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SUBSURFACE MONITORING OF LARGE ROCKSLIDES IN NORWAY: A KEY REQUIREMENT FOR EARLY WARNING

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ABSTRACT

The risk posed by large rockslides in Norway is due to long run-out, the possibilities for river damming and the generation of disastrous tsunamis in fjords. The investigations, monitoring and early-warning that have been designed and implemented for the Norwegian rockslides follows strong requirements guided in national codes.

Extensive investigations and implementation of relatively dense sensor network is needed in order to achieve reliable and robust monitoring of large and complex rockslides. The Norwegian codes have strong and specific requirements for using early-warning to reduce risk. The need of gaining sufficient knowledge is especially important for the operative handling of the total early-warning systems.

Subsurface borehole logging and instrumentation is a mandatory part of the requirements. A real-time instrumentation with a continuous coverage from the surface and down to potential sliding planes of the rockslides is implemented for the Norwegian examples. These example shows that the multiparametric borehole probe DMS used in these cases can be regarded as a geotechnical lab within the rockslide, and gives in detail crucial data about deformations, water-pressure and temperatures at the active zone. This are considered to be critical data during an acceleration phase.

KEY WORDS: *Early warning, rockslides, instrumentation, subsurface monitoring, displacements*

INTRODUCTION

The risk posed by large rockslides in Norway is due to long run-out, the possibilities for river damming and the generation of disastrous tsunamis in fjords (BLIKRA *et alii*, 2006).

In order to have a good understanding of large and complex landslides it is of vital importance to achieve subsurface geological data, including the depth of the instability and the related deformation. Borehole instrumentation is essential for both the investigations of subsurface characteristics (sliding planes, depth, etc) and for real-time operative early-warning. In Norway, three large rockslides have been instrumented by the multi-probe DMS system (Differential Monitoring of Stability), which can be used both in the investigation phase and later in the real-time operational monitoring.

Subsurface instrumentation have been established at the Åknes rockslide (BLIKRA, 2012), the Mannen rockslide (KRISTENSEN & BLIKRA, 2011) and at the Jettan rockslide in northern Norway. Examples will be given from the Åknes and Mannen rockslides in western Norway (Fig. 1).

REQUIREMENTS AND CONCEPTS OF SUBSURFACE MONITORING

Subsurface instrumentation and monitoring are important both for the investigation stage and for successive real-time early monitoring and early warning (BLIKRA & KRISTENSEN, 2011). No guidelines or handbooks exist, which define specific requirements for the type and level of investigations needed in order to perform reliable monitoring and early-warning of large landslides. However, the European Standard EN 1997-2:2007 (Eurocode 7) describes principles and requirements related to geotechnical design and ground investigations.

The regulations in the Norwegian technical building codes (TEK §7-4) from 2010 introduces some major requirements that are needed to be fulfilled in order to allow further construction and development in tsunami hazard areas generated by large rockslides. The population safety needs to be taken care of by real -time monitoring, warning and evacuation. The warning time shall not be shorter than 72 hours and the evacuation time shall be maximum 12 hours. The notes linked to the regulations also include specific terms related to the monitoring and early-warning systems:

- A system for daily continuous monitoring of the conditions, e.g. by measurements of displacements. Independent monitoring instruments and duplicate data communication systems must be implemented. The early-warning system needs to be based on real-time monitoring, without long time delay.

- Need of sufficient competence for management of monitoring network and interpretation of results on a daily and continuous scheduling.

- Demand of sufficient personnel and competence for safe and reliable monitoring, warning and evacuation systems.

- Continuous operation of the monitoring systems, for example technical supervision of sensors, power supply, communication systems and signal transmission etc.

-The warning time must be sufficiently long in order to ensure a proper evacuation. The warning time shall never be less than 72 hours. Evacuation of people in the hazard zone must be ended in due time before the expected rockslide event.

