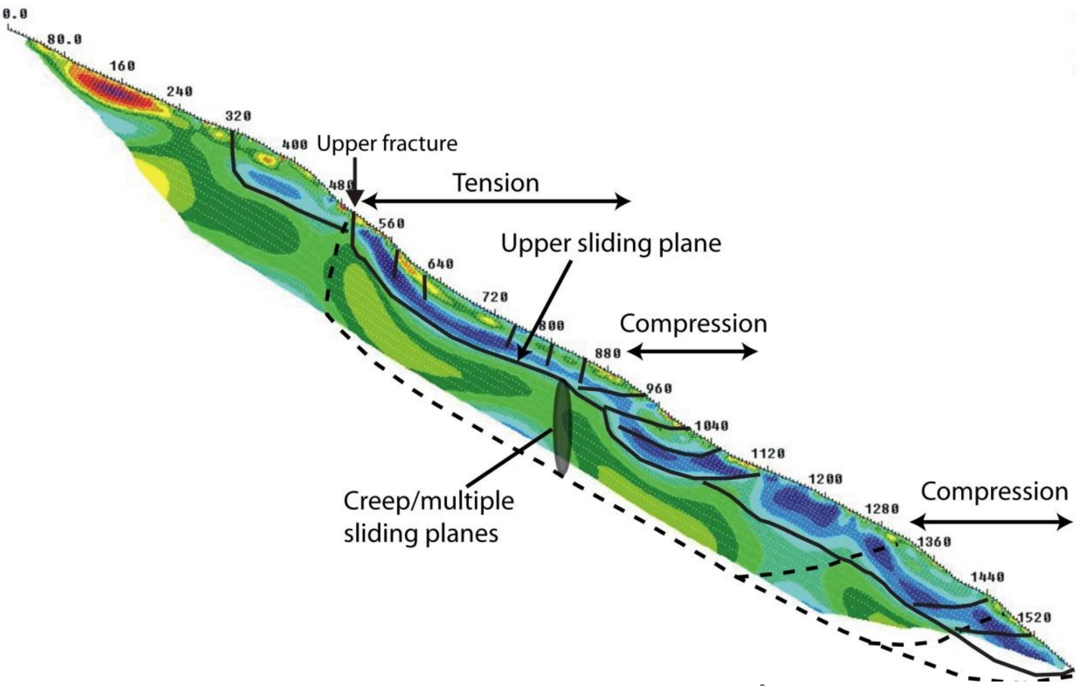


FIGURE 4: A PROPOSED GENERAL GEOLOGICAL MODEL FOR 2D LENGTH PROFILE AT ÅKNES. THE COLOURS SHOW THE 2D RESISTIVITY DATA, WITH BLUE CODES REFLECTING LOW RESISTIVITY.

Measurements of displacement

The instrument data which is presented in this report is from: Differential GPS, robotic total station, laser, extensometer, meteorological station, surface tiltmeter, crackmeter, LISALab GB INSAR radar, DMS boreholes and geophones. The location of the several instruments on the landslide can be seen in Figure 5; the location of the total station prisms is shown in Figure 8 and some other sensors in Figure 12.

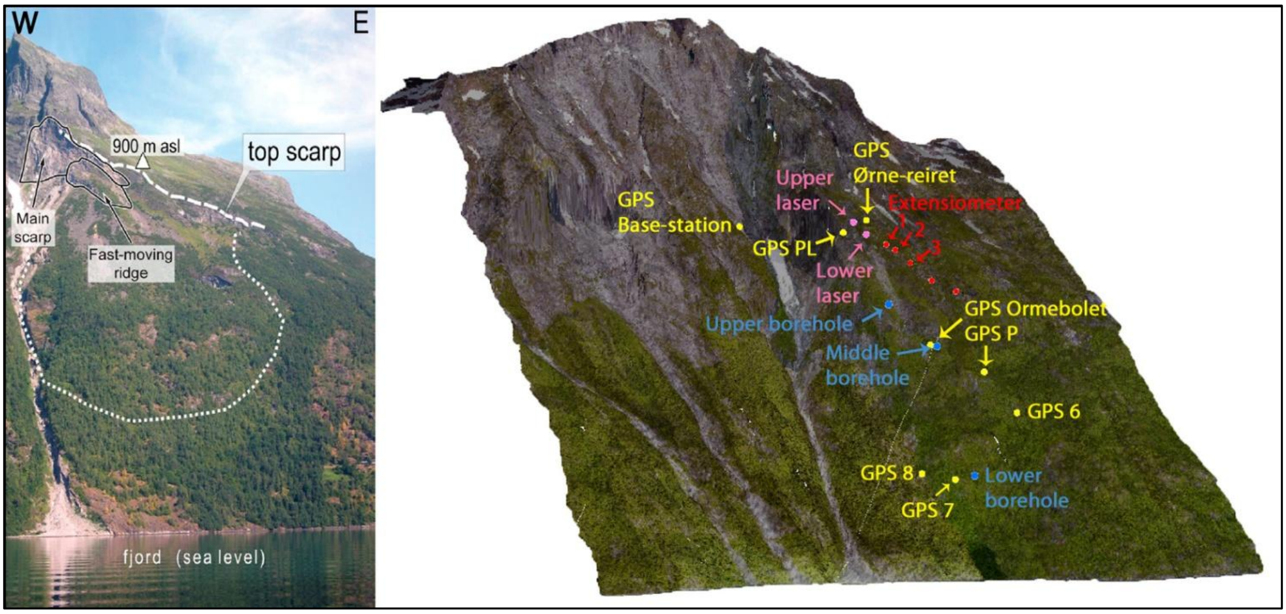


FIGURE 5 LEFT: GEOMETRY OF THE LANDSLIDE. FROM OPPIKOFER 2010. RIGHT: LOCATION OF THE INSTRUMENTS PRESENTED IN THIS REPORT. THE LOCATIONS OF THE PRISMS ARE SHOWN IN FIGURE 8, WHILE OTHER INSTRUMENTS ARE SHOWN IN FIGURE 12.

Differential GPS measurements

Displacement on Åknes is measured continuously by seven GPS antennas (positions: Figure 5). The data is collected and processed automatically in the field using a stable antenna at Fjellvåken west of the landslide as base station. The quality of the processing is checked every month by Cautus Geo AS. Two types of GPS data are processed: EHP where 12 hours data are averaged and protrack where 5 minutes data are averaged. The errors are greater for the protrack than for the EHP data and the protrack datafiles are huge, so for longer time-series only EHP data are shown. Protrack data are briefly presented, in order to investigate the uncertainty of the measurements. The protrack data is important during periods of accelerated movement, when 12 hours delay of data is unacceptable.

The GPS-data exist from 27 March 2007. The GPS antenna on Ørnereiret was moved >2 m on 23 November 2007 and therefore only data after that date is presented. The six other antennas all show a 5-8 cm vertical drop around 18-19 September 2007 because of a change in settings for atmospheric correction. For this reason only data from 19 September 2007 and onwards are presented. The data presented here ends on 17 December 2009.

Presentation of DGPS EHP-data

The easiest way to compare the movements from the different antennas is to plot the displacements in x, y and z dimensions. Least square straight lines were used to find the start and end point of each data series. The relative displacement of the antennas in three dimensions can be seen in Figure 6, while the displacement of the GPS antennas together with some other instruments is shown on a map Figure 38. In Figure 6, the initial position (found from the regression line) was subtracted from all positions in order to plot the data on the same graph. A straight line through the data fits fairly well, showing that expected seasonal fluctuations are low compared to the resolution of the data.

Table 1 and Figure 6 provide an overview of the GPS data. It shows that three of the antennas (Ørnereiret, GPS 7 and GPS 8) are almost stable in position. The movements recorded here appear to be within the uncertainty of the method (though it is not statistically proven) and therefore not considered further. A thorough statistical analysis of the GPS data for Åknes (though for a shorter time span) was published by Nordvik & Nyrnes (2009). The four other antennas move down slope with different velocities ranging from 62 mm/yr to 14 mm/yr. They all move south and three move to the east, while the fastest (GPS_PL) move westward.

GPS name	E (mm)	N (mm)	Z (mm)	Direction (°)	Dip (°)	Total displace-ment (mm)	Velocity (mm/yr)	Comment
Ørnereiret	-1.7	+0.9	-1.6	298	40	2.50	1.21	Almost stable
Ormebolet	+22	-39	-24	151	28	50.80	22.64	Some movement
GPS_PL	-21	-64	-121	198	61	138.48	61.64	Fastest
GPS_P	+17	-20	-18	140	34	31.83	14.17	Some movement
GPS 6	+37	-48	-14	142	13	62.20	27.69	Second fastest
GPS 7	+1.4	-1	+2.5	126	-55	3.03	1.35	Almost stable
GPS 8	-0.7	-2.2	+1.5	198	-33	2.75	1.23	Almost stable

TABLE 1 SUMMERY OF THE DISPLACEMENT OF THE SEVEN ANTENNAS FROM 19 SEPTEMBER 2007 TO 17 DECEMBER 2009. IN E COLUMN (+) MOVEMENT IS TOWARDS EAST AND (-) WEST; IN N COLUMN (+) MOVEMENT IS TOWARDS NORTH AND (-)SOUTH. IN THE Z-COLUMN (+) IS UPWARDS AND (-) IS DOWNWARDS, in the dip-column (+) is downwards and (-) is upwards.

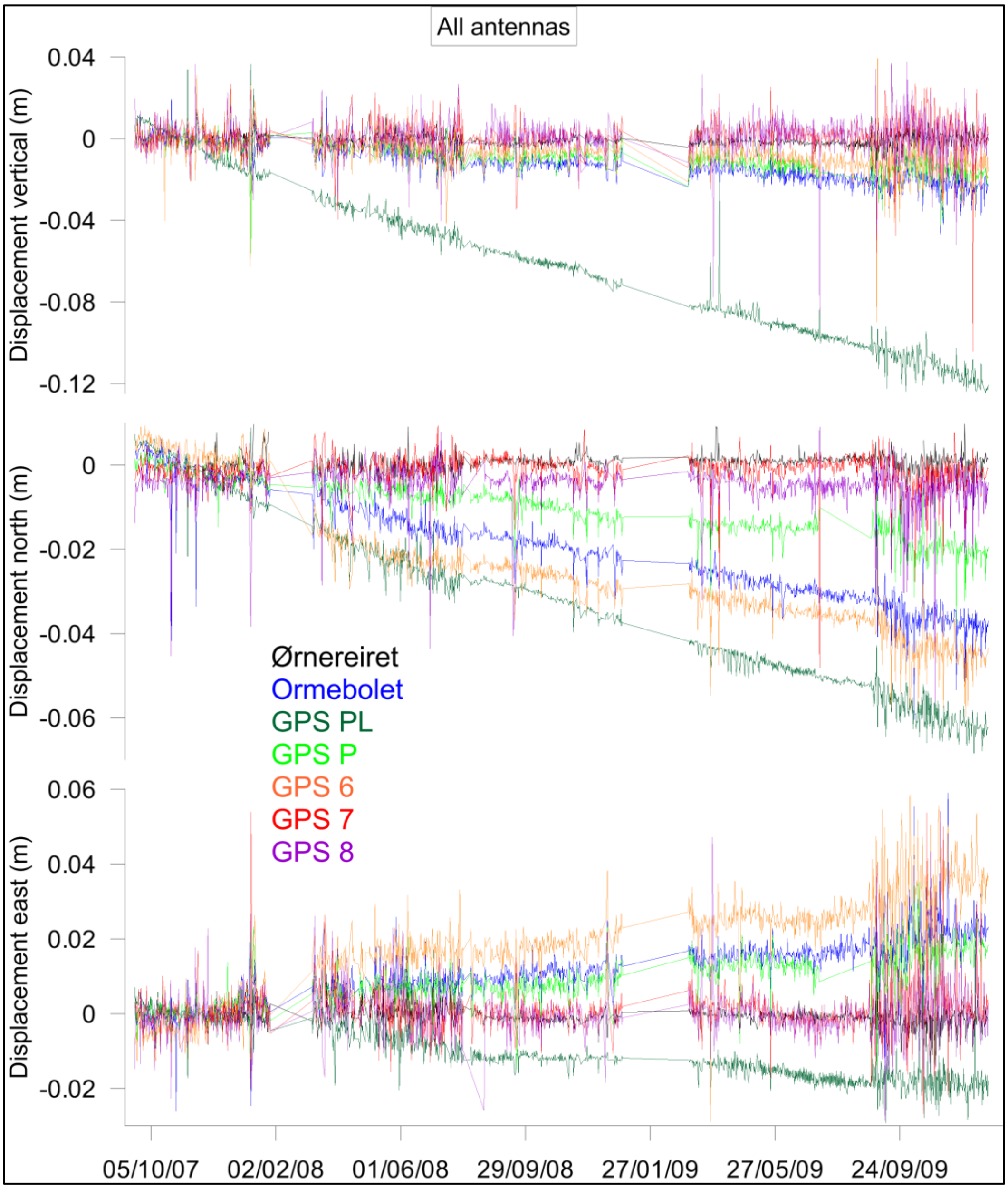


FIGURE 6: RELATIVE DISPLACEMENT OF THE SEVEN GPS ANTENNAS.

GPS Protrack

In Figure 7, the protrack data (5 min averages) of GPS_PL (the fastest antenna) is plotted from 26 March 2007 to 18 December 2009. Two events that relates to the data processing are evident in the plot and are marked with arrows on the graph. The first event is a step in X,Y,Z position occurring on 18-19 September 2007, which is due to a change of settings of parameters for atmospheric correction. More interestingly, a large change occurs after 06 August 2008. Before this date frequent fluctuations of >10 cm and even greater on the Z-axis are seen. After this date the fluctuations were greatly reduced; this change was also caused by a change in processing.

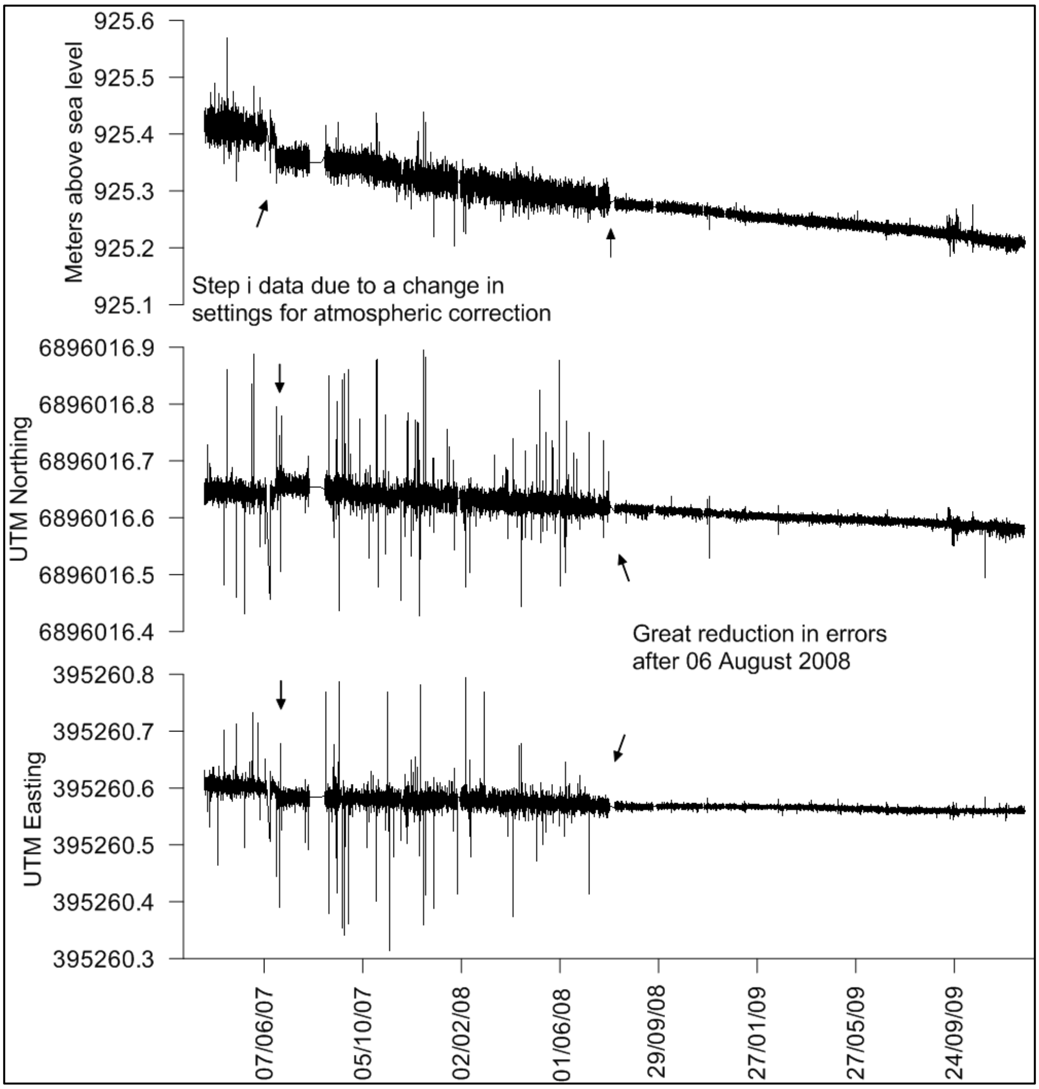


FIGURE 7: PROTRACK POSITIONS IN X,Y AND Z FOR GPS PL.

Using DGPS EHP and protrack for automatic messages

In a normal situation, the EHP 12-hour averages data are well suited to analyze slow displacements, since the errors and amount of data are smaller than for the 5 min protrack data. However, in the case of increased activity, it is important to monitor the movement more closely, and in this case it is a disadvantage to wait 12 hours for each averaging procedure. Here it will be useful to study the movement using the protrack data.

The protrack plot in Figure 7 shows that the errors were greatly reduced after 06 August 2008. It appears that we would today be able to set an automatic alarm of perhaps 10-15 cm of movement in relation to a fixed point (which should be modified on a monthly interval) and receive quite few false alarms. During acceleration of the landslide, we have confidence that the GPS' in general are amongst the most reliable source of data on the movement. The data transmits wireless, but they have their power supply from cables, which can break. An independent power supply (battery pack) for the most important GPS antennas has been planned so they can transmit data for some time even if the power system fails.

Robotic total station

An automatic robotic total station was installed together with c. 25 prisms in 2007. Due to various technical problems, the instrument has never worked properly until 12 December 2009. From this day we have hourly measurements for 22 prisms, but some gaps are evident in the time series, see Figure 8 for location. Seven prisms do not cover the entire period (Table 2) and Prism 2 was excluded, as a new zero point was defined in the middle of the time series. The X, Y and Z positions of the prisms were plotted as a function of time. A least squares straight line were fitted to all plots and the starting and ending point of the lines was used to estimate the displacement in 3D, see Table 2 below.