Fig. 1 - The monitored rockslides in Norway (Åknes, Hegguraksla, Mannen and Jettan)

These restrictive and specific regulations and terms require availability of a daily operative geological competence. It is also clear that it puts extensive demands on the level of knowledge which will be the basis for geological interpretations. In our opinion, an extensive investigation program and implementation of surface and subsurface monitoring systems are needed in order to fulfill these requirements (see also Blikra & Kristensen, 2011).

Therefore, the implementation of surface and subsurface monitoring systems related to large and complex rockslides in Norway are mainly based on the national technical building codes, but the guidelines in the international standard Eurocode 7 have been important. It has to be stressed however, that the final design of the investigations and monitoring must be based on the local conditions.

The design of the investigation program is important for several critical issues. Firstly, the rockslide scenarios need to be defined as the base for rockslide and tsunami modeling. Secondly, the position and distribution of the unstable area and the displacement pattern are the most important sets of information for the final design and implementation of a proper monitoring system. Thirdly, a reliable knowledge platform is needed in order to perform reliable and real-time operative monitoring and early warning. The understanding of the deformation dynamics is especially important during critical events, when decisions regarding alarm levels and evacuation have to be taken on relatively short notice. In order to reach a good understanding of the landslide it is of vital importance to achieve subsurface geological data, including the depth of the instability and the related deformation. The investigations should provide data for a realistic

3D geometric model of the instability. Therefore some selected borehole drillings combined with geophysical investigations and instrumentation are required in order to investigate and monitor active displacements.

SUBSURFACE MONITORING TECHNIQUE

Borehole instrumentation is essential for both the investigation of subsurface characteristics (sliding planes, depths, etc) and for real-time operative early-warning. The Norwegian site characteristics with steep slopes and harsh environment lead to very costly drill holes, since all transportation is by air lift and the water supply for core-drilling is often complicated and costly. It is thus important that the expensive drill holes can be used for multipurpose in terms of instrumentation. The concepts that have been chosen for the Norwegian borehole instrumentation have the following requirements:

- be used both for investigation and later real-time monitoring. This means that it must be a flexible system to be used in several portions of the boreholes;
- allow to measure several parameters (displacements, water pressure, temperature);
- be easy to install, robust and capable to survive as long as possible inside the borehole;
- provide real-time data and as much as possible remote controlled.

At Åknes and Mannen, four boreholes have been instrumented by the DMS system (Differential Monitoring of Stability, Lovisolo *et alii*, 2003). This system meets the requirements and specifications listed above. The DMS column is like a sensorized spinal cord or long, thin, bundle of hard tubular modules connected to each other by specially designed joints (Fig. 2).

The adopted DMS systems are 100 to 120 m long columns measuring the movement in 2D. The 120 m long columns consists of a total of 245 sensors. The sensors include biaxial inclinometers, temperature sensors as well as piezometers and digital compasses in selected modules. The DMS system has a very robust structure in order to support high pressure, traction and deformations. Each module contains all the electronic devices for measurement, control and digital transmission. The special 2D/3D strong and flexible joints allow continuous adaptability to bending and twisting of the drilling hole, whilst maintaining rigorously the orientation with respect to a reference system defined during installation. All the cables are inside the case and joints, so providing a complete protection from external environment.

THE ÅKNES ROCKSLIDE

The Åknes rockslide is located on the northwest flank of Sunnylvsfjorden in western Norway (Fig. 1). It has an estimated volume of up to 54 Mm^3 and is moving at a velocity of up to 8 cm/year. The risk is associated with the generation of catastrophic tsunamis, having run-up potential of up to 80 m in nearby villages (Blikra, 2012; Glimsdal & Harbitz, 2011). The rockslide is located in the Western Gneiss Region and is seated in medium-grained granitic and granodiorite gneiss of Proterozoic age (Braathen *et alii*, 2004; Ganerød *et alii*, 2008). The gneiss has well developed foliation and mineral banding (Braathen *et alii*, 2004) and numerous centimetre to decametre-scale, close to tight folds. At Åknes, biotite-rich layers up to 20 cm thick coincide with zones of high fracture frequency (Ganerød *et alii*, 2008). The foliation generally dips parallel to the slope surface. Well defined, very steep, sharp folds are related to the tension cracks at the top of the landslide (Ganerød *et alii*, 2008; Jaboyedoff *et alii*, 2011).

Morphological investigations have revealed several characteristic features of the landslide (Fig. 3), including a prominent upper fracture system that can be followed for more than 500 m.

The slope-parallel foliation and weak biotite-rich layers control the large-scale displacement dynamics. A large depression or graben has developed in the upper west corner of the rockslide (Fig. 3), with a total vertical displacement of 20-30 m. Tension cracks are also present in the upper and the middle parts of the slope.

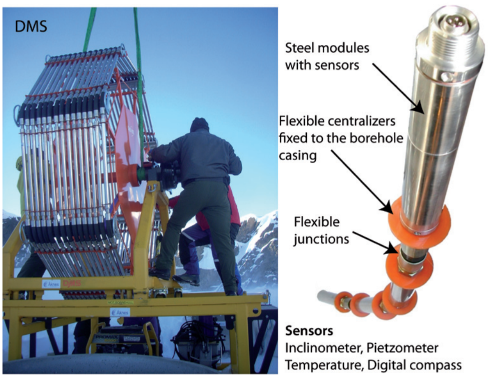

Fig. 2 - The DMS borehole installation of a 120 m long column at Mannen (left) and an overview of the system (right)

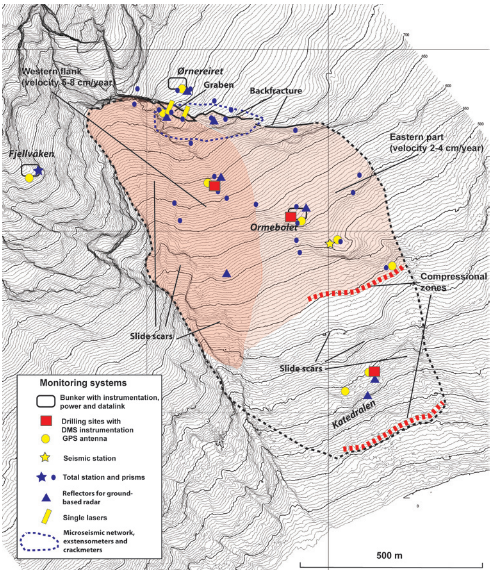

Fig. 3 The Åknes rockslide with the main scenarios in different colors, geomorphological features and the instrumentation (modified from Blikra, 2012)

Prominent slide scarps characterize the east side of the deep canyon that defines the western landslide boundary. Small slide scars also characterize the lower part of the rockslide. Springs discharge water at the lowermost part of the slope at about 100 m asl, and smaller springs are located in the middle part of the landslide (Frei, 2008).

The surface monitoring system is based on extensometers/crackmeters, tiltmeters, single lasers, GPS, a total station and a microseismic network, in addition to a meteo station (Fig. 3). Large efforts have been paid to the establishment of subsurface investigations and monitoring systems in deep boreholes. Deep core drillings down to 200 m depth were completed at 3 localities (Fig. 3), with geophysical logging and core logging (Ganerød *et alii*, 2007). In addition to the geophysical logging (e.g. temperature, conductivity, resistivity, velocity), several methods were applied for identification and characterization of groundwater flow in the boreholes (Rønning *et alii*, 2006; Thöny, 2008).Three boreholes have been instrumented with 100 to 120 m long DMS instrumentation (see location in figure 3 and depth data in Figs 4 and 5).

The DMS data has documented a well-defined upper sliding zone in two boreholes at depth of 35 and 50 m depth. This is above the water-level measured in open standpipes. The displacements from the last two years in upper borehole are shown in figure 4. The largest deformation is seen at 49-50 m depth, and the differential displacements along the axis of movement direction (SW, 225°), show a total annual displacement of nearly 3 cm/year. Some less-pronounced sliding planes are also seen at 9-10 m, 28-30 m and 40-42 m depth (Fig. 4). At the moment the deeper sectors seem to be stable.