Prism name	North	East	Down	Direction (°)	Dip (°)	Nr of days	Total velocity mm/yr
Berg 1	-11	3	9	165	38	97	54.7
Berg 2	-9	-4	5	204	27	143	28.2
GPS 6	-19	-10	4	208	11	143	55.7
Graben GPS	-13	3	14	167	46	143	49.4
Graben Nede	-14	4	12	164	40	143	48.2
Graben Top	-16	2	16	173	45	143	58.0
Kant	-9	2	6	167	33	93	43.2
Kul GPS	-12	-1	5	185	23	143	33.3
Ny 08 Nede	-1	5	5	101	44	52	50.1
Ny 08 Oppe	1	3	3	71	43	67	23.7
Orm GPS	-12	-1	5	185	23	143	33.3
Osteklokke	-19	0	9	180	25	143	53.7
Upper borehole	-16	0	8	180	27	143	45.7
Ovre Laser	-4.2	4	1.5	136	15	143	15.3
Prisme 2	zero	point	changed	-	-	143	-
Prisme 3	-4	1	1	166	14	143	10.8
Prisme 14	-10	0	11	180	48	143	37.9
Renne 1	-9	1	7	174	37	67	62.4
Renne 10	-9	1	7	174	37	67	62.4
Renne V	-9	1	7	174	37	67	62.4
Skog	-30	-7	1	193	2	143	78.7
Stein 2	-10	-7	2	215	9	143	31.6

TABLE 2 DISPLACEMENT OF EACH PRISM FROM A LEAST SQUARES LINEAR REGRESSION LINE THROUGH THE DATA POINTS. NEGATIVE VALUES IN THE NORTH COLUMN INDICATE SOUTHWARD DISPLACEMENT WHILE NEGATIVE VALUES IN THE EAST COLUMN WESTWARD DISPLACEMENT.

Summary of measurements of displacement

Table 2 summarizes the displacement of the prisms and Figure 8 illustrates the direction and magnitude of displacement. Random and weather dependent fluctuations of between 8-40 mm are evident in the measurements.

The average total velocity (XYZ) for 21 prisms was 44.7 mm/yr. For some of the prisms the coefficient of determination is low as the fluctuations are large compared to the small displacement over a short time span and also the time series are incomplete. Nevertheless the trend of movement is clear when comparing the displacement from all the prisms (Figure 8 &Table 2):

1) 20 out of 21 prisms moved towards south and all moved down. One moved north but only 1 mm, which is within the uncertainty of the method.
2) 13 prisms move towards east while 8 moved towards west or only south.

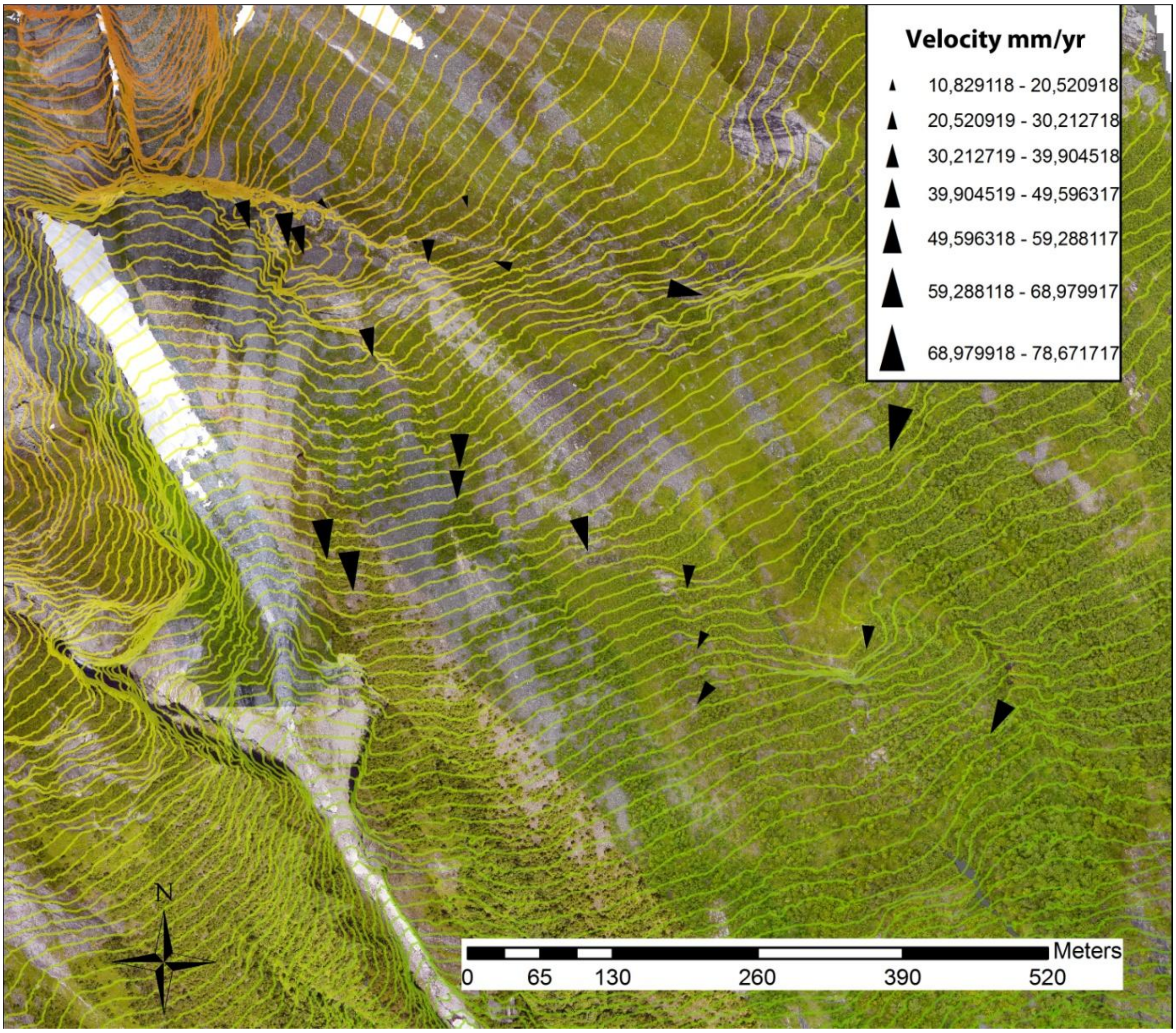


FIGURE 8: MAGNITUDE (IN MM/YR) AND DIRECTION (X,Y) OF THE PRISMS FROM 3 MONTHS MEASUREMENTS.

Interpretation of the movement

The southward and downhill movement is as expected and the largest movement is seen in the upper western part of the landslide. In the eastern part of the landslide the velocities are smaller and appear to be more westward, though the magnitude of the westward components may be too small to be considered certain. Earlier measurements by total station documented that the eastern part of the rockslide has displacements against southeast (Figure 39), demonstrating that we need a longer time span with the new total station in order to get properly direction in areas with low velocities.

Using the prisms for early warning

Reliability in a stable situation: There has earlier been much trouble with the robotic total station and several changes of equipment have been made, and we still experience gabs in the data series. We need still more time in order to evaluate the stability and redundancy of the robotic total station.

Reliability at the time of failure: We must expect that the robot will be unable to find the prisms when large enough displacement of the landslide has occurred. However, it should be able to find the prisms even if they have moved a couple of meters if the mirror is still turned towards the total station. Another advantage is that there are no electrics or cables on the landslide itself, which could break during accelerated movement. In summary the total station is probably not the most reliable instrument during an accelerated phase of the landslide, but it provide details of differential displacement which otherwise are difficult to obtain.

No readings were more than 40 mm from the mean, which is less noise than in the GPS data. This may indicate that an SMS messages could be set on the prisms, but we need to investigate the reliability further before implementing automatic alarm functions.

Laser data

Two lasers measure distance across the uppermost extension cracks at Åknes (location: Figure 5). Figure 9 show data from 1 March 2007 to 13th (upper laser) and 18th (lower laser) of December 2009. 1877 measurements with varying degree of "bad-read" were removed. The distances between the laser and reflectors are measured every 5 minutes and were plotted on Figure 9 with different Y-axis that has equal distance intervals. Some data points beyond the Y-axis' were removed. There is data gap from 30 July 2008 to 22 August 2008 due to a strike of lightning which destroyed the power supply. Several other shorter data gaps exists which for example may be due to heavy snow in wintertime.

Both lasers show an easily identifiable trend with many outliers. They seem to have about the same amount of outliers that are >50 mm from the trend, while the upper laser has more small scale noise than the lower laser.

Figure 10 shows five days of measurements of both lasers, and in particular the upper laser displays a strong diurnal cycle. Temperature and humidity are plotted above, and not surprisingly the humidity is inversely correlated to the temperature. It appears as if the upper laser records a peak in distance when the humidity is near to 100%. The variations of the lower laser are much smaller, but also appear to measure shortest distance when the temperature is at a maximum and humidity at a minimum.

Using the laser data for automatic messages/alarms

Even after filtering away "bad-reads" the dataset is rather noisy. One source of error may be ice/ snow or dew covering the reflectors when the power of the inbuilt heating elements is insufficient to melt or evaporate it. The frequent measuring intervals make the lasers useful during an acceleration phase of the landslide but large movement might change the line of sight from the lasers to the reflectors, and thus the signal may be lost.

Setting SMS messages on the laser measurements is a bit difficult, as the number of outliers is quite large. We receive too many false alarms at the moment, especially on the upper laser.

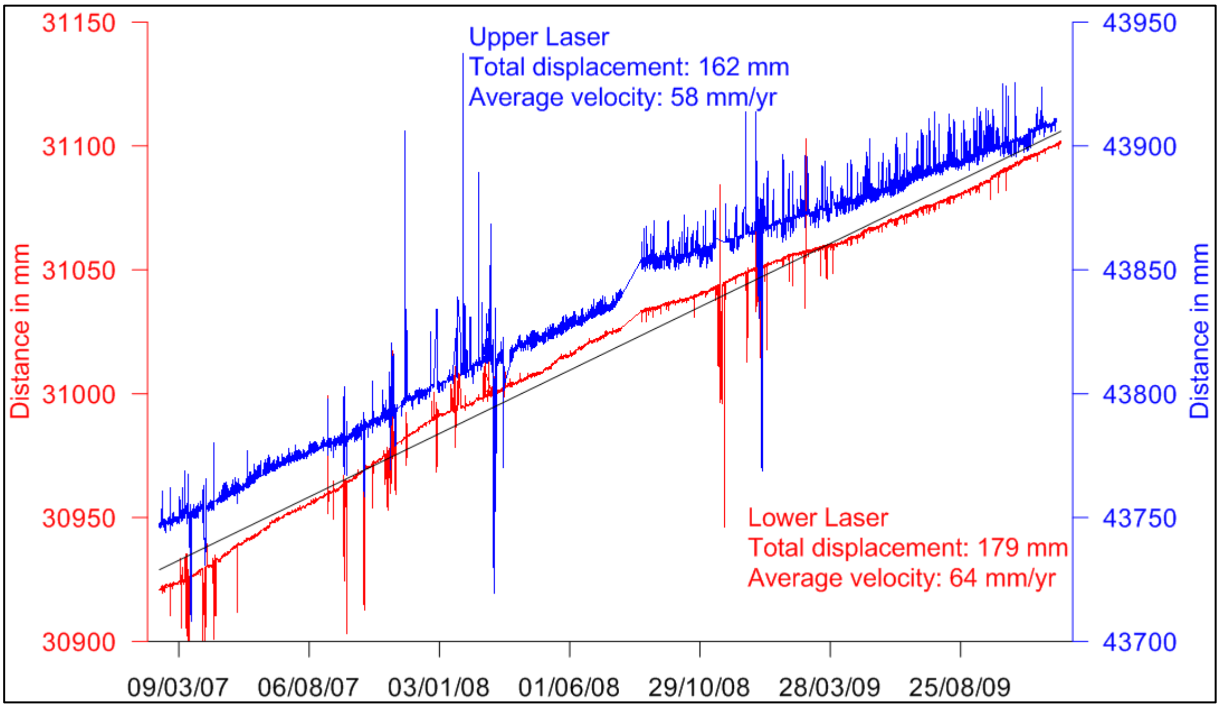


FIGURE 9: UPPER LASER IN BLUE AND LOWER LASER IN RED. THE BLACK LINE IS A LEAST SQUARES REGRESSION LINE THROUGH THE LOWER LASER DATA.

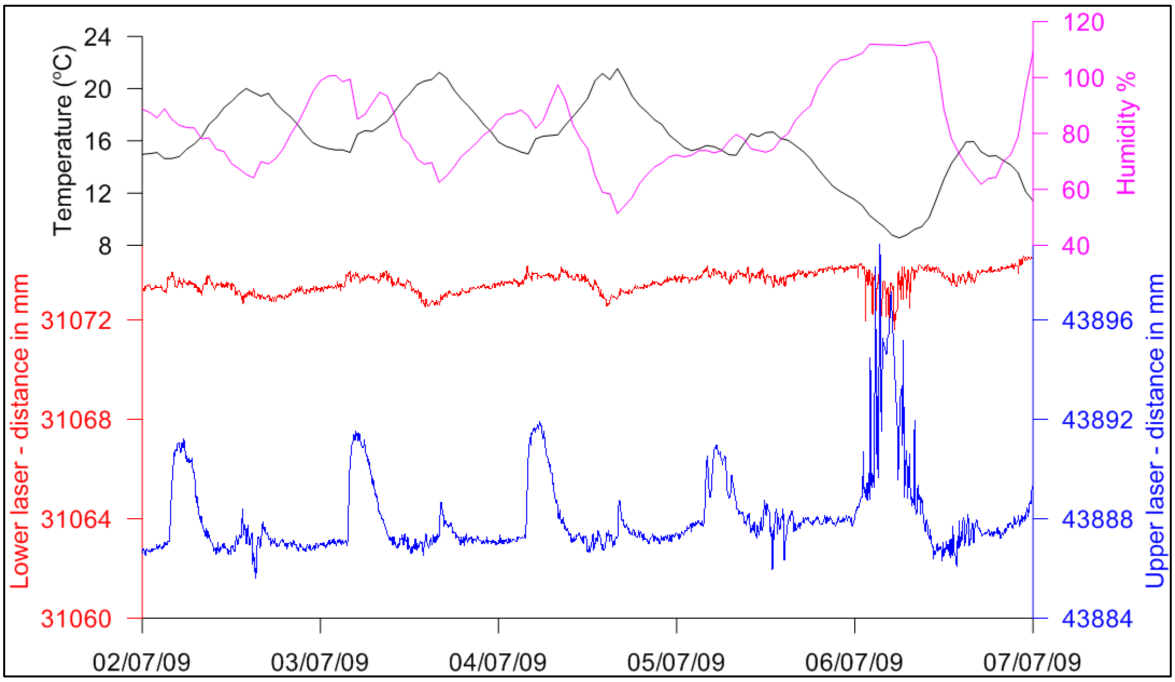


FIGURE 10: THE BLUE AND RED CURVE SHOW FIVE DAYS OF DISTANCE MEASUREMENTS OF UPPER AND LOWER LASER IN JULY 2009. THE AIR TEMPERATURE AND HUMIDITY FOR THE SAME PERIOD IS SHOWN IN UPPER PART.

Extensometers

Three extensometers have been operative since 15 August 2006 across the upper crevasse; their location can be seen on Figure 5. It was attempted to place the instruments parallel to the direction of movement. The displacement recorded by the extensometers is logged every 5 minutes. On Figure 11 the movement is plotted until 23 March 2010. The Y-axis is relative because the initial length of each sensor is different; thus for comparison between the sensors, only the relative start and end point of each data series and the changes of slope throughout the measurement period is important.

The data series of extensometer 2 is continuous and interrupted only by a short interval in August 2008 due to a thunderstorm that destroyed the power supply. Data are missing from extensometer 1 from August 2008 to September 2009. The curve on extensometer 3 is combined from two sensors from the same location; the sensor was changed in early August 2008.

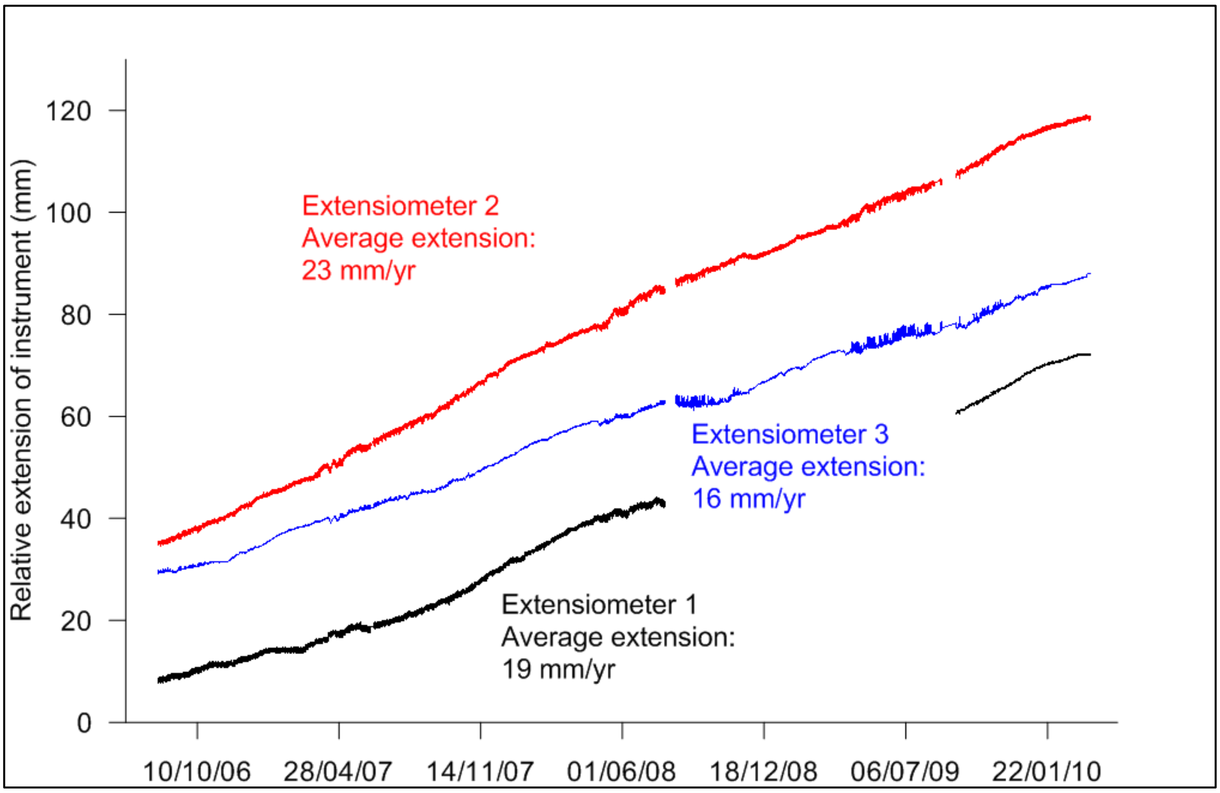


FIGURE 11: MOVEMENT OF THE UPPER FRACTURE AS SEEN FROM 3 EXTENSOMETERS

Comparing the extensometer data with other surface displacement data (for the DGPS the maximum displacement is 62 mm/yr) it is clear that the extensometers do not capture the entire movement of the landslide. Extensometers only capture local displacement within the landslide body, and in periods there are also movements backwards due to back-rotation of individual blocks. Also, the greatest movement is found further west, where the crack is much wider.

Using the extensometer data for automatic messages/alarms

As can be seen of the curves, all three extensometers record a continuous widening of the crack. There are small daily fluctuations that may be due to changes in the temperature of the sensor, but they are at maximum in the order of 3 mm and usually less than 1 mm.

When acceleration of the landslide initiates, the extensometers will most likely supply frequent and reliable information of the movement, unless new crevasses are responsible for most of the movement. The extensometers are only able to expand up to some maximum level and beyond that they will fail, so they are not suited for monitoring the landslide in the latest stages of acceleration. However, the reliability of the sensors makes them very well suited for automatic messages/alarms.

Crackmeters

4 crackmeters (small extensometers) were installed in the upper parts of Åknes landslide to measure movement across small cracks in the landslide and were connected on 19th of January 2009. Their position is shown in Figure 12. Crackmeters 2 and 3 are at the same location but measure in different directions. In Figure 13 the measurements of the crackmeters are plotted until the 26th of March 2010.

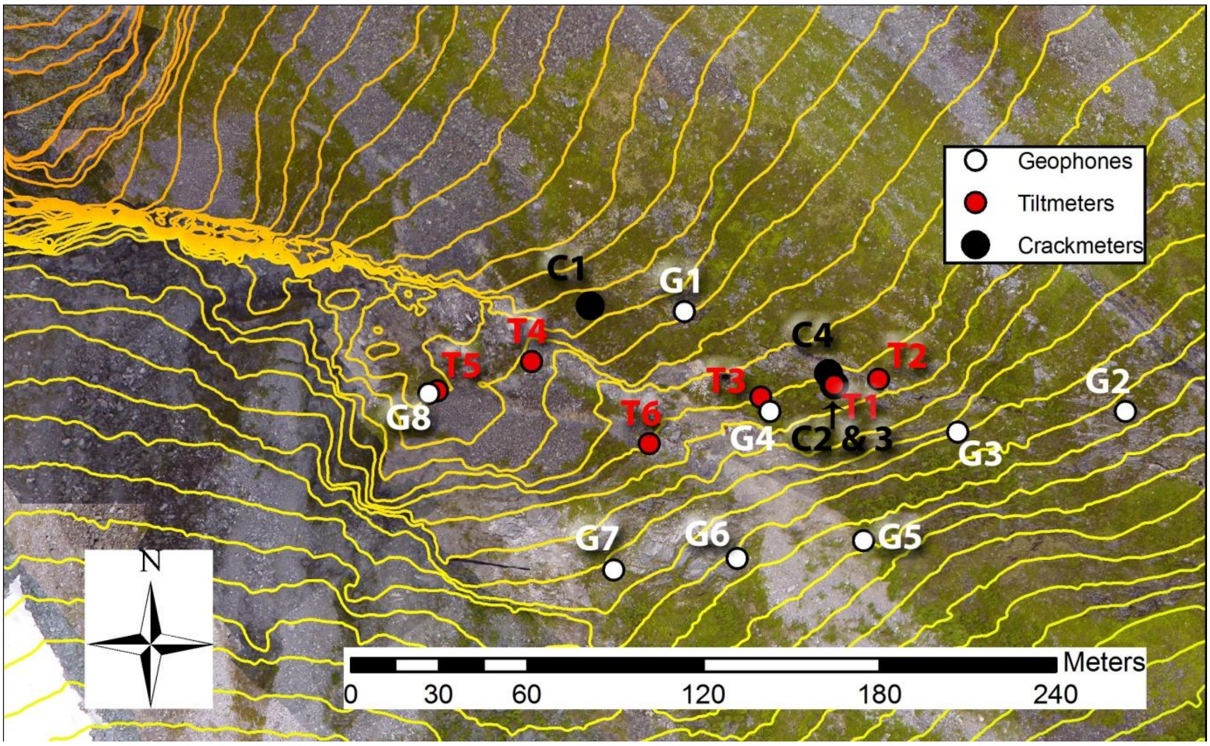


FIGURE 12: POSITION OF THE CRACKMETERS (BLACK DOTS) AND TILTMETERS (RED DOTS) AND GEOPHONES (WHITE DOTS) ON EITHER SIDE OF THE LARGE EXTENSION CRACK AT THE UPPERMOST PART OF THE LANDSLIDE.

The crackmeters only measure across small extensional features and do therefore not capture the total displacement of the landslide. Crackmeter 3 and 4 measured up to 3 mm contraction while crackmeter 2 measured about the same amount of extention. Crackmeter 1 measured a very small extension. The contraction took place primarily in the spring and summer 2009, while the extension seems most pronounced during the autumn. During the winter all the sensors measured a neglectable change. The measurements show that the cracks are active, but without a clear trend of expansion or contraction. Crack 2, 3 and 4 is also located in an area with back-rotation of blocks, probably initiation of a graben structure, and may thus have a complex pattern of deformation.

The crackmeters have the potential of recording spreading activity in smaller cracks, which may be important for the landslide dynamics. Although they record very small amounts of the total movement, they are suited for automatic SMS messages and alarms. Due to the fact that they only capture local movements and that the movement can be larger than they can expand, they will be difficult to use in late stages of an event.

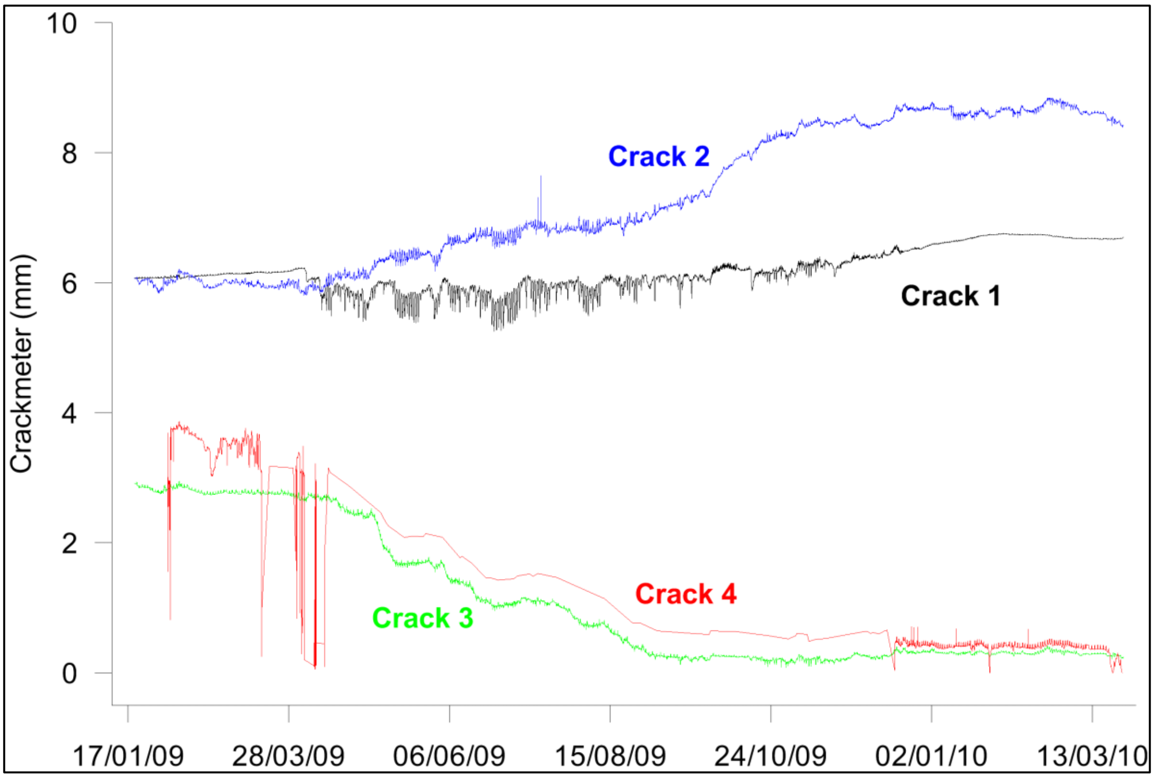


FIGURE 13: MEASUREMENTS OF THE 4 CONNECTED CRACKMETERS DURING 14 MONTHS.

Tiltmeters

Six tiltmeters have measured tilt of vertical rock faces in two dimensions from 19 January 2009 (location on Figure 12). The tiltmeters at Åknes were placed so their A-axis is parallel to the dip of the slope and their B-axis perpendicular. A plot of all the A-axis can be seen in Figure 14 and the B-axis in Figure 15. The values measured vary, so the Y-axis is not absolute, but the Y-axis' cover the same interval.

Tiltmeter 6 measured the largest fluctuations; in the A-axis up to 30 mm/m on an almost daily basis, which indicate great movement of the rock where it is attached. It makes it hard to find a trend in the data, and it should probably be moved to a more stable site. Tiltmeter 4 also measured large fluctuations which appear to show some cyclicity, which however does not fit well with a seasonal pattern. Tiltmeters 1, 3 and 5 measured stable inclinations, some with small changes that may be seasonal. Their day to day fluctuations were typically less than 1 mm/m. Tiltmeter 2 would fall in this group, but showed larger daily fluctuations (4 mm).

So far we need more time to evaluate the use of the tiltmeters in terms of studying the dynamics of the rockslide and the potential use for SMS messages.

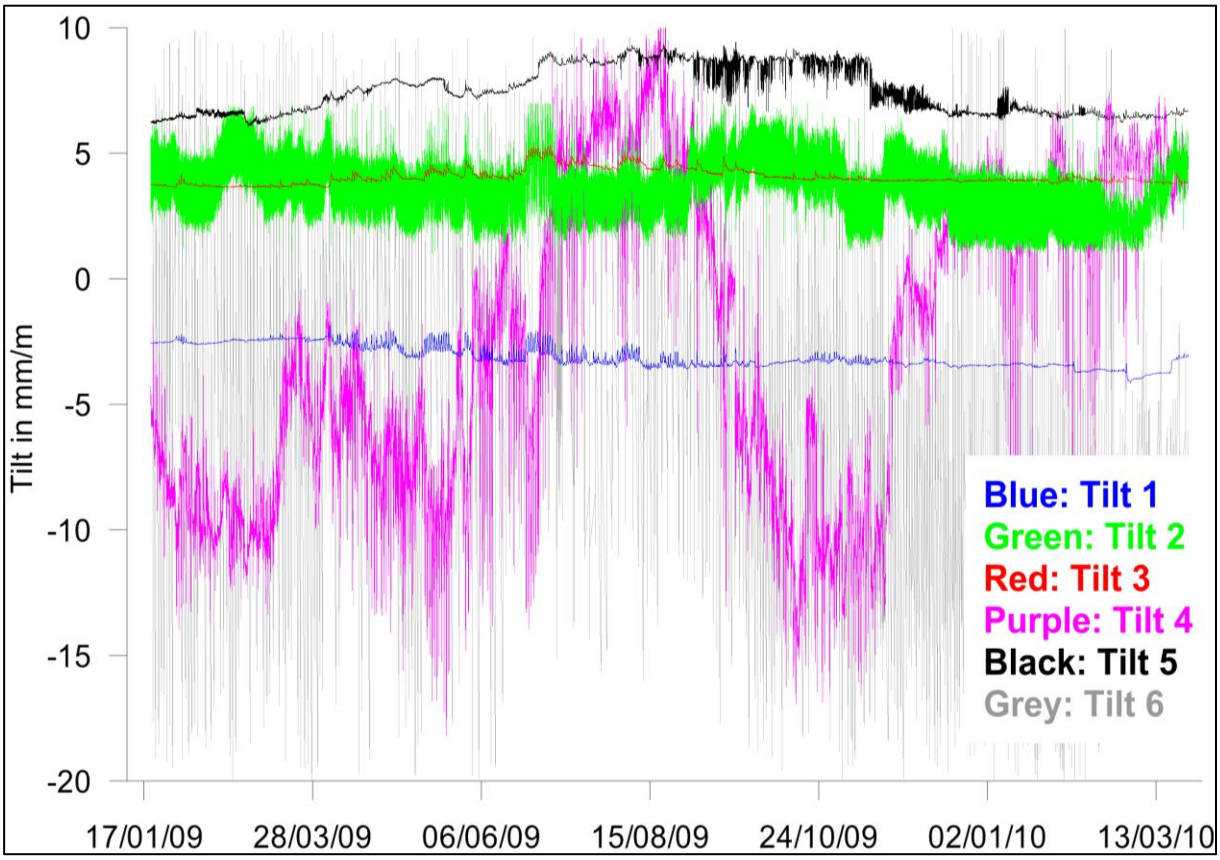


FIGURE 14: TILTMETER 1, 2, 3, 4, 5 & 6. A-AXIS WHICH IS SLOPE PARALLELL.

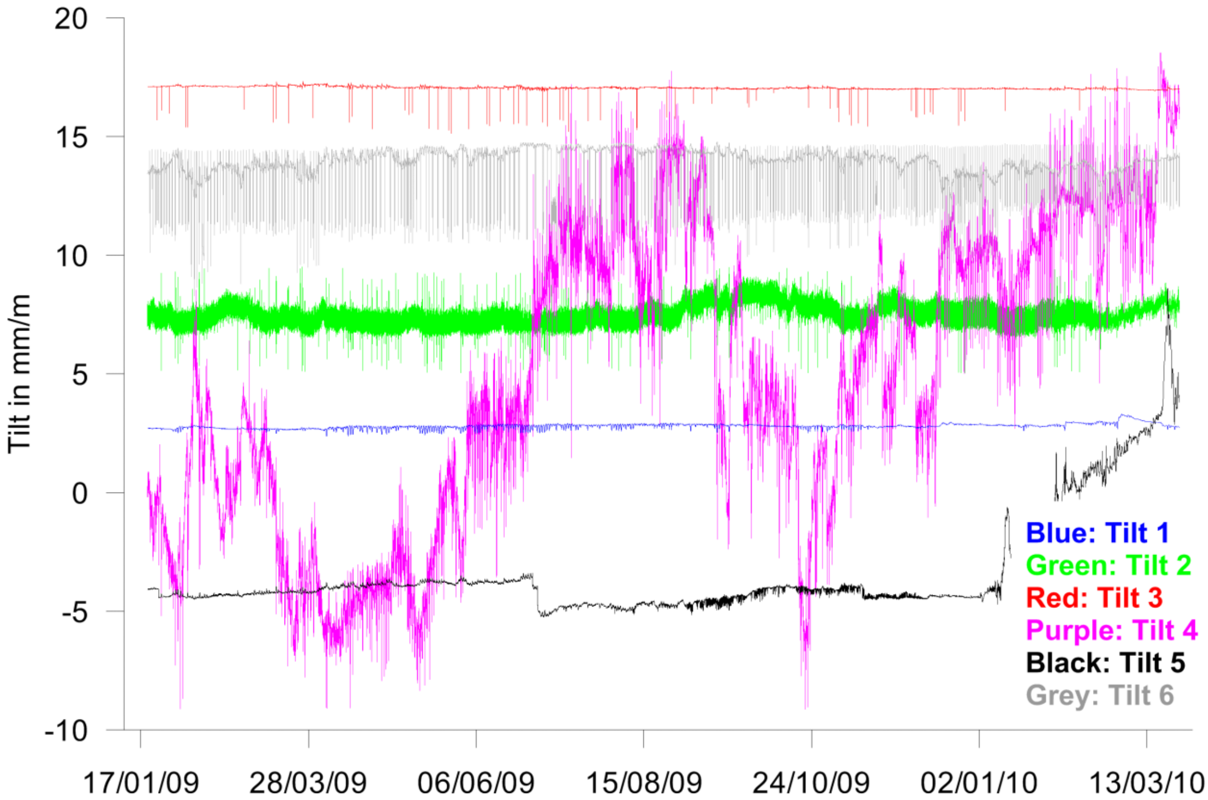


FIGURE 15: B-AXIS OF TILTMETERS 1-6, WHICH MEASURES PERPENDICULAR TO THE MOUNTAIN SLOPE

Ground Based Interferometric Radar measurements

In the summers 2005, 2006, 2008, 2009 and 2010 a ground based INSAR system from LiSALab Ellegi srl has measured distributed displacement of the Åknes landslide. Here some data from 2009 are presented, which were measured in a 108 days campaign from 1st July to 17th October 2009.

The radar was located across the fjord from the landslide (Figure 16). Using interferometry it measured changes in distance along the Line Of Sight (LOS). Correction for atmospheric disturbance was necessary due to large temperature and humidity variances across the fjord.

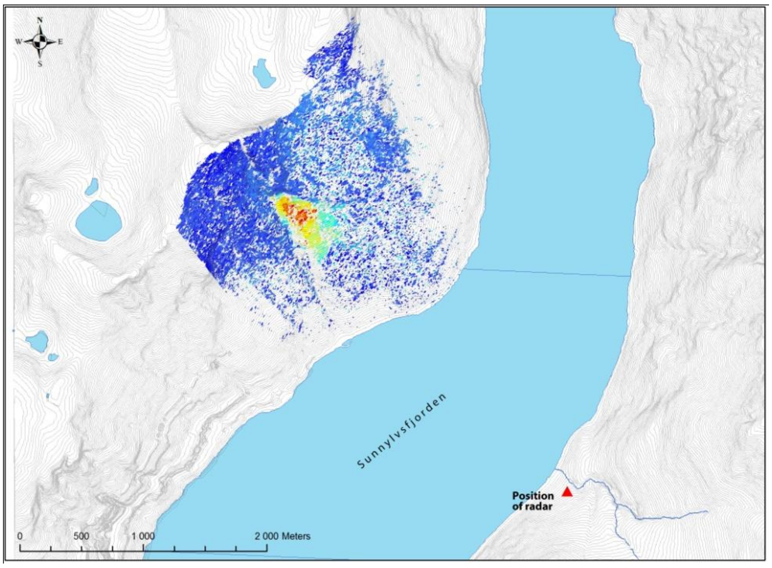


FIGURE 16 POSITION OF THE RADAR, OPPOSITE THE LANDSLIDE. THE COLORED AREA AT ÅKNES SHOW THE MEASURED AREA, AND THE YELLOW AND RED COLOURS THE MEASURED AREA OF DEFORMATION.