The mode of deformation varies from continuous

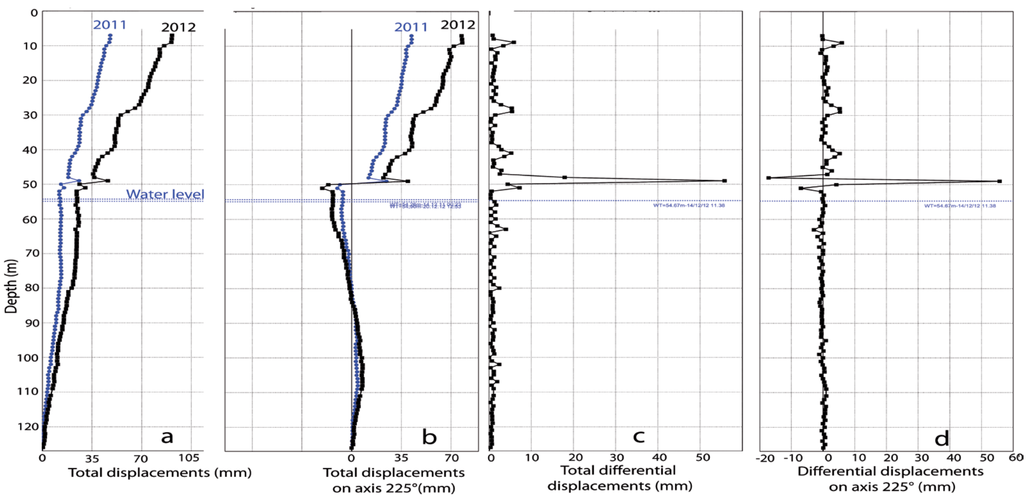

Fig. 4 - An example of recent DMS data from the upper borehole at Åknes measured in the period 22nd of November 2010 until the 14th of December 2012 (see location in figure 2). a) total displacements, b) total displacements along the main sliding direction towards SW , c) the differential displacements and d) the differential displacement in the main sliding direction (right). It clearly documents the sliding zone at 50 m depth, in accordance with core and borehole data. Note also several sliding zones on shallower depths

displacements through time to suddenly and abrupt steps in movement rates. The advantages with real-time monitoring along the entire depth of the rockslide are the possibility to observe in detail at a certain time and depth windows, what happen along the sliding surfaces. This is exemplified with the DMS data for sensor 77 at 49-50 m (see Fig. 4) depth together with the water-level fluctuations and temperatures measured in the same borehole (Fig. 5). An increase in deformation along the sliding plane occurred in late March 2011, followed by a sudden increase in the water level (7 m) at the 2nd of April 2011. The temperature also dropped by 1°C at the same time, indicating inflow of water from snowmelt. After the peak the water-level dropped again some meters and stabilized nearly 5 m higher than before the event. The displacement continued at the same rate for a long time. This event can be explained with an internal change in fractures opening due to the deformations, which has led to a change in the hydrological conditions. The stabilized higher water level led to a general increase in displacement of about 50% compared to the years before, and demonstrates that the stability conditions can be changed drastically due to the internal dynamics of the rockslide. This highly unstable area of the rockslide is presently carefully followed, and we are especially concerned about the situation during the snowmelt periods. A new borehole drilled in 2012, close to the upper site, documented a 40 cm thick breccia at 63 m below ground surface that seem to be correlated to the 49-50 m zone. This indicates that a large collapse of the south-western flank could also occur as one large event (Fig. 3). The DMS instrumentation is like a geotechnical lab that gives us the possibility to study and follow in detail the internal deformations, water-pressure and temperature conditions.