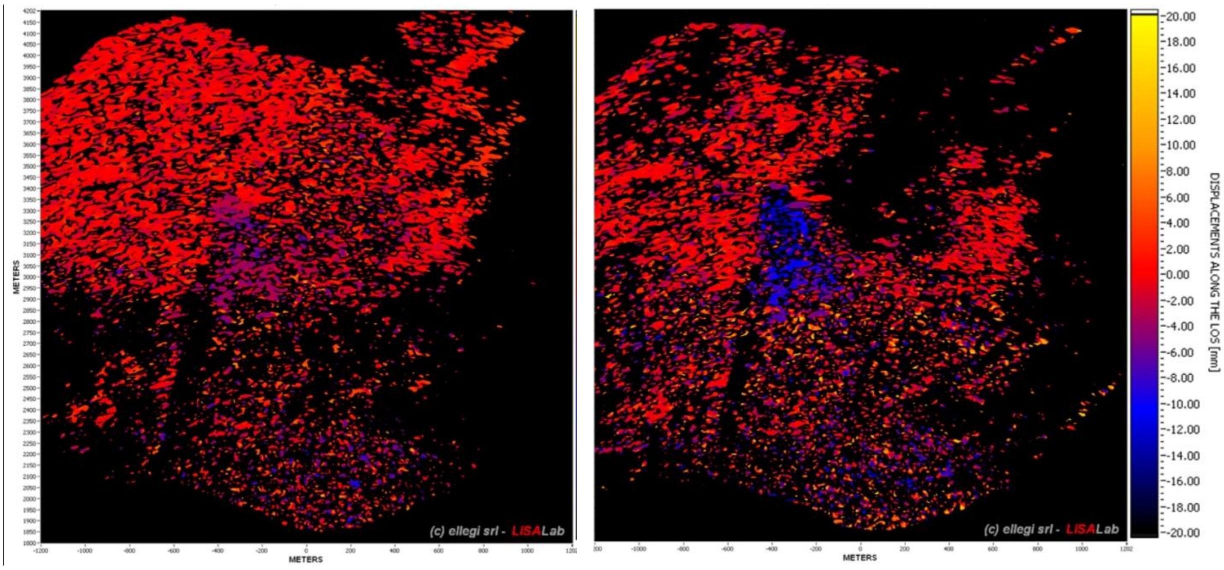


FIGURE 17 INTERFEROGRAMS FROM THE GB INSAR SYSTEM SHOWING DISPLACEMENT ALONG LOS. LEFT: 45 DAYS (01 JULY – 15 AUGUST); RIGHT: 108 DAYS (01 JULY – 17 OCTOBER 2009). NEGATIVE VALUES (BLUE) ARE MOVEMENT TOWARDS THE RADAR.

Interferograms are calculations of displacement in a time interval. In Figure 17, interferograms with time intervals of 45 days and 108 days respectively, are shown. The radar clearly identifies the upper moving part of the landslide with the most active area having an average displacement of -12.3 mm in 108 days, corresponding to 42 mm/yr. Lower in the slope the correlation is much lower (weak coherence) due to dense vegetation.

At Åknes, 9 corner reflectors have been installed to be used by an alternative radar system. These reflectors appear as bright spots in the LiSALab images (Figure 18) and the displacement of the reflectors have been analyzed (Figure 19). The measured corner reflector point velocities compare well to the distributed measurements. The somewhat lower velocity measured by the radar compared to the laser and DGPS measurements can mainly be explained by the LOS being different to the direction of movement. Therefore the measured displacement will somewhat underestimate the true displacement. The data from the corner reflectors indicate that the lower part is relatively stable.

The radar measurements have so far been used for mapping purposes, and not as an operative system for landslide monitoring or early warning. However, the system will be used during landslide acceleration.

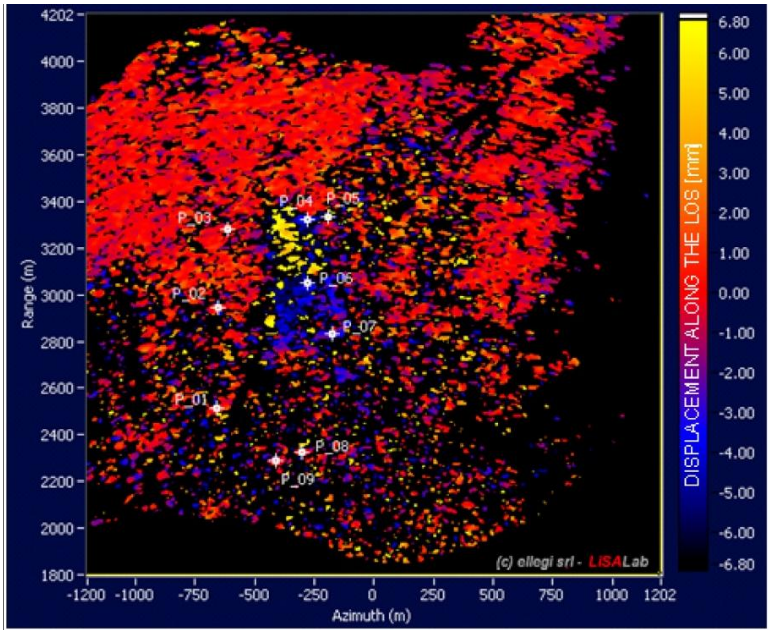


FIGURE 18 THE NUMBERED LOCATION OF THE CORNER REFLECTORS IN AN INTERFEROGRAM.

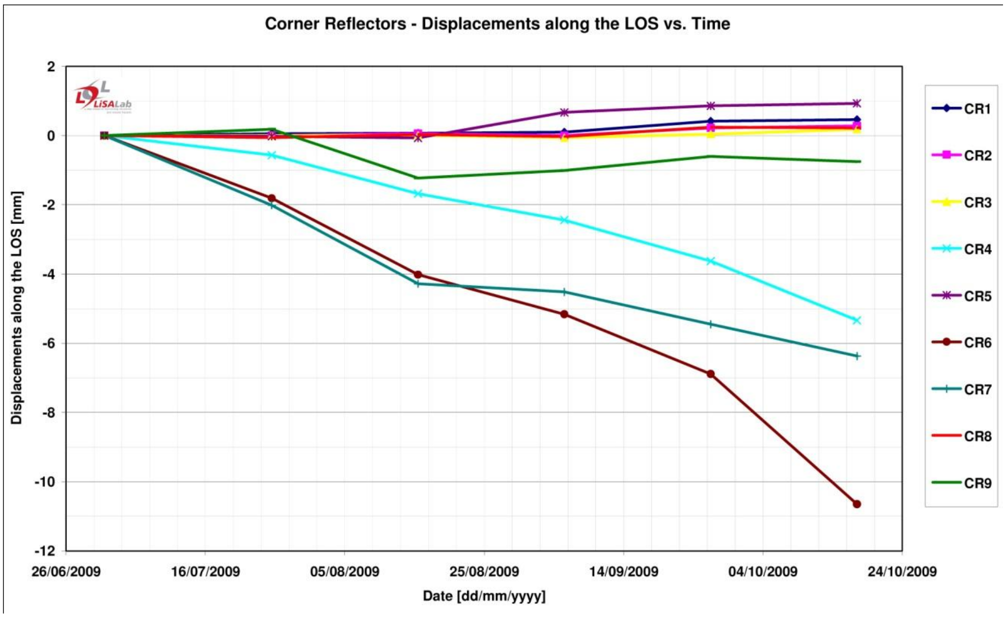


FIGURE 19 DISPLACEMENT OF THE CORNER REFLECTORS ALONG LOS IN 108 DAYS.

Borehole measurements

Seven 150 – 200 m deep boreholes at three locations have been drilled at Åknes. The cores were described and logged (Ganerød *et al.*, 2007) and the boreholes were filmed and logged using different geophysical sensors (Rønning *et al.*, 2006). Three of the boreholes are instrumented with the DMS (Differential Monitoring of Stability) system. The DMS is a multiparametric column for investigations and permanent monitoring of subsurface and the one meter long modules are linked to each other by special 2D/3D joints. The present system at Åknes composes 3 continuous columns 50, 100 and 120 m long measuring the movement in 2D. The 120 m long column consists of totally 245 sensors. The sensors are inclinometers, temperature sensors and in selected modules pietzometers and digital compass. They record displacement in two dimensions on the basis of inclination every meter on an hourly basis movements, temperature and water pressure, and have been developed and patented by the Italian company CSG srl.
The level of details allows for the investigation of the subsurface processes responsible for the movement, which is impossible to infer from surface measurements alone. Of particular interest are shear zones and zones of creep. Table 3 below shows the depth and time-intervals covered by the three columns.

Borehole name	Time intervals of measurements	Depth intervals of column (m)
Upper borehole	14/9 2006 – 20/10 2007	32 – 82
	22/10 2007 - 30/07 2008 and	83 – 133
	29/10/09 – today	8 - 128 m
Middle borehole	24/11/06 – 14/09/07	16.5 – 55.5
	22/10/2007 – today	31.5 - 81.5m
Lower borehole	28/06/08 - 30/07/08	21 – 121
	29/10/09 – today	20 – 120

TABLE 3 TIME AND DEPTH INTERVALS OF MEASUREMENTS BY DMS IN THE THREE BOREHOLES.

To give reliable information on the subsurface displacement, the column has to penetrate the entire zone of movement. If shear or creep takes place below or above the column, the total displacement will not be detected. The displacement found from the boreholes should thus be considered as minimum values, and should preferably be compared with measurements of surface displacement, to ensure that the entire movement is represented in the borehole.

Upper borehole

The upper borehole was instrumented with a 50 m column in 2006-2008 in different depth intervals and with a 120 m column in late 2009. The slope at the borehole site is SE.

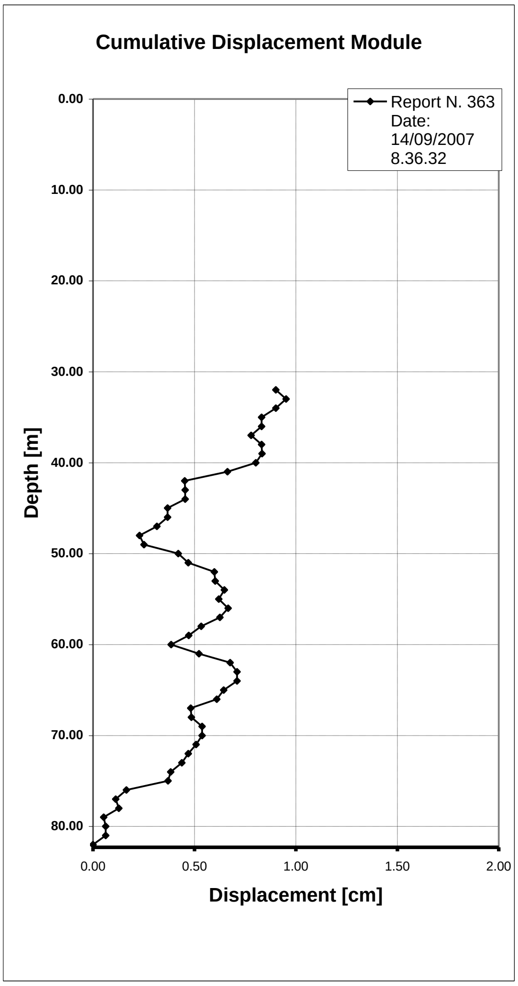
Early measurements

The first measurements showed no clear sliding plane, but rather enhanced movement in several levels (Figure 20) and in different directions (Figure 21). There was a change in direction of displacement west (lower) to east (upper) in ca. 49 m depth. It was however concluded that there were displacement concentrated around 75 and 50 m depth.

DMS AKNES upper site (diff. 14/09/2007 - 15/12/2006)

Report N. 363 Date: 14/09/2007 8.36.32

Contractor:	AKNES/TAFJORD PROJECT
Site:	Aknes upper site
Monitoring Interval	32-82 m
Installation Date	14/09/2006
Project:	48 I modules, 2 IU modules
Note:	HDPE f int = 61.4 mm depth 140 m



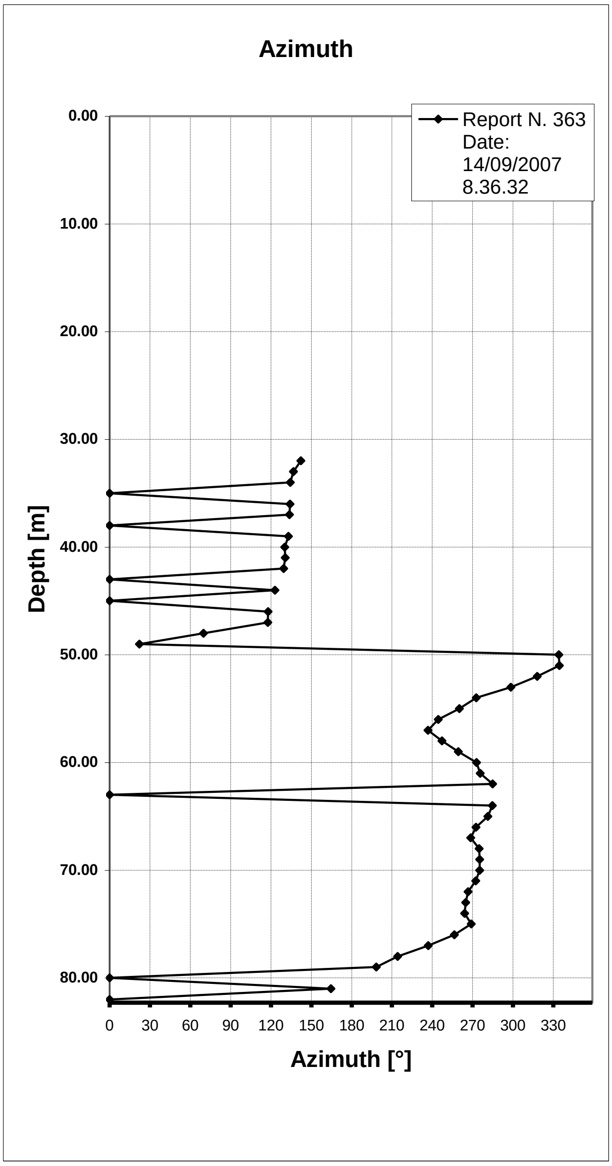
Depth [m]	Displ. [cm]
82.0	0.00
81.0	0.06
80.0	0.06
79.0	0.05
78.0	0.13
77.0	0.11
76.0	0.16
75.0	0.37
74.0	0.38
73.0	0.44
72.0	0.47
71.0	0.51
70.0	0.54
69.0	0.54
68.0	0.49
67.0	0.48
66.0	0.61
65.0	0.64
64.0	0.71
63.0	0.71
62.0	0.68
61.0	0.52
60.0	0.39
59.0	0.47
58.0	0.53
57.0	0.63
56.0	0.67
55.0	0.62
54.0	0.65
53.0	0.60
52.0	0.60
51.0	0.47
50.0	0.42
49.0	0.25
48.0	0.23
47.0	0.32
46.0	0.37
45.0	0.37
44.0	0.45
43.0	0.45
42.0	0.45
41.0	0.66
40.0	0.80
39.0	0.83
38.0	0.83
37.0	0.78
36.0	0.83
35.0	0.83
34.0	0.90
33.0	0.95
32.0	0.90

FIGURE 20: TOTAL CUMULATIVE DISPLACEMENT IN UPPER BOREHOLE15 DECEMBER 2006 TO 14 SEPTEMBER 2007.

DMS AKNES upper site (diff. 14/09/2007 - 15/12/2006)

Report N. 363 Date: 14/09/2007 8.36.32

Contractor:	AKNES/TAFJORD PROJECT
Site:	Aknes upper site
Monitoring Interval	32-82 m
Installation Date	14/09/2006
Project:	48 I modules, 2 IU modules
Note:	HDPE f int = 61.4 mm depth 140 m



Depth [m]	Azimut [°]
82.0	0
81.0	165
80.0	0
79.0	198
78.0	214
77.0	237
76.0	256
75.0	269
74.0	264
73.0	265
72.0	267
71.0	272
70.0	275
69.0	275
68.0	275
67.0	269
66.0	272
65.0	281
64.0	285
63.0	0
62.0	285
61.0	276
60.0	273
59.0	259
58.0	247
57.0	237
56.0	244
55.0	260
54.0	273
53.0	298
52.0	318
51.0	334
50.0	334
49.0	22
48.0	70
47.0	118
46.0	118
45.0	0
44.0	123
43.0	0
42.0	130
41.0	131
40.0	130
39.0	133
38.0	0
37.0	134
36.0	134
35.0	0
34.0	134
33.0	137
32.0	142

FIGURE 21: DIRECTION OF DISPLACEMENT IN THE UPPER BOREHOLE, 15 DECEMBER 2006 TO 14 SEPTEMBER 2007.

Upper borehole, middle period

The column was now placed below the level of the column at the earliest measurements, and it thus covered the deep part of the borehole. Displacement is indicated down to at least 124 m (Figure 22). The azimuth direction of displacement changes from south in the uppermost and lowermost position of the borehole to east-northeast in the lower and middle parts. The total displacement of the time interval was 6.9 mm but because of the complex direction of movement, the maximum displacement was reached on 30 April rather than on 30 July 2008. The total displacement averages to 9.2 mm/yr, but this is most likely an underestimation, as the early measurements showed displacement further up in the borehole as well.

Figure 23 shows the total displacement and the borehole water pressure. A visual inspection reveals that there may be a relation between the two. The displacement towards south appear to peak when the water pressure is at maximum, whereas at other times the total displacement in the column moves towards north.

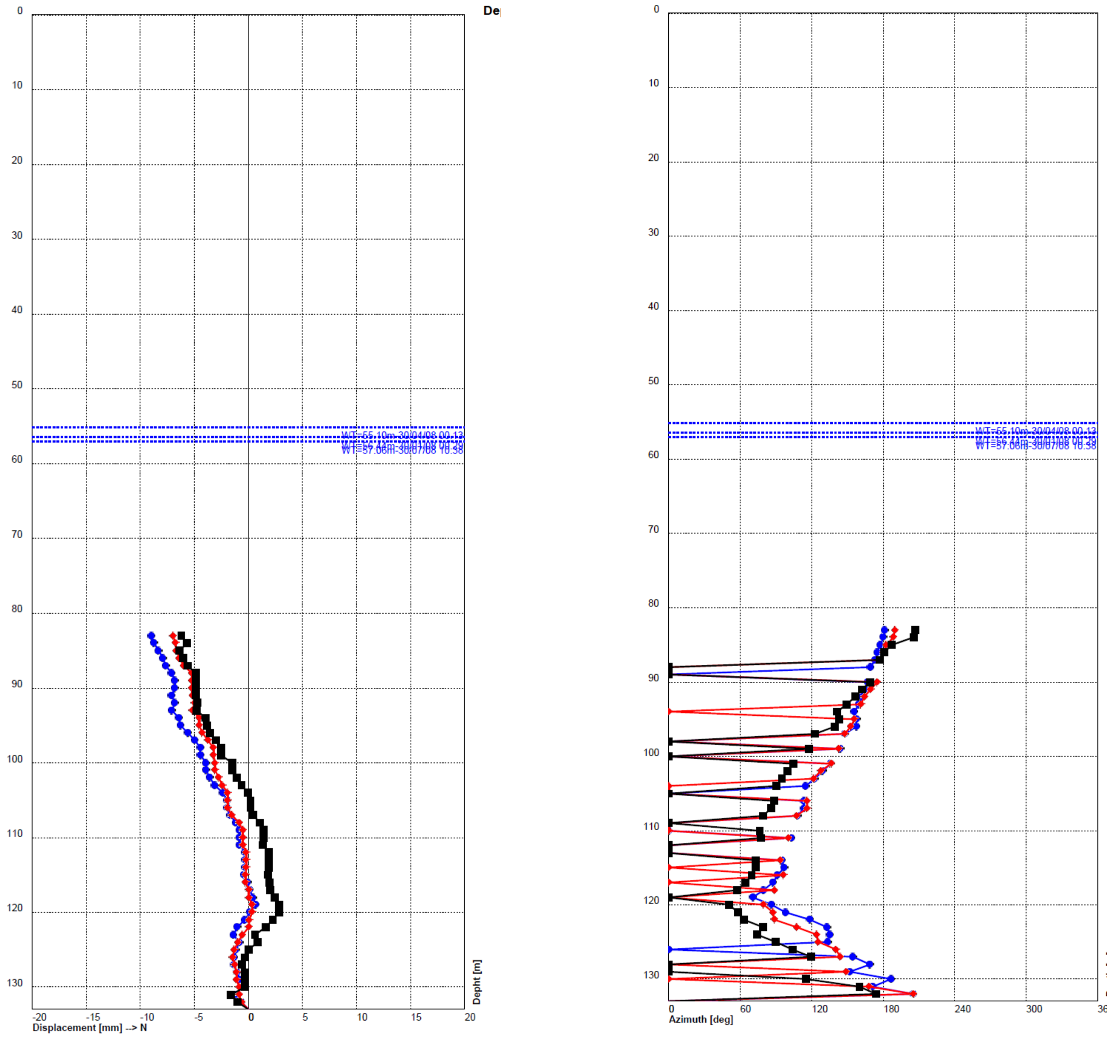


FIGURE 22: BLACK: 30 JULY 2008; BLUE: 30 APRIL 2008, RED: 30 JANUAR 2008. LEFT: DISPLACEMENT IN SOUTH-NORTH DIRECTION, RIGHT: DIRECTION OF DISPLACEMENT

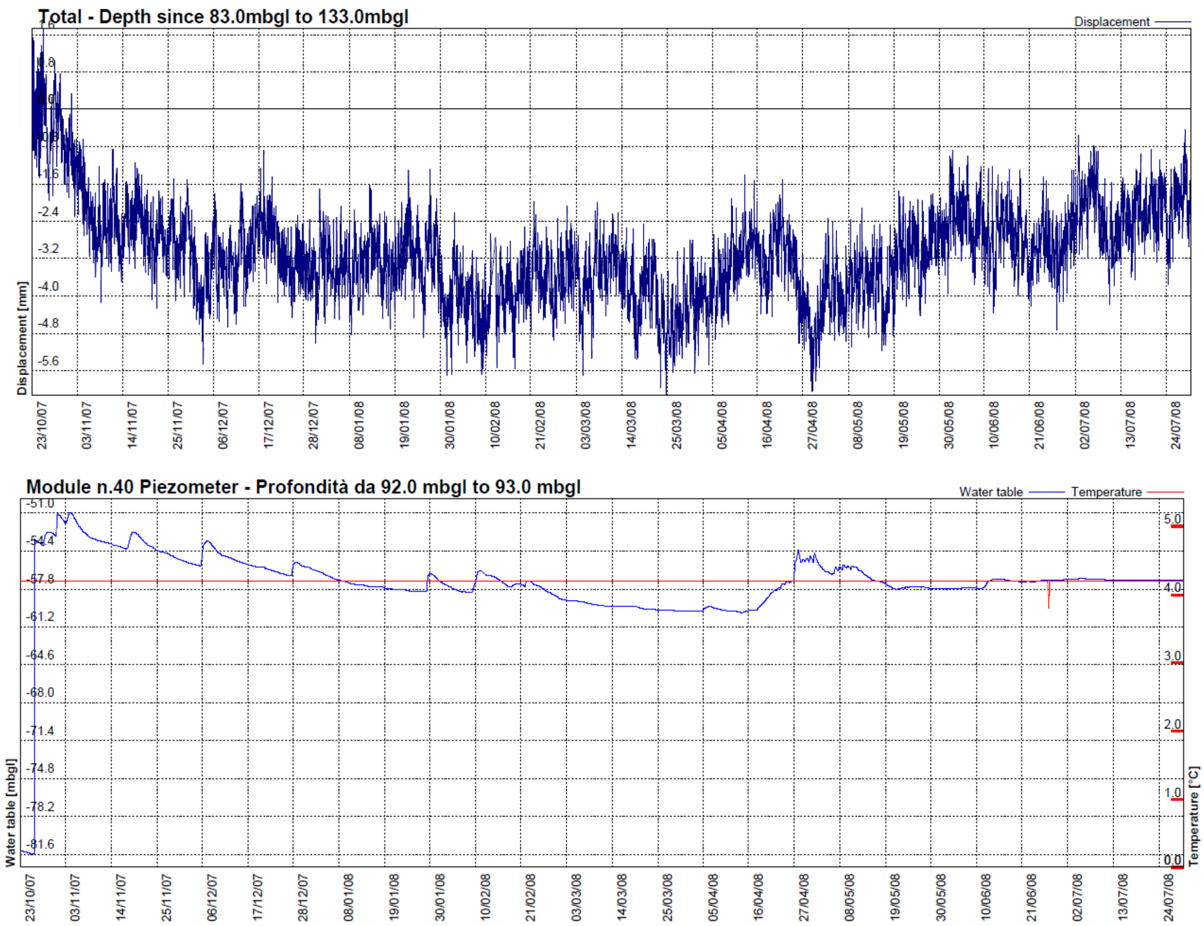


FIGURE 23: UPPER: THE TOTAL DISPLACEMENT (OF THE SURFACE) OF THE BOREHOLE TOWARDS SOUTH. BELOW: THE WATER PRESSURE IN THE BOREHOLE (BLUE LINE) DURING THE SAME TIME INTERVAL.

Recent measurements

The present DMS column in the Upper Borehole is 120 m long and has measured a complex movement, as can be seen in Figure 24. The lower part of the borehole moved towards south and south-east as would be expected, but the middle part moved to the north, which is uphill. The northerly displacement was > 5mm from 28 January 2010 to 29 March 2010. The largest movement of the borehole was seen in 49-50 m depth, which clearly is a sliding zone, and here the movement is downhill. This level corresponds to where the change in direction was measured during the early measurements. The total displacement (all modules cumulated) was towards south until 28 January, but from that day it moved towards north.

Tentatively we suggest that the peculiar differential movement may be caused by back-movement of blocks due to differential movement of different blocks (both on surface and in depth). Such complex geometries and deformation can lead to free space for a possible back movement of individual blocks (Figure 25).

Figure 26 show the southern displacement in the sliding zone (modules 77 and 78) the water pressure and the surface movement in the same time-interval measured by the total station. During the first couple of weeks the water level dropped about 2.5 meters which somewhat correspond to a decreased velocity. As seen from Figure 26 the surface displacement is larger than the total displacement in the DMS column. This is either due to displacement in upper 8 m, or more likely that there occurs movement below the DMS instrumentation (below 128 m depth).

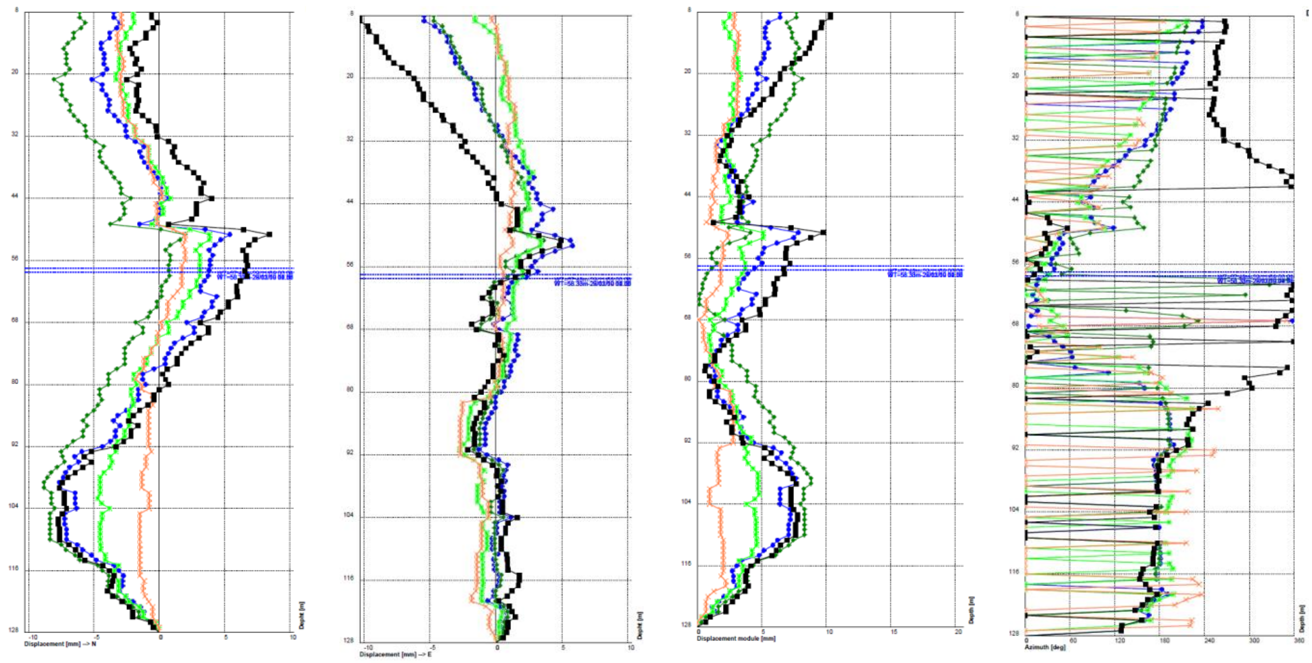


FIGURE 24: DISPLACEMENT IN ALL DIRECTIONS, SHOWN WITH MONTHLY INTERVALS. BLACK: 29 MARCH 2010, BLUE: 28 FEBRUARY 2010, DARK GREEN: 28 JANUARY 2010, LIGHT GREEN: 28 DECEMBER 2009, ORANGE: 29 NOVEMBER 2009. LEFT: NORTH DISPLACEMENT; MIDDLE LEFT: EAST DISPLACEMENT; MIDDLE RIGHT: TOTAL DISPLACEMENT, RIGHT: DIRECTION OF DISPLACEMENT.

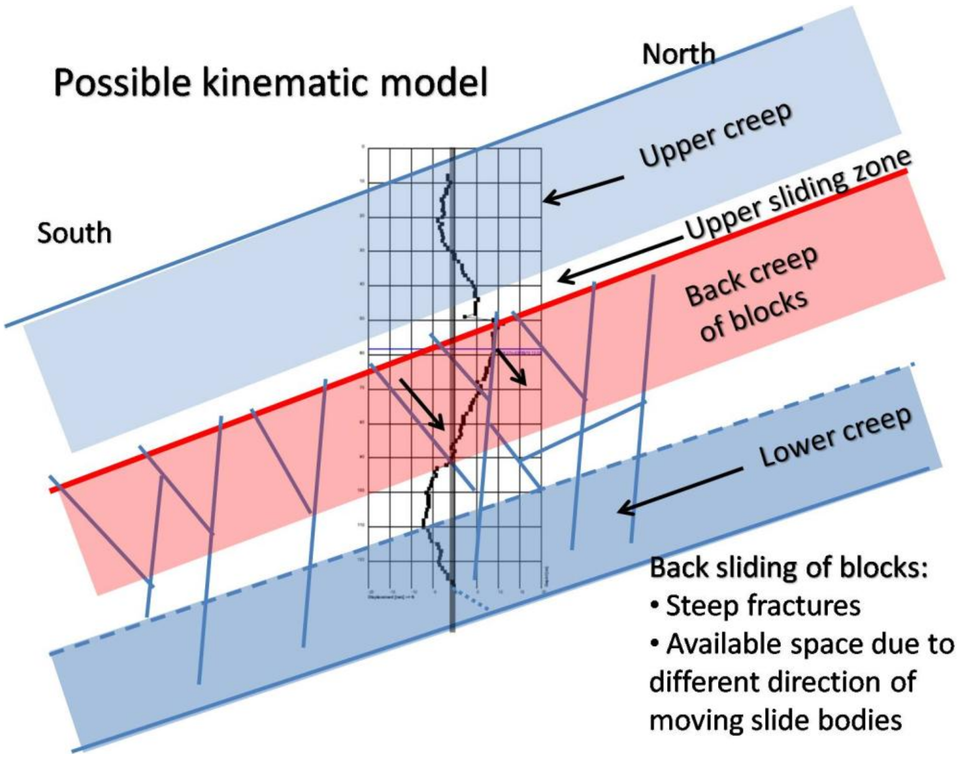


FIGURE 25: A SIMPLIFIED POSSIBLE KINEMATIC MODEL EXPLAINING THE DEFORMATION PATTERN IN UPPER BOREHOLE.

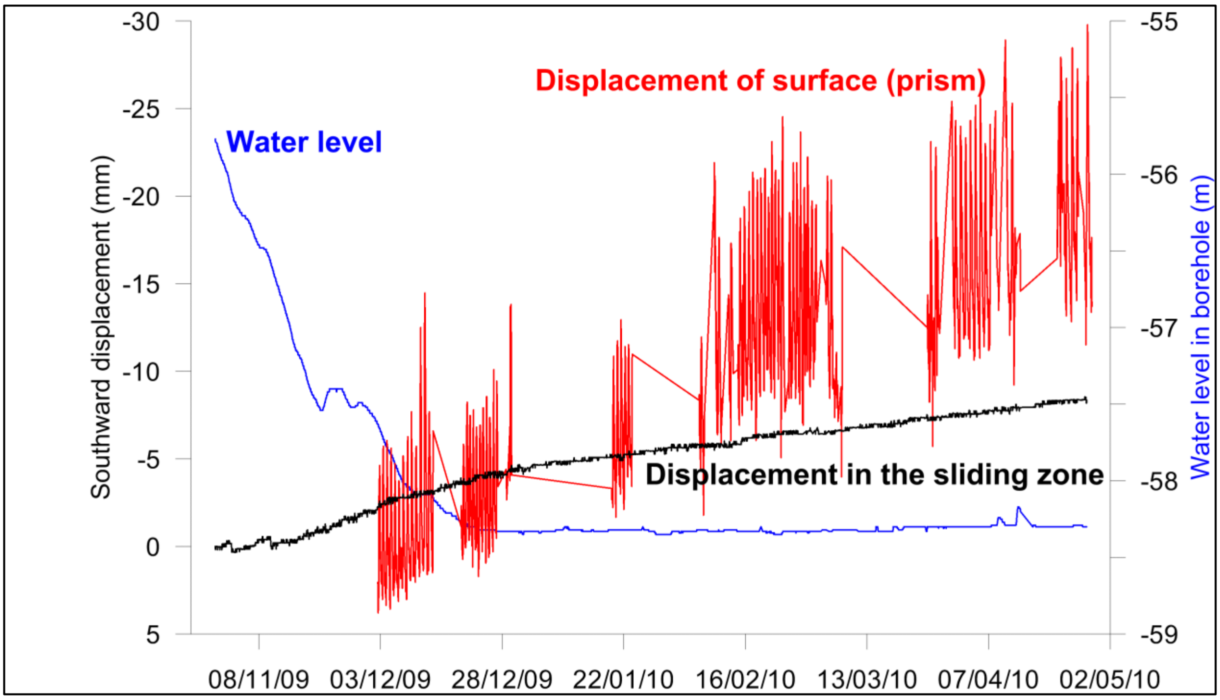


FIGURE 26: DISPLACEMENT IN THE SLIDING ZONE (MODULES 77 AND 78: 49-50 M DEPTH) OF THE UPPER BOREHOLE. ALSO SHOWN IS THE SURFACE DISPLACEMENT AND THE WATER LEVEL IN THE BOREHOLE.

Middle borehole

The mountain slope at the middle borehole is towards SSE.