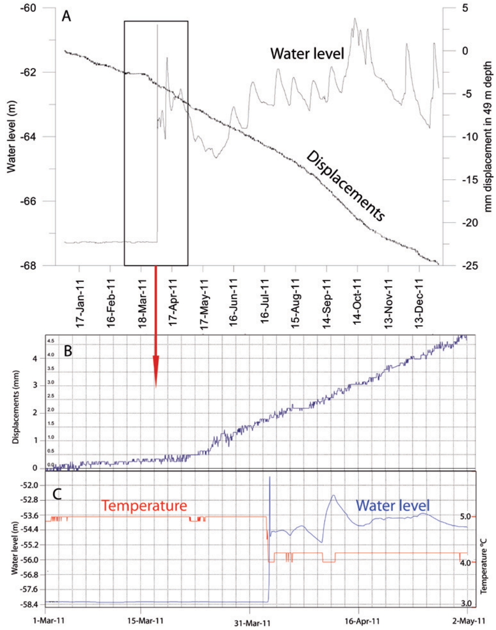

Fig. 5 - Time line for sensor 77 at 49-50 m depth at the upper borehole at Åknes, see location in figure 2. The upper curve shows the displacement and water level in 2011, while the lower diagrams show displacement, water level and water temperature for the selected time period between the 1st of March until 2nd of May 2011. Note that the increased displacements start about one week before the increased water level and lowering of water temperature

THE MANNEN ROCKSLIDE

Mannen is a 1295 m high mountain which is a part of a plateau above the steep, glacial eroded Romsdalen valley in western Norway. A part of the plateau (100 mill. m^3) towards the valley is bounded by deep clefts indicating past movement, but most of this seems not to be active today. A portion of the outer edge, of possibly 15-20 million m^3, moved downslope 15-20 m from the plateau, and a smaller part of this (2-3 mill. m^3) shows an annual displacement of 2-5 cm dipping 45-50 against ENE (Fig. 6). These blocks are the basis of the proposed scenarios A and B in Fig. 5 (Dahle *et alii*, 2011). Runout modelling shows that a rockslide would destroy the road and railroad at the valley bottom as well as some farms. Furthermore, the rock debris may dam the river Rauma, with a subsequent risk of dam collapse and flooding downstream of the river.

The bedrock consists of Proterozoic gneiss (Saintot *et alii* 2011) with structural weaknesses from the tectonic deformation. At the top, where the main backcrack developed, foliation is near vertical. In the upper part of the moving area, a borehole showed foliation dipping about 30° to the north and downslope, but further down the pattern is more complex, as the gneiss is intensely folded. The bedrock within the instability is extremely fractured. The morphology is characterized by the well-defined backscarp and numerous smaller slide scars (Fig. 6). These smaller scars indicate multiple recent rock falls or smaller rock avalanches.

A 137 m deep borehole was drilled in the upper part of the instability, see Fig. 6. Core logging demon-