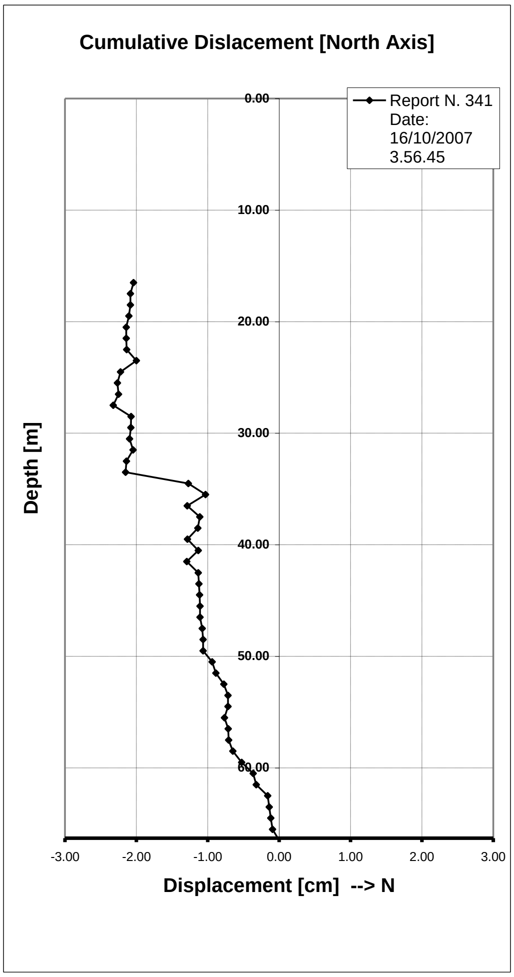
Early measurements

The first measurements in this borehole are plotted in Figure 27 and Figure 28. A pronounced sliding surface is seen at ca. 33 m depth. This zone is nicely correlated with the rock-core characteristics with well-defined breccias with silt and clay at this level (Figure 29). The entire column is displaced towards south and the data also show movements at 58 to 62 m depth.

DMS AKNES middle site

Report N. 341 Date: 16/10/2007 3.56.45

Contractor:	AKNES/TAFJORD PROJECT
Site:	Aknes middle site
Monitoring Interval	16.5-66.5 m
Installation Date	24/11/2006
Project:	48 I modules, 2 IU modules
Note:	HDPE f int = 61.4 mm depth 155 m



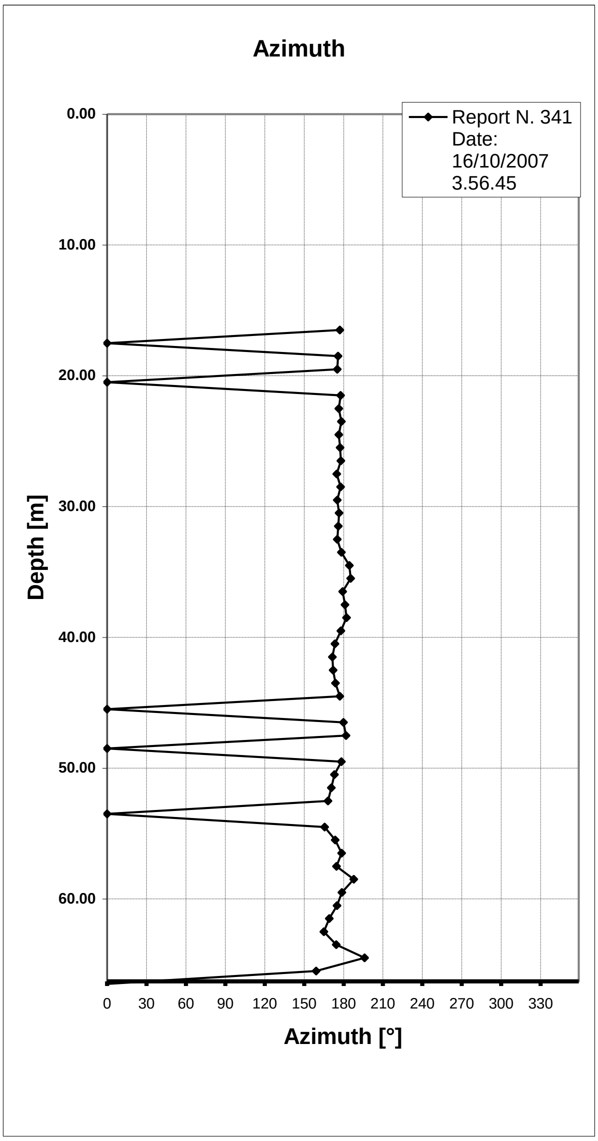
Depth [m]	Displ. [cm]
66.5	0.00
65.5	-0.09
64.5	-0.12
63.5	-0.14
62.5	-0.16
61.5	-0.32
60.5	-0.36
59.5	-0.53
58.5	-0.65
57.5	-0.71
56.5	-0.71
55.5	-0.77
54.5	-0.72
53.5	-0.72
52.5	-0.77
51.5	-0.89
50.5	-0.94
49.5	-1.06
48.5	-1.06
47.5	-1.08
46.5	-1.11
45.5	-1.11
44.5	-1.11
43.5	-1.12
42.5	-1.13
41.5	-1.29
40.5	-1.13
39.5	-1.28
38.5	-1.14
37.5	-1.11
36.5	-1.29
35.5	-1.03
34.5	-1.27
33.5	-2.15
32.5	-2.14
31.5	-2.05
30.5	-2.09
29.5	-2.08
28.5	-2.07
27.5	-2.33
26.5	-2.25
25.5	-2.27
24.5	-2.22
23.5	-2.00
22.5	-2.14
21.5	-2.14
20.5	-2.14
19.5	-2.11
18.5	-2.08
17.5	-2.08
16.5	-2.04

FIGURE 27: SOUTH - NORTH DISPLACEMENT OF THE MIDDLE BOREHOLE 24 NOVEMBER 2006 – 16 NOVEMBER 2007

DMS AKNES middle site

Report N. 341 Date: 16/10/2007 3.56.45

Contractor:	AKNES/TAFJORD PROJECT
Site:	Aknes middle site
Monitoring Interval	16.5-66.5 m
Installation Date	24/11/2006
Project:	48 I modules, 2 IU modules
Note:	HDPE f int = 61.4 mm depth 155 m



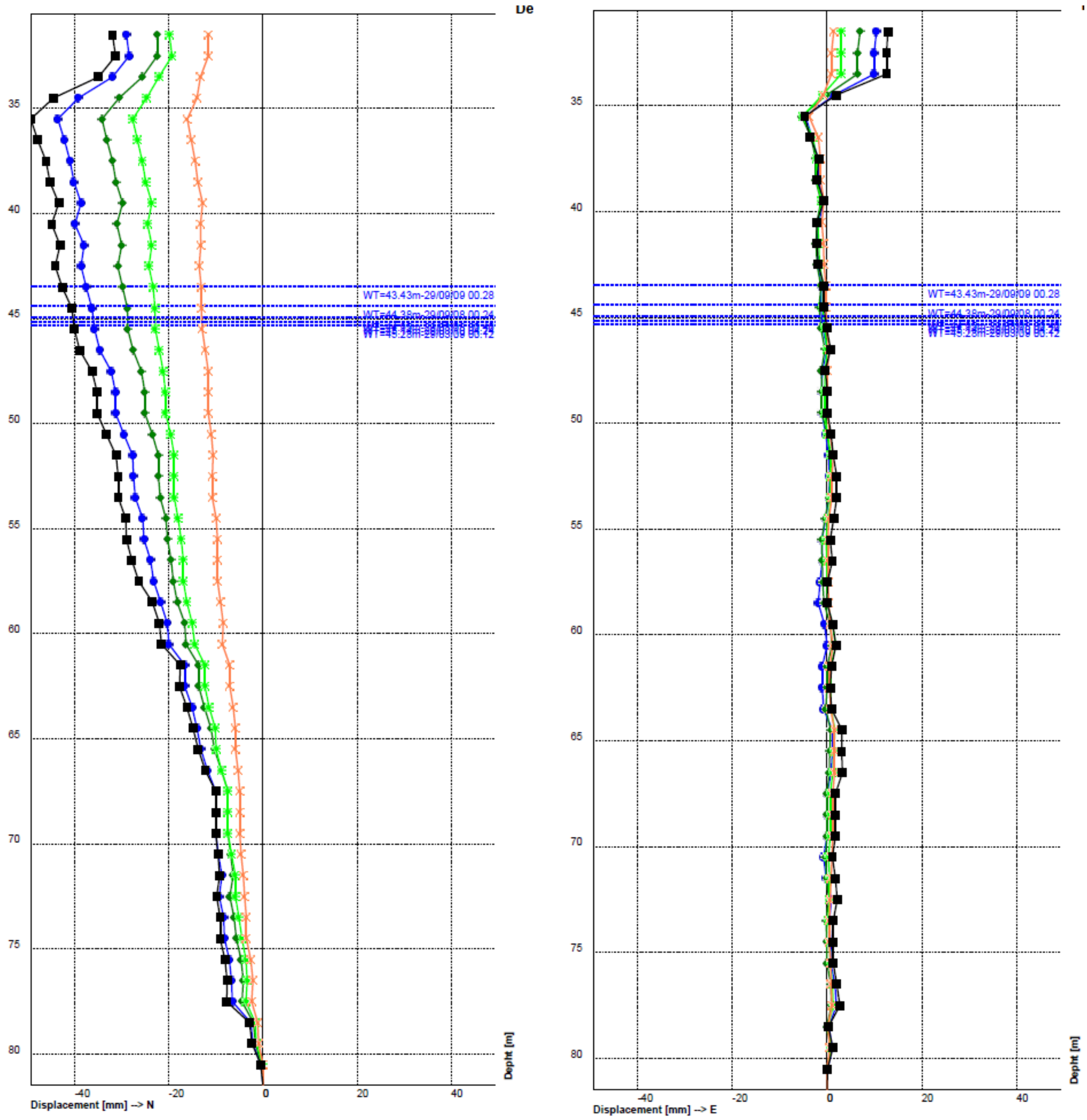
Depth [m]	Azimut [°]
66.5	0
65.5	159
64.5	196
63.5	174
62.5	165
61.5	169
60.5	175
59.5	179
58.5	188
57.5	175
56.5	179
55.5	174
54.5	166
53.5	0
52.5	168
51.5	171
50.5	173
49.5	178
48.5	0
47.5	182
46.5	180
45.5	0
44.5	177
43.5	174
42.5	172
41.5	171
40.5	173
39.5	178
38.5	182
37.5	181
36.5	179
35.5	185
34.5	184
33.5	178
32.5	175
31.5	176
30.5	177
29.5	175
28.5	178
27.5	175
26.5	178
25.5	177
24.5	176
23.5	178
22.5	176
21.5	178
20.5	0
19.5	175
18.5	176
17.5	0
16.5	177

FIGURE 28: AZIMUTH DISPLACEMENT OF THE MIDDLE BOREHOLE, 24 NOVEMBER 2006 – 16 NOVEMBER 2007

FIGURE 29: DRILLING CORE AT 33,5 M DEPTH AT THE MIDDLE BOREHOLE AT ÅKNES, SHOWING A CRUSHED AND BRECCIATED ZONE WITH SILT AND CLAY, REPRESENTING THE UPPER SLIDING ZONE. THIS SLIDING PLANE IS ALSO DOCUMENTED BY DISPLACEMENT IN DMS™ COLUMN (FIGURE 23).

Latest measurements

The present measurements in the middle borehole cover the longest time span of DMS measurements from Åknes, and the displacement has been constant throughout the period (Figure 30). From 80.5 - 35.5 m there was a gentle creep to the south with faster movement in 77.5 and 61.m meters; almost no E-W displacement. From 35.5 m to 32.5 the movement was larger and this is probably a sliding zone. Quite surprisingly the movement in this shear zone was NE and uphill. The total displacement of the column was 34.5 mm which is 14.1 mm/yr. Comparing with the early measurements, showing a pure southward displacement at the sliding plane, we interpret this NE displacement to be an artifact caused by bending of the casing in the borehole. The borehole at this part is filled with gravel around the casing, and this may also allow for bending or buckling.



Movement left = south

Movement right = east

FIGURE 30 MOVEMENT OF MIDDLE BOREHOLE. BLACK: 29 MARCH 2010, BLUE: 29 SEPTEMBER 2009, DARK GREEN: 29 MARCH 2009, BRIGHT GREEN: 29 SEPTEMBER 2008, ORANGE: 29 MARCH 2008.

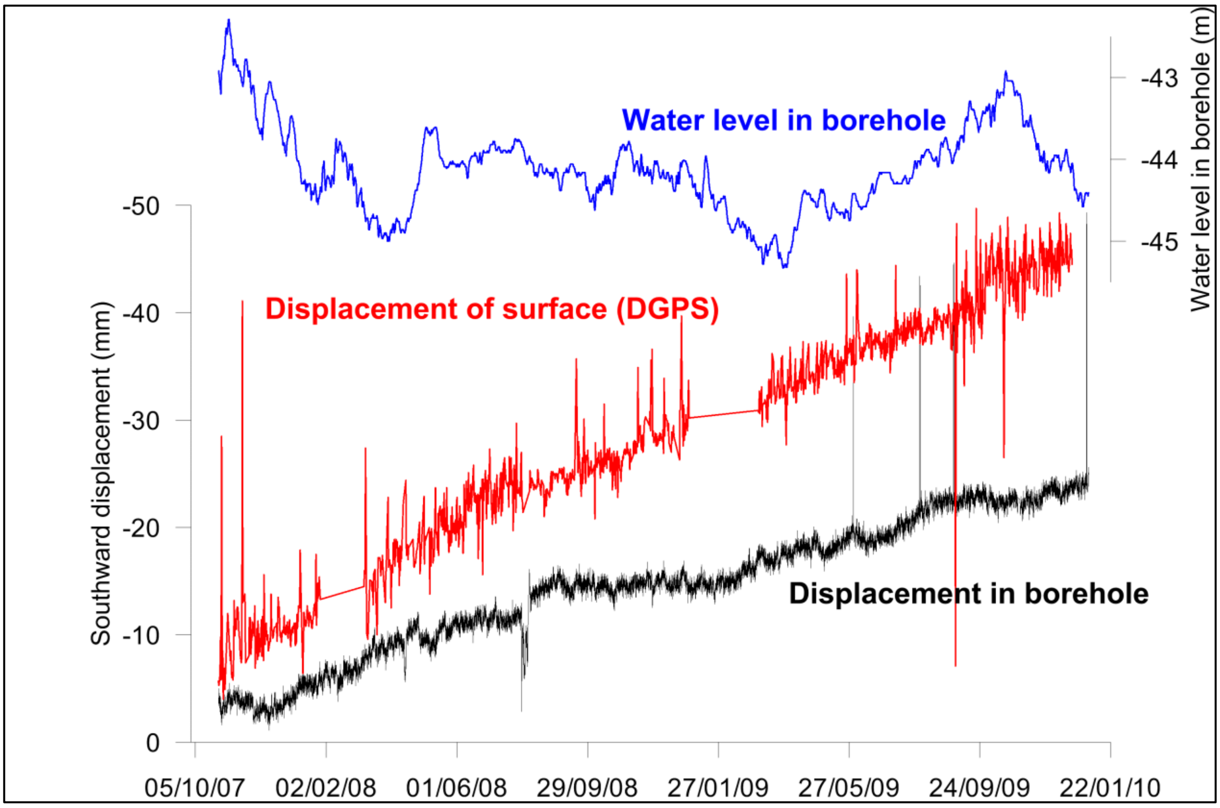


FIGURE 31: THE SOUTHWARD DISPLACEMENT IN MIDDLE BOREHOLE WITH THE EXCEPTION OF THE UPPERMOST MODULES, WHICH PROBABLY SHOW A WRONG DIRECTION OF MOVEMENT. ALSO SHOWN IS THE WATER TABLE AND THE SURFACE DISPLACEMENT AT THE SAME SITE MEASURED BY DGPS.

Figure 31 shows the total southward displacement (except the few upper modules that probably show a wrong direction of movement) together with the water table and surface displacement measured by DGPS. It shows that only about half of the movement is recorded in the borehole, which may be because the upper sliding zone is not included. There is not a very clear correlation between the movement and the water table.

Lower borehole

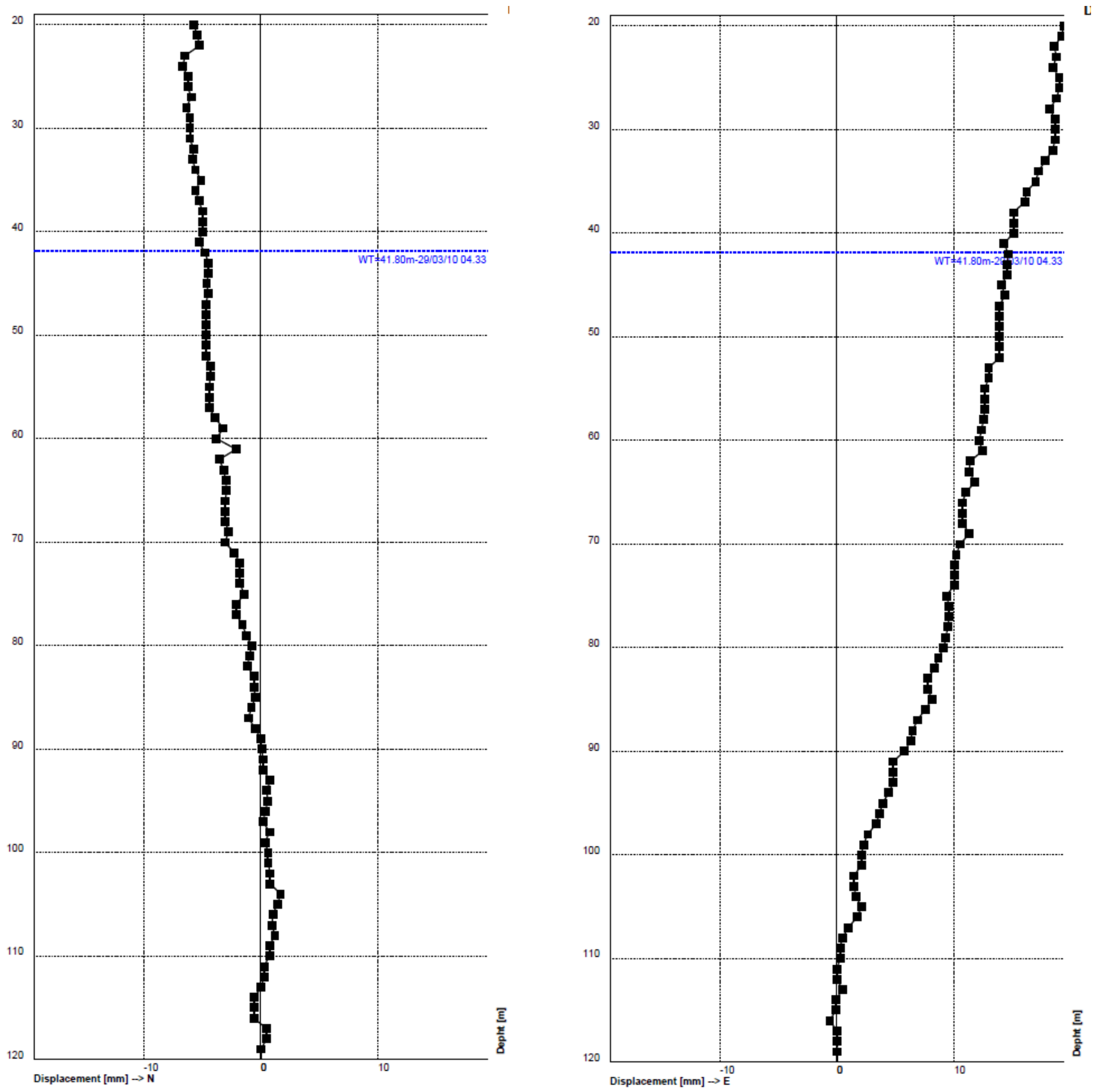
The Lower borehole faces SE. It was instrumented in 2008, but due to lightning damage it only was operative for one month. It was established again in late 2009.

First measurements

The displacement was towards east in the lower part turning towards south upwards. The total displacement was 11.6 mm giving a velocity of 132 mm/year. This is larger than we have seen elsewhere, but the time interval and the absolute scale of the displacement may be too small to infer about the general velocity.

Latest measurements

The data plotted covers only the period 22 December 2009 to 29 March 2010 because of a break in the data-series. The direction of movement was between E NE and S SE, more southerly upwards (Figure 32). While some sensors exhibit greater movement, there is no distinct shear zone, but rather creep throughout the column. The total displacement (cumulative at the uppermost module at 20 m) was 20.2 mm - a velocity of 78 mm/yr. This does not fit with the surface displacement showing nearly stable conditions, and there is a need for a longer time series before firm conclusions about the displacements can be drawn.



Movement left = south

Movement right = east

FIGURE 32: LOWER BOREHOLE. MOVEMENT TOWARDS SOUTH AND EAST FROM 22 DECEMBER 2009 TO 29 MARCH 2010

In Figure 33 the total displacement and the water level is plotted, but a clear connection between the two is not apparent in this short time span.

Comparison of the boreholes

The upper and the middle borehole have shear zones in 50 and 35 m depth respectively, whereas the lower borehole indicates creep throughout the profile. The movement is in general downhill, but surprisingly in large parts of the Upper borehole an uphill movement is recorded in some depths and during some time intervals. This deformation may be due to back movement of individual blocks, see Figure 25.

The velocities of the Lower borehole (78 mm/yr) is greater than for the Middle and Upper boreholes, while most surface measurements show larger velocities further up the landslide. The borehole is located close to GPS 7, which is almost stable. The reason for the large subsurface deformation is not clear, and a longer time series is needed before conclusions can be made. The instrumentation should also cover the upper 20 m in order to be able to compare with surface displacements.

The hydraulic system is well coupled in the boreholes (Figure 34). The water level was lowest at the Upper borehole and highest at the Lower borehole. The water level was highest in the spring-time and decreased throughout the late summer and winter, and Figure 34 suggests that temperature (and thus snowmelt) is more important for the water level than precipitation. A link between the water level and displacement needs to be investigated further.

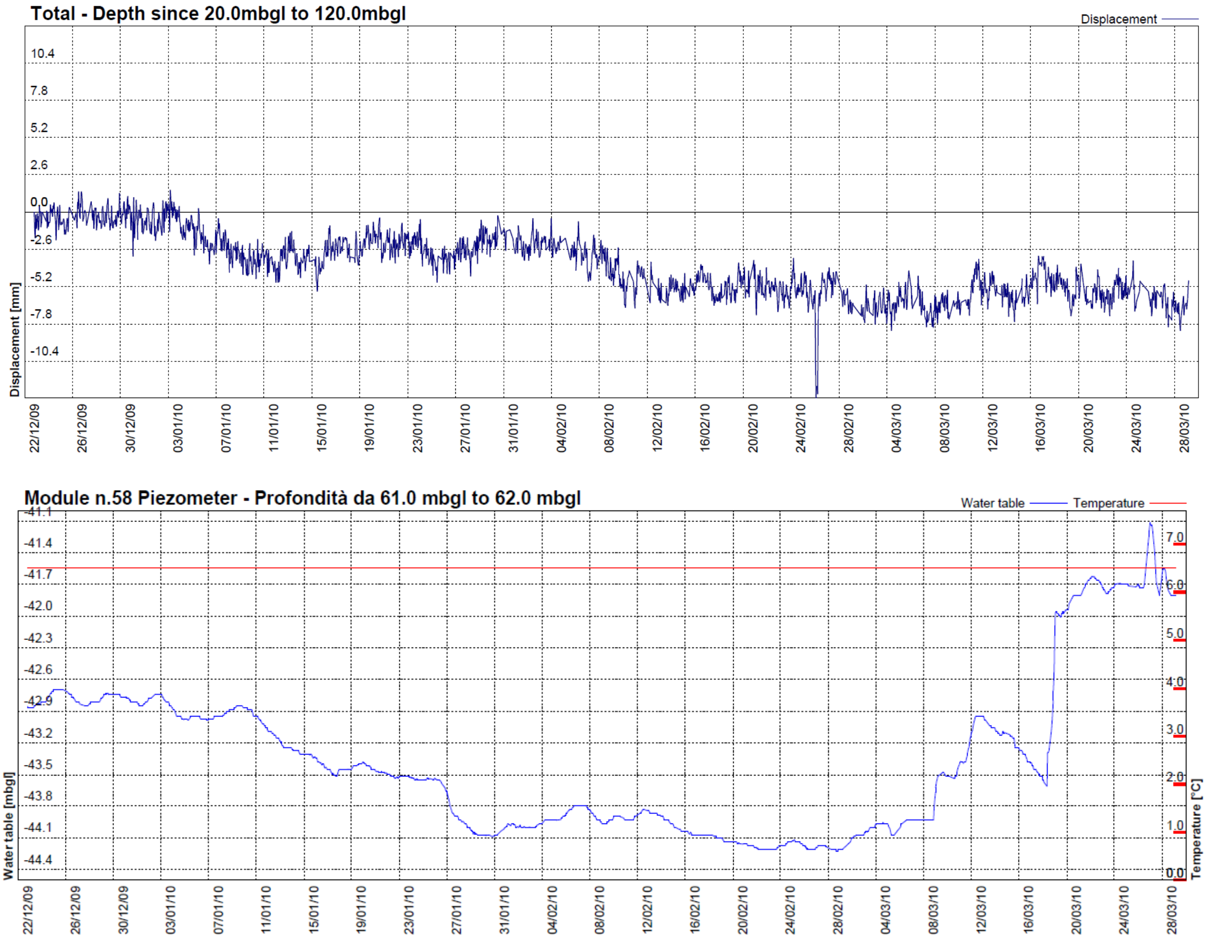


FIGURE 33: LOWER BOREHOLE, 22 DECEMBER 2009 TO 29 MARCH 2010. UPPER: TOTAL DISPLACEMENT OF THE LOWER BOREHOLE; LOWER: WATER LEVEL IN THE BOREHOLE.

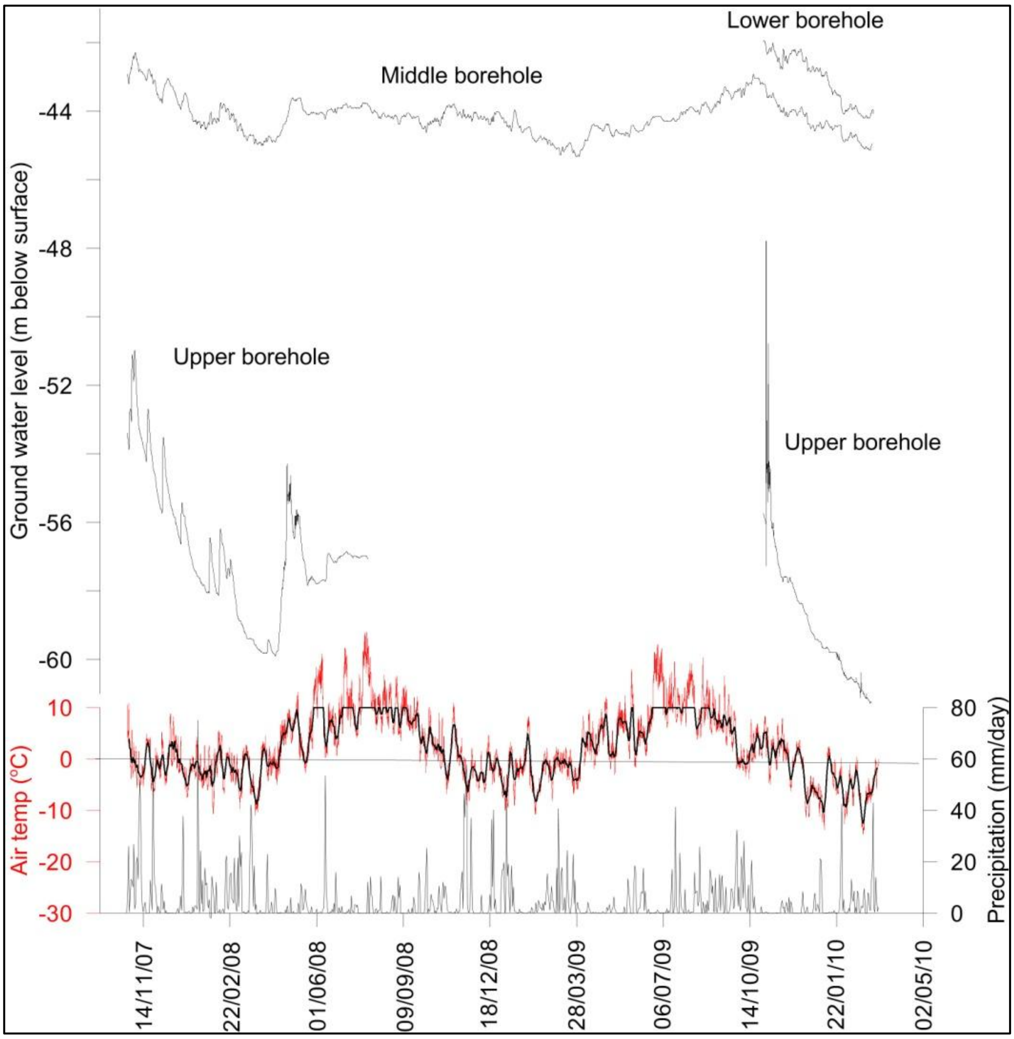


FIGURE 34: THE WATER LEVEL IN THE BOREHOLES FOR THE AVAILABLE TIME PERIODS. AT THE BOTTOM THE AIR TEMPERATURE AND DAILY PRECIPITATION CAN BE SEEN.

Seismic measurements

From the 4 November 2005 seismic activity has been measured on the Åknes landslide by eight geophones installed by NORSAR. Activity in the rockslide will be recorded by the geophones, but the system also records other processes like snow avalanches, rockfalls or regional seismic activity as well as animal or human activity. The seismic data should therefore not be interpreted as an indication of landslide activity alone, but we would expect a large increase in seismic activity during increased velocity or acceleration when the landslide starts accelerating.

Figure 35 shows the number of daily seismic events from the 4 November 2005 to 20 April 2010, recorded by each geophone and summarized. Thus, if a single event was recorded by 6 geophones, it was counted as 6 events on the figure. A seasonal pattern of increased seismic activity as temperature (also plotted) rises above 0° each spring can be seen, which may both relate to increased snow avalanche and rockslide activity. An example of monthly activity can be seen in Figure 36.

A waveform plot of each the records is saved and a study of the waveform may reveal whether certain seismic activity is earthquakes far away, human activity (for instance offshore seismic mapping), snow avalanches or rockslide activity. In Figure 37, 15 seconds waveform plot is shown. Some experience is required to interpret the waveforms and Åknes Early warning Centre obtain help from seismologists from NORSAR for this purpose.

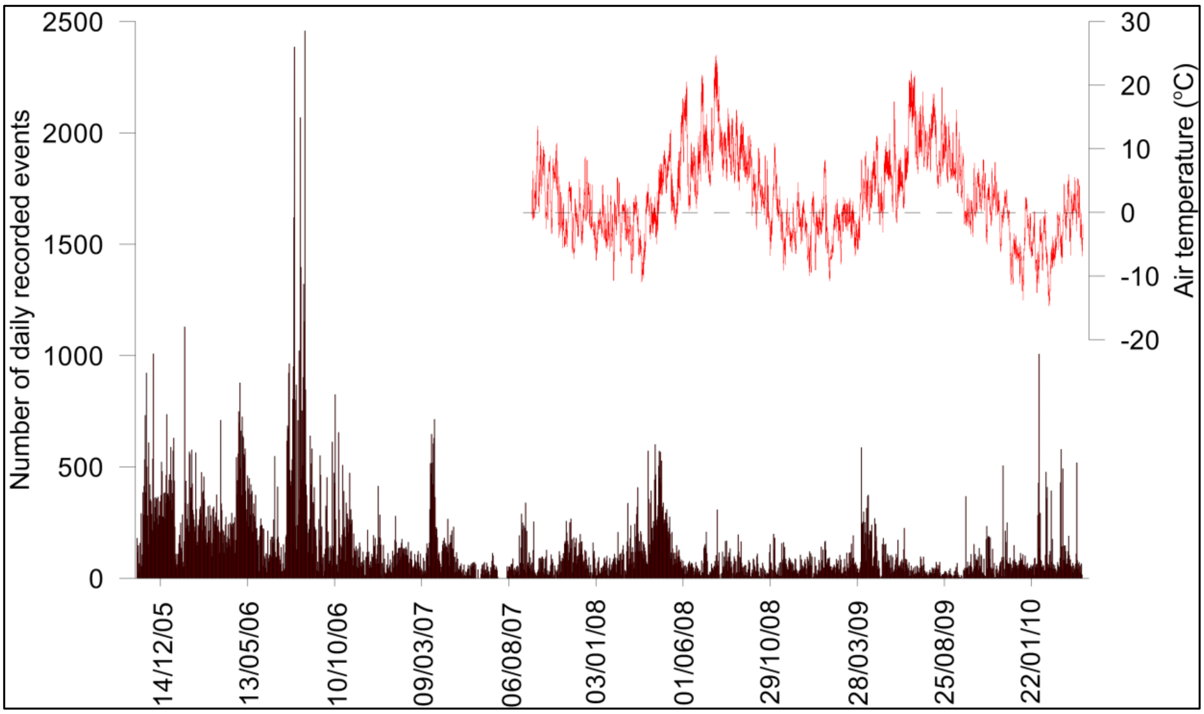


FIGURE 35: SEISMIC ACTIVITY RECORDED BY THE EIGHT GEOPHONES FROM 4 NOVEMBER 2005 TO 19 APRIL 2010. THE PLOT SHOW THE SUM OF DAILY RECORDS SUMMARIZED FOR ALL GEOPHONES. THE AIR TEMPERATURE IS PLOTTED IN RED COLOR AND IT APPEARS THAT THE SEISMIC ACTIVITY INCREASES AS TEMPERATURE RISES ABOVE ZERO DEGREES IN THE SPRINGTIME, WHICH MAY BE AN EFFECT OF INCREASED DEFORMATIONS IN THE ROCKSLIDE AND SNOW AVALANCHES.

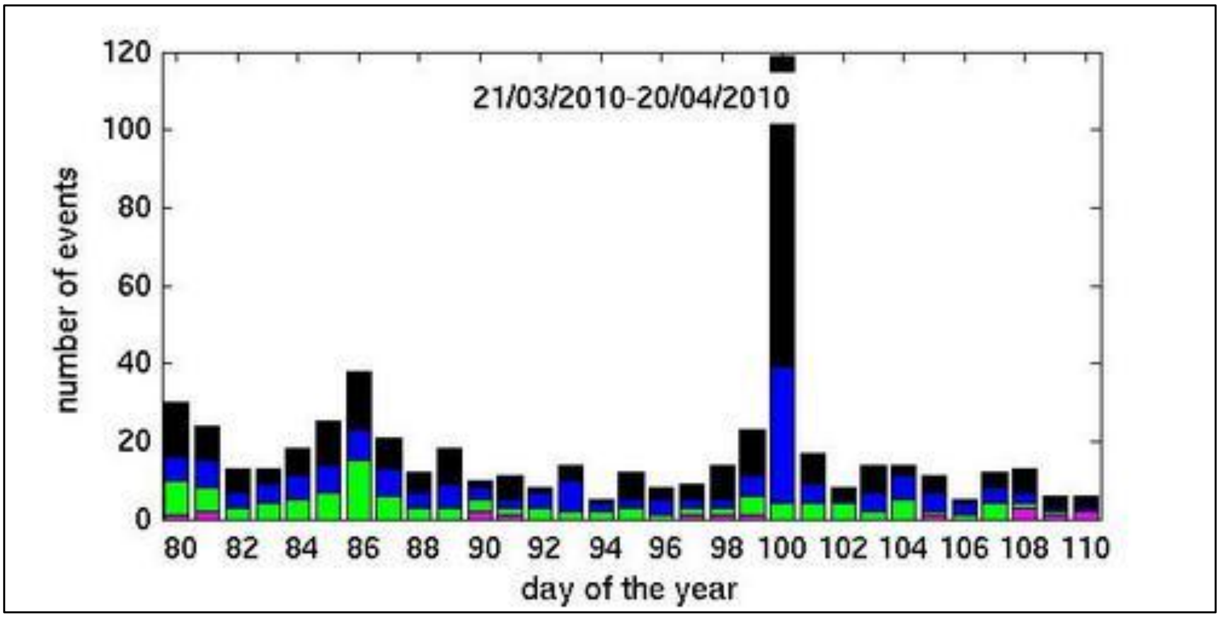


FIGURE 36: NUMBER OF DAILY SEISMIC EVENTS 21 MARCH TO 20 APRIL 2010. THE COLOR CODE INDICATE HOW MANY OF THE GEOPHONES RECORD THE SAME EVENT, WHERE BLACK IS 3 GEOPHONES AND PINK IS 6. THE DATA IS AVAILABLE AT: WWW.NORSAR.NO

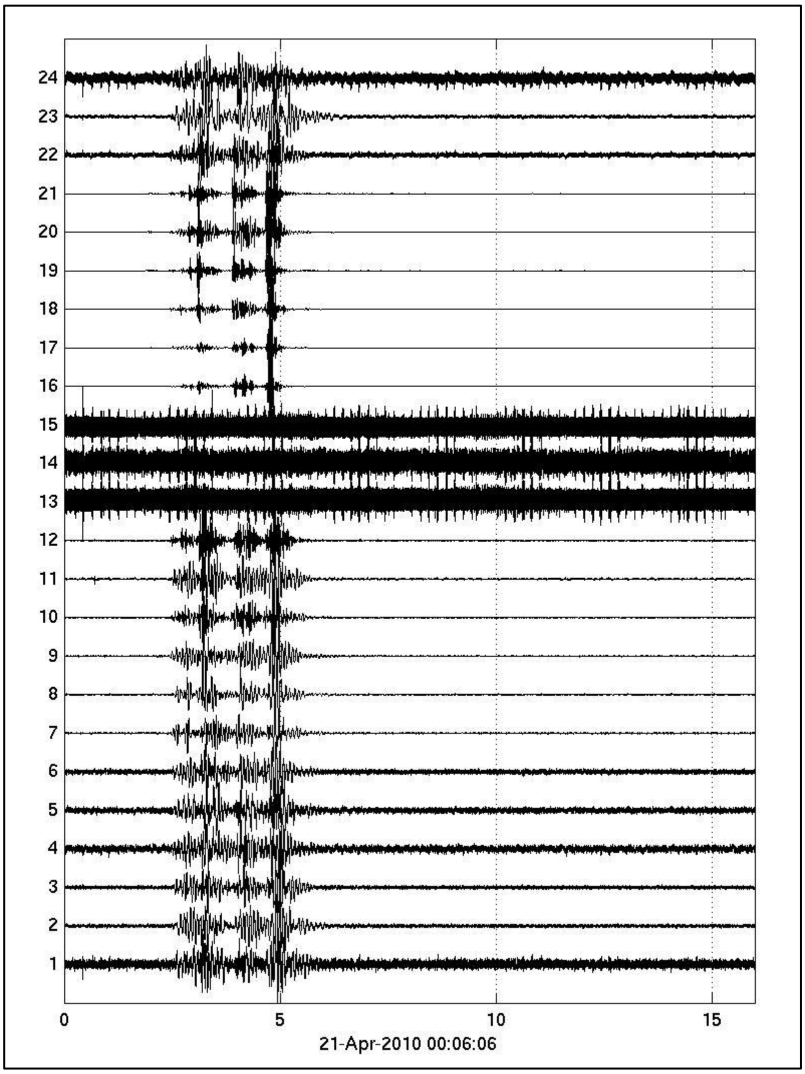


FIGURE 37: WAVEFORM-PLOT OF SOME RANDOM SIGNAL, WHICH WAS RECORDED ON MOST OF THE CHANNELS (NUMBERS ON THE LEFT SIDE). EACH GEOPHONE HAS 3 CHANNELS.