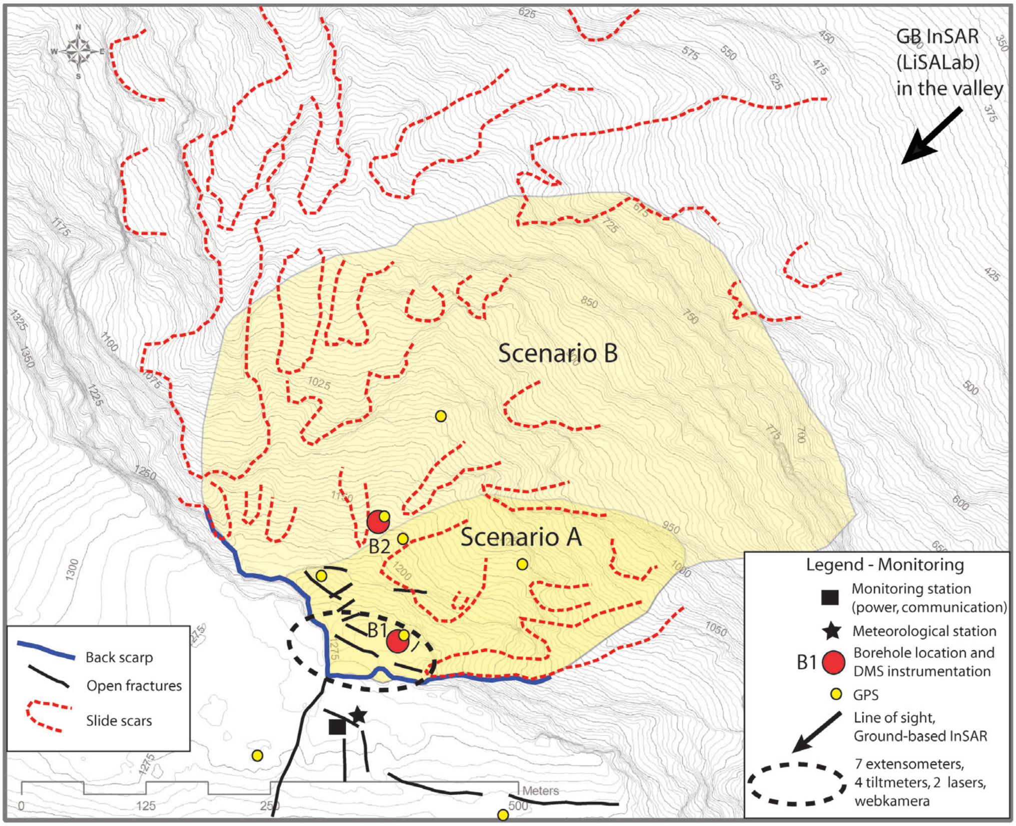

Fig. 6 - The Mannen rockslide located on the south-western side of the valley Romsdalen. The two scenarios, A & B are indicated in yellow as well as the position of the GB InSAR system in the valley

strated that the bedrock is highly fractured to a depth of 113 m, with several levels of breccia as well as bedrock crushed to silt fraction. It was instrumented with a 120 m long DMS column, measuring displacement or tilt every meter (Fig. 7).

The displacement pattern during a 15 months period between 2011 and 2012 along the DMS column in the upper borehole is shown (Fig. 7). Sliding planes are clearly defined at 24 and 28 m depth, where also the recovered borehole core and the televiewer logging revealed well-defined breccias (Fig. 7, middle). However, at the moment we cannot exclude the presence of other sliding planes at greater depths. The movement along the sliding planes is towards NE, and this is in accordance with the surface GPS displacement data (Kristensen & Blikra, 2011). The piezometers installed in the column show that the entire borehole is dry, and the temperature conditions during the winter is close to 0. This indicates that the temperature regime at the locality is close to permafrost conditions.

The time-line data (Fig. 7, upper right) from the sliding at 24-25 m depth shows increased displacement starting during the snowmelt period from late May to middle June. In general, the displacement rate is limited during the winter time, and the increased velocity in late spring is interpreted as an effect of water seeping into fractures and percolating along the sliding planes reducing the shear strength even if the main landslide body remains prevalently dry.

CONCLUSIONS

Extensive investigations and implementation of relatively dense sensor network is needed in order to achieve reliable and robust monitoring of large and complex rockslides. The Norwegian codes have strong and specific requirements for using early-warning system to reduce risk. The need of sufficient knowledge is especially important for the operative handling of the total early-warning system.