The seismic measurements are expected to work even during rapid movement of the landslide and we expect to see a strong rise in recorded events in an accelerated phase of sliding. It may not be feasible to use the measurements for automatic sms messages, as too many factors other than landslide activity affect the measurements.

Discussion and comparison of all measurements of displacement

A map of the average displacement of all GPS antennas, lasers and extensometers is shown in Figure 38. The direction of displacement of the GPSs was SW for GPS_PL on the uppermost "Fast-moving ridge" (Figure 5) while it was SE for the other antennas. At GPS_PL the downhill displacement was much greater than elsewhere. It may be an additional effect of an anticlockwise rotation of the landslide, which is also suggested by the decrease in extensional cracks towards east which is shown in much greater detail by Kjeldsvik et al. (2008) (using photogrammetry). However – this is contradicted by the measurements with the total station (Figure 8) though these data are probably less reliable. Old measurements by periodic GPS and total station demonstrate a southeast direction of movement in the easternmost part (Figure 39) and the differential movement may be an effect of the rockslide being divided by different blocks with different displacement direction.

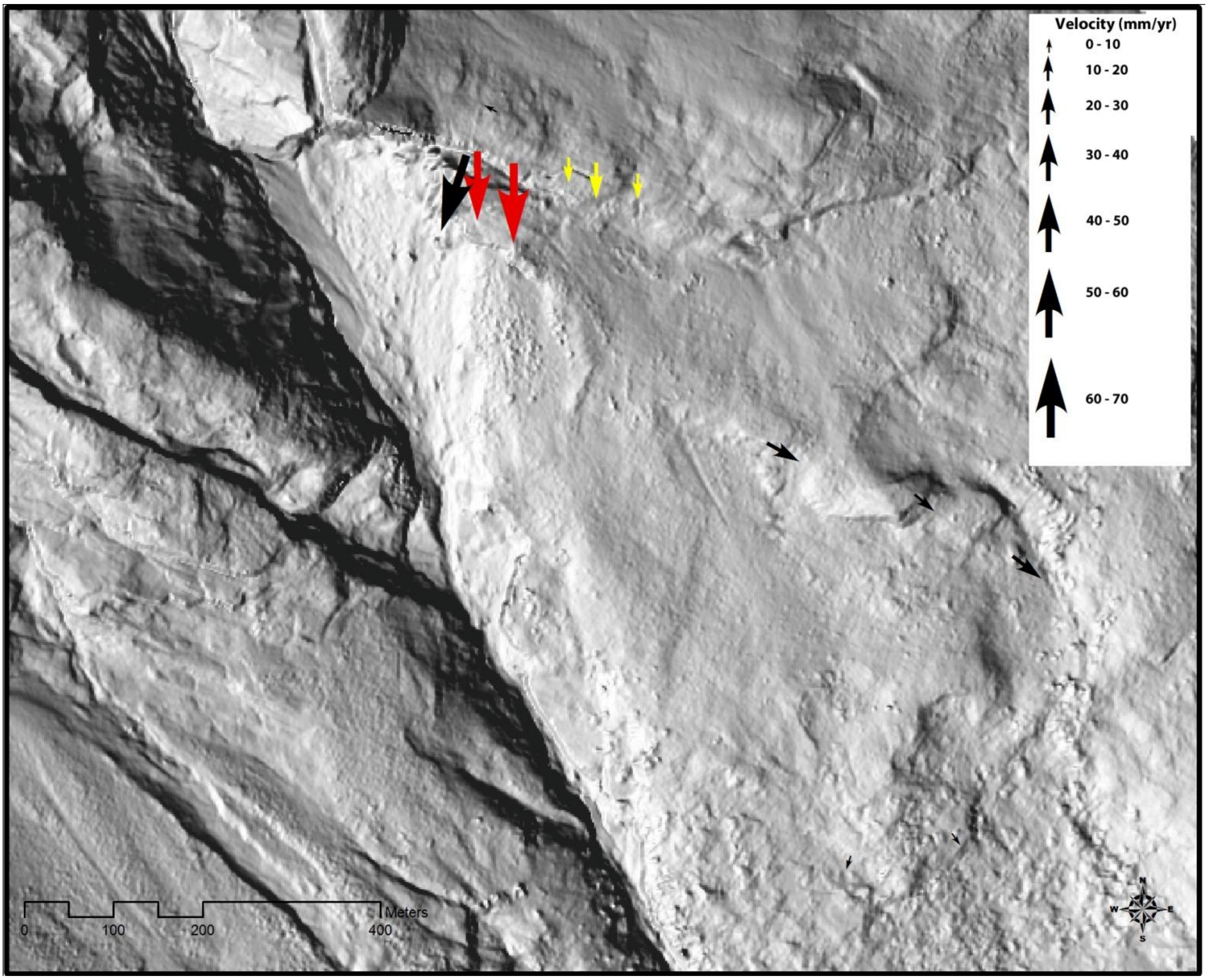


FIGURE 38: DISPLACEMENT OF GPS ANTENNAS (BLACK ARROWS), EXTENSOMETERS (YELLOW ARROWS) AND LASER REFLECTORS (RED ARROWS) WHERE THE MAGNITUDE OF DISPLACEMENT IS SHOWN BY THE SIZE OF THE ARROWS. NOTE THAT WHILE THE ARROWS INDICATE THE DIRECTION OF MOVEMENT OF THE GPS', THE LASERS AND EXTENSOMETERS ARE DRAWN TO MOVE SOUTH, AS WE DO NOT KNOW THE EXACT DIRECTION OF MOVEMENT.

The LiSALab radar measurements should help to delineate blocks of differential movement. One weakness of the measurements is that it only measures displacement in LOS. The interferograms clearly show that the upper and western parts of the landslide are most active, but it is not easy to define blocks within this area. Further down the landslide the results are obscured by vegetation. The LOS for the radar compared with the displacement direction in upper area also show that the movement from the radar is underestimated in this part.

It is important to compare the borehole data with the surface measurements. For the Upper and Middle boreholes it appears that the columns do not capture the total displacement measured at the surface (Figure 26 & Figure 31). At the lower borehole the displacement in the borehole seem to exceed the surface movement. The discrepancies need to be studied further.

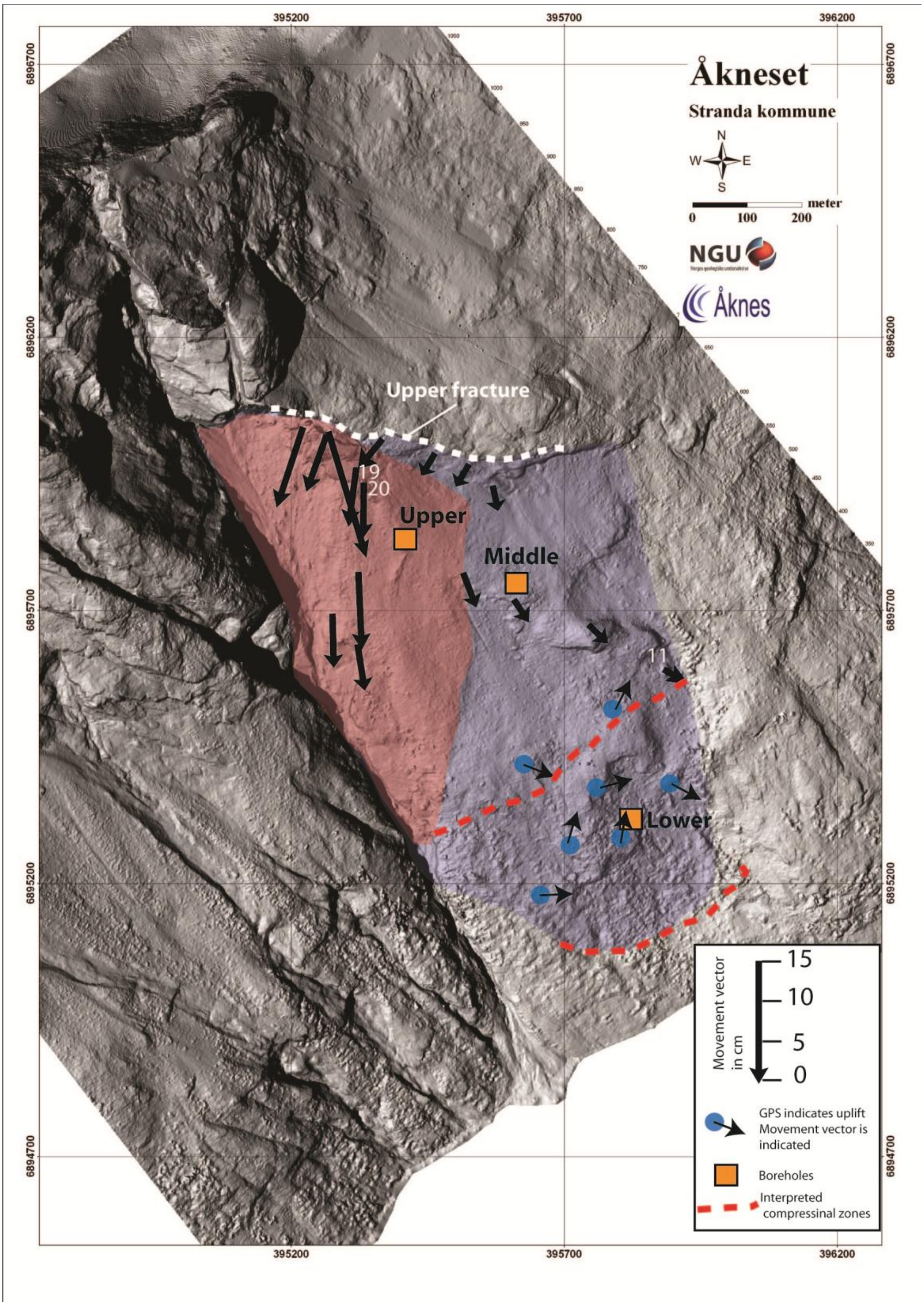


FIGURE 39: THE DISPLACEMENT VECTORS BASED ON PERIODIC MEASUREMENTS BY GPS AND TOTAL STATION UNTIL 2007. THE EXTENT OF THE POSSIBLE UNSTABLE AREA IS SHOWN IN COLOUR. THE FAST MOVING UPPER WESTERN PART IS INDICATED BY RED COLURES, AND THE INTERPRETED COMPRESSIONAL ZONES ARE INDICATED.

Alarm levels and SMS messages

An operative early-warning system needs different alarm levels. All the monitoring data achieved from the unstable areas need to be processed and analysed in order to find movement behaviour and velocity trends. This is the basis for establishing threshold values for the different levels of warning. So far we use velocity and acceleration as the criteria for the different levels (Figure 40).

The velocity threshold will be different from instrument to instrument, also the time period for the threshold. For the extensometer, which is very stable, we can go down to one day or one hour, while the total station and GPS needs much longer time due to larger fluctuations/noise. The normal situation is the green level, were the movement is in the order of 0,1 to 0,2 mm/day, but this increases 5-10 times during the observed seasonal fluctuations (Figure 40). The next level (yellow) is when the velocity trend from the large seasonal changes continues to develop. Orange level is the level when acceleration occurs, and red is the evacuation stage when an event is in progress.

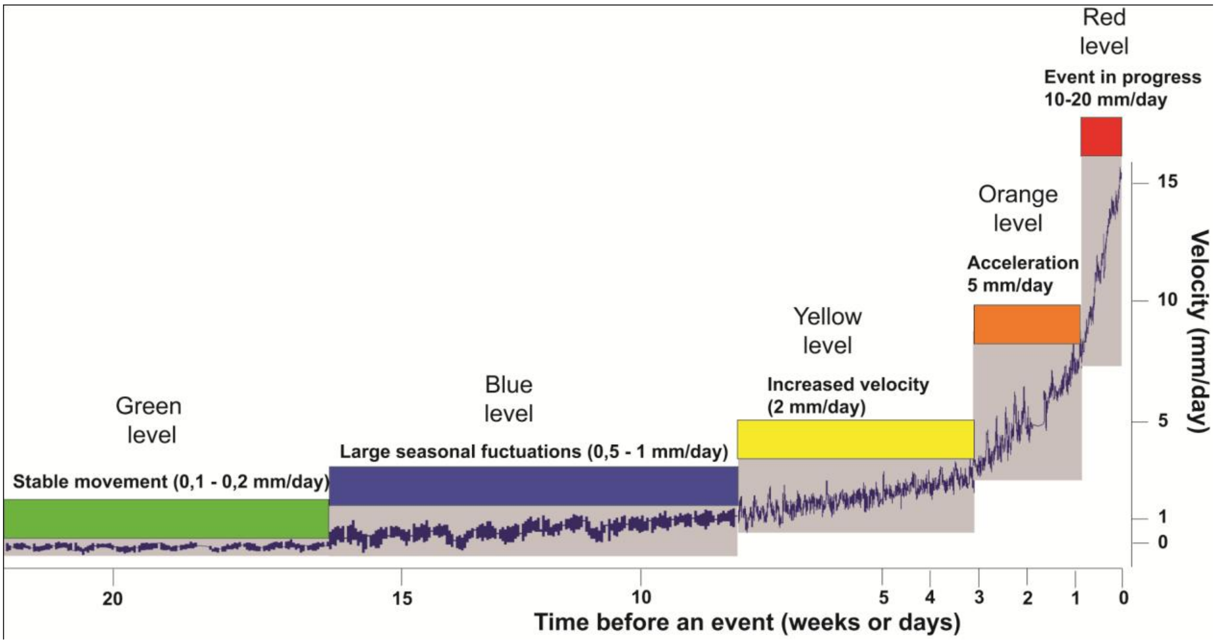


FIGURE 40: A SCHEMATIC DIAGRAM SHOWING POSSIBLE MOVEMENT AT THE UPPER LASERS DURING AN EVENT AT ÅKNES. THE DIFFERENT ALARM LEVELS ARE INDICATED.

The operational system today is based on the following routines:

1. Daily check of all sensors by the person on duty
2. Data check by geologist on duty
3. SMS messages on selected sensors
4. Contracts with monitoring companies with different types of operational level (SMS messages, daily check, availability etc)

SMS messages and/or e-mail messages are a difficult task and one main issue is to find the different types of noise in the data and finally to define thresholds that:

1. Not give too many false alarms.
2. Are able to catch real events
3. Provide adequate warnings

SMS messages will never be used alone to change alarm levels, but is an important support and help for the persons on duty. Table 4 gives some preliminary levels for SMS messages that are and will be used for testing. Lasers, extensometers and GPS are already in the testing phase. One of the challenges is that sensors with large noise levels create a large amount of messages (e.g. the single lasers). The DMS system in the boreholes is very stable and SMS messages have been implemented for a long time.

Sensor type	**Normal movement / seismic events / water level**		**Noise level (mm)**	**SMS threshold (mm/day)**
Extensometers	16-25 mm/year	< 0,2-0,3 mm/day	1,5 – 3 mm	1,5-3 mm
Crackmeters	1-3 mm/year	< 0,1 mm/day	0,5 mm	0,5 mm
Lasers	50-70 mm/year	0,1-0,2 mm/day	3-30 mm	3 - 7 mm
Total station	10-60		5-20	20 mm
GPS	1-65 mm/year	< 0,1 - 0,25 mm/day	10-30 mm	15-20 mm
DMS (single inclinometers)	30 mm/year			1,3 mm or 0.1°/m
Seismic events		2-30 events		50 events
Water level (DMS)				2 mm

TABLE 4 OVERVIEW OF SOME OF THE MONITORING SYSTEMS WITH PRELIMINARY THRESHOLD VALUES FOR SMS MESSAGES.

Conclusions

Numerous instruments measure the movement in the Åknes rockslide. The extensive multi-sensor instrumentation at Åknes has been established on the basis of need of redundancy, the large consequences of failure and the regulations in Norwegian building codes. Especially important is the need of having enough knowledge to provide a safe early warning to the public. Raising a false alarm may also decrease the Åknes Centre’s credibility and should be avoided if possible.

The new data from the deep monitoring at upper borehole may indicate that movements can occur deeper than earlier expected (below 130 m deep). The need for deeper instrumentation needs to be followed up.

We still need more focus on evaluating the levels of movement that trigger SMS messages for individual sensors, in addition to threshold values for alarm levels.

This report is a base for the evaluation by the established advisory group for the Åknes/Tafjord Early Warning Centre.

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