Subsurface borehole data and instrumentation is a

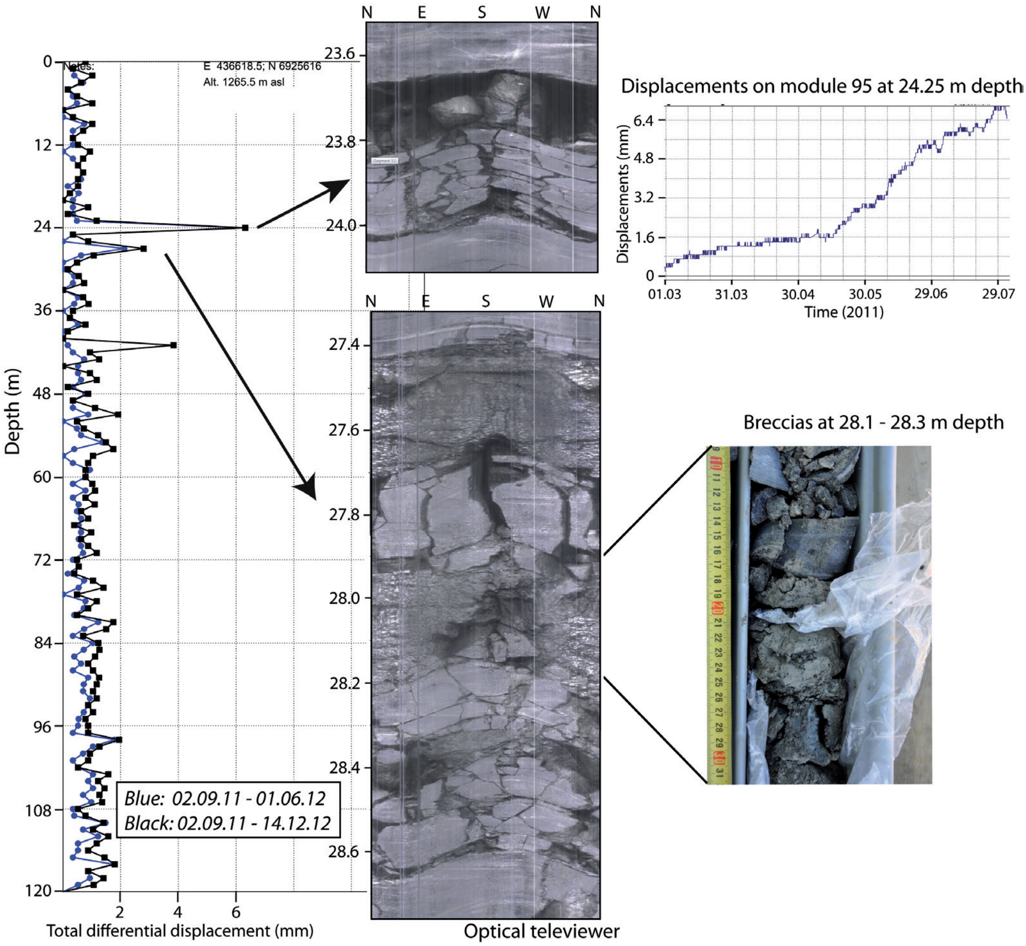

Fig. 7 *Data from the upper borehole at the Mannen rockslide. DMS depth data from the 2nd of September 2011 until the 14th of December 2012 (left), televiewer images (middle), a time history from the sensor at 24-25 m depth (upper right) and a photo of the clay-rich breccia at 28 m depth (lower right). Note the documented displacements at 24 and 28 m depth. The displacement spike at 41 m might be due to a problem with one of the sensors. The televiewer images are oriented and show also the dip and direction of foliations, fractures and breccias. The images show that the sliding planes dips towards N-NE*

vital part of the requirements. A real-time instrumentation with a continuous coverage from the surface and below potential sliding planes of the rockslides is implemented for the Norwegian examples. The subsurface monitoring has given critical data for the evaluation and revision of scenarios (depth and volume), and for the understanding of deformation mechanisms and seasonal changes. These example shows that the DMS instrumentation used in these cases can be regarded as a geotechnical lab within the rockslide, and gives in detail crucial data about deformations, water-pressure and temperatures at the active zone. This will be critical data during an acceleration phase.

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REFERENCES

Blikra Lh. (2008) - *The Åknes rockslide; monitoring, threshold values and early-warning.* In: Chen Z., Zhang J.-M., Ho K., Wu F.-Q. & Li Z.-K. (eds.). *Landslides and engineered slopes.* Proceedings of the 10th International Symposium on Landslides and Engineered Slopes, 30 June - 4 July 2008, Xi'an, China. Taylor and Francis. ISBN: 978-0-415-41196-7.

Blikra L.H. (2012) - *The Åknes rockslide, Norway.* In: Clague J.J. & Stead D. (eds.). *Landslides: types, mechanisms and modeling*. Cambridge, 323-335.

Blikra L.H. & Kristensen L. (2011) - *Monitoring concepts and requirements for large landslides in Norway*. Proceedings of the Second World Landslide Forum Abstracts. 3-7 October 2011, Rome, Italy.

Blikra L.H., Longva O., Braathen A., Anda E., Dehls J. & Stalsberg K. (2006) - *Rock-slope failures in Norwegian fjord areas: examples, spatial distribution and temporal pattern.* In: Evans S.G., Scarascia Mugnozza G., Strom A. & Hermanns R.L. (eds.). *Landslides from massive rock slope failure.* NATO Science Series: IV: Earth and Environmental Sciences, **59**.

Braathen A., Blikra L.H., Berg S.S. & Karlsen F. (2004) - *Rock-slope failures of Norway; type, geometry, deformation mechanisms and stability.* Norwegian Journal of Geology, **84**: 67-88.

Dahle H., Saintot S., Blikra L.H. & Anda E. (2010) - *Mannen i Romsdalen - geofaglig oppfølging 2009*. Geological Survey of Norway, Report 2010.022. (In Norwegian)

Frei C. (2008) - *Groundwater Flow at the Åknes Rockslide Site* (Norway). *Results of multi-tracer test*. M.Sc. thesis, ETH Zurich, Zurich, Switzerland.

Ganerød G.V., Grøneng G., Aardal I.B. & Kveldsvik V. (2007) - *Core logging of seven boreholes from Åknes, Stranda municipality, Møre and Romsdal County.* Geological Survey of Norway report no. 2007.020, 222 pp.

Ganerød G., Grøneng G., Rønning J.S., Dalsegg E., Elvebakk H., Tønnesen J.F., Kveldsvik V., Eiken T., Blikra L.H. & Braathen A. (2008) - *Geological model of the Åknes rockslide, western Norway.* Engineering Geology, **102**: 1-18.

Glimsdal S. & Harbitz, C.B. (2011) - *Numerical simulations of tsunamis from potential and historical rock slides in Storfjorden: hazard zoning and comparison with 3D laboratory experiments.* Norwegian Geotechnical Institute Report 20051018.

Jaboyedoff M., Oppikofer T., Derron M-H., Böhme M., Blikra L.H. & Saintot A. (2011) - *Complex landslide behaviour and structural control: a 3D conceptual model of Åknes rockslide,* Norway. In: Jaboyedoff M. (ed.). *Slope Tectonics*. Geological Society of London Special Publication, **351**: 147-161.

Kristensen L. & Blikra L.H. (2011) - *Monitoring displacement on the Mannen rockslide in Western Norway.* Proceedings of the 2nd World Landslide Forum Abstracts. 3-7 October 2011, Rome, Italy.

Lovisol, M., Ghirotto S., Scardia G. & Battaglio M. (2003) - *The use of Differential Monitoring Stability (D.M.S.) for remote monitoring of excavation and landslide movements.* In: Myrvoll (ed.) - Proceedings of the 6th International Symposium on Field Measurements in Geomechanics, 519-524, Oslo, Balkema.

Rønning J.S., Dalsegg E., Elvebakk H., Ganerød G. & Tønnesen J.F. (2006) - *Geofysiske målinger Åknes og Tafjord, Stranda og Nordal kommuner, Møre og Romsdal.* Geological Survey of Norway Report 2006.002 (in Norwegain).

Saintot A., Elvebakk H., Ganerød G., Oppikofer T. & Farsund T. (2011) - *Mannen unstable rock slope (Møre & Romsdal): logging of borehole and drill core KH-01-10, geomorphologic digital elevation model interpretation and displacement analysis by terrestrial laser scanning.* NGU report no. 2011.026.