Multi-sensor monitoring network for real-time landslide forecasts in early warning systems

E.T. Peters
Alert Solutions, Delft, Netherlands.

J.-P. Malet
School and Observatory of Earth Sciences, Institute of Earth Physics, CNRS UMR 7516, University of Strasbourg, Strasbourg, France.

T.A. Bogaard
Water Resources Section, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, Netherlands.

ABSTRACT: GeoBeads multi-sensor modules offer a simultaneous measurement of pore water pressure, temperature and inclination in soil layers. These modules can be linked together to form a multi-point sensor network over large areas. First sensor networks were installed in July 2008 and are operational at the Super-Sauze and La Valette landslides in the Alpes-de-Haute-Provence region in southern France. Installation of a system at Villerville, Normandy followed in July 2010. Automatic data gathering throughout the year, including winter, offers a detailed look at the dynamics of the landslide process. Depending on the system configuration the data can be transmitted in real time to an online database, which enables implementation of automatic and instantaneous risk signaling. Correlation between pore water pressure build-up and measured change in inclination of the sensor module allows analysis of the conditions that give rise to an onset of landslide displacement. Spatial and temporal trends of soil temperature at the network nodes support analysis of the origin of water flow and infiltration, for example caused by snow melt. Ongoing data analysis (over long time periods) focuses on distilling a set of parameters and conditions that provide a timely assessment of landslide initiation. Coupling of real-time data with ground mechanical models is a valuable development step in providing input for operational early warning systems.

1 INTRODUCTION

The sensor network GeoBeads was developed to provide all essential dynamic parameters for the determination of soil stability in structures such as levees and mountain sides (Peters & van der Vliet, 2009). The network of miniaturized sensor modules applied at landslide sites can detect a set of geotechnical and hydrological parameters, such as pore water pressure, temperature and inclination, in any soil layer.

The system is designed to be deployed in remote locations. It offers high temporal resolutions of acquisition and continuous monitoring over prolonged periods. Results can be relayed to centrally accessible databases in near real-time.

2 SENSOR NETWORK FOR LANDSLIDES

2.1 *Multi-parameter sensor modules*

Every individual GeoBeads module houses multiple sensor elements based on semiconductors fabrication technology. These different sensor elements are read out simultaneously at user-defined intervals. The GeoBeads modules communicate via a standardized and addressable serial network bus, thereby allowing them to be connected together in flexible configurations to form a scalable network of digital nodes in order to cover a wide area of measurement locations.

The enclosures of the sensor modules, limited in size to 22mm diameter, are robust and waterproof. Installation methods have been developed complying to geotechnical standards which allow positioning in all relevant underground layers using minimally invasive techniques.

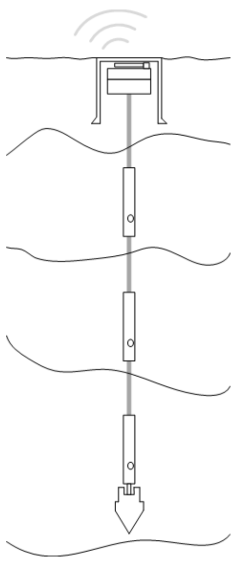

Figure 1. Schematic overview of a GeoBeads sensor string configuration as applied at the landslide sites. Each string can consist of a several multi-parameter sensor modules to monitor different depths in a single borehole or probing.

2.2 *Real-time monitoring*

The system architecture of the GeoBeads sensor network is such that it can provide real-time availability of measurement data. A typical system set-up consists of several strings of sensor modules linked to a single or several strategically positioned network controllers, which control measurement settings, collect the data and send it to a remote database. The long range link to the central database can consist of any common communication technology and is usually TCP/IP based, being the most prevalent internet protocol. It allows for two-way communication with the network controllers enabling remote management of sensor network settings such as sampling intervals. Keeping the communication pipe open continuously will make data availability virtually immediate. Activating this mode will depend on desired battery lifetime and urgency of monitoring a changing situation. Triggers can be build into the field system in order to go into live transmit mode based on pre-programmed alarm conditions.

Alert Solutions has developed online access to the database via a web application called the Data Panel, which visualizes time trends into graphs and allows data export for further offline analysis. The Data Panel can be reached via any internet connection. A personal log-in account secures safe access.

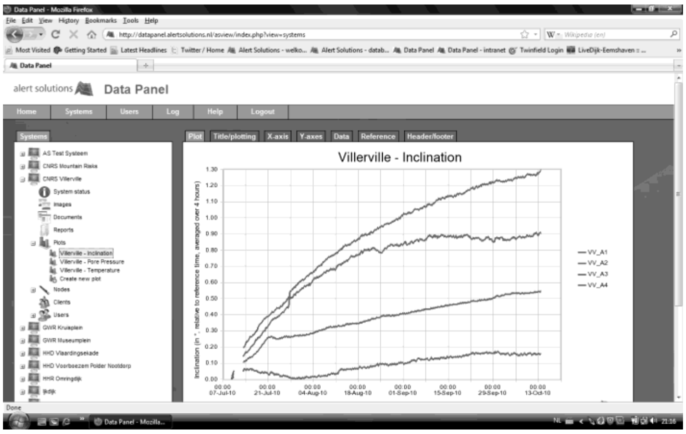

Figure 2. A web application gives worldwide instant access to measurement data and analysis results from all monitored sites.

3 LANDSLIDE MONITORING

3.1 *Installations at landslide sites*

In July 2008 the first landslide site was equipped with several strings of GeoBeads sensor modules. At the Super-Sauze mudslide in the Alpes-de-Haute-Provence region, France (Malet, 2003), sensor strings were vertically lowered in boreholes at three different altitudes on the slope. Each string consisted of three sensor modules to monitor at different installation depths ranging between 0,5 and 2,0 meters below the surface.

In July 2009 the installation of a similar three-depth string was carried out at the La Valette mudslide (Colas & Locat, 1993). This probe was positioned immediately next to a GPS monitoring station (Squarzoni et al, 2005).

In July 2010 followed the placement of a GeoBeads string of four sensor modules at the slow-moving slide on the coastal slopes near Villerville, Normandy (Lissak et al. 2009). Installation depths at this site are -1,0m, -2,0m, -4,0m and -5,8m with respect to the ground surface. This sensor network enjoys a continuous communication link via ADSL, providing live data availability.

3.2 *Measured parameters*

Each of the GeoBeads modules at the landslide sites registers three different parameters simultaneously. These parameters are pore water pressure in the soil layer, temperature and inclination of the sensor housing with respect to the gravitational field. This specific set of three parameters was inspired by the needed data for computational models for levee stability in The Netherlands (Peters, 2009). However, the parameters are expected to be relevant for ground stability in general and landslide monitoring specifically. Pore water pressure is a measure for hydrological forces in soil layers that can trigger displacements. Furthermore pore water pressure contributes to assessing conditions for the formation of slip surfaces, lowering the shear resistance of soil layers on slopes. Temperature is used as a measure for soil moisture, groundwater flow and infiltration (Steele-Dunne, et al, 2010, Krzeminska et al, 2010). Inclination, as measured by the integrated inclinometers, is the detection mechanism of movement of soil layers on the landslide. This technique is especially effective when there is a difference in displacement between shallow and deeper layers, leading to a rotation of the vertically installed sensor string.

An important topic of study at the landslide sites is the correlation between pore water pressure and the onset of slope displacements. The multi-sensor design of the measurement modules allow comparison of the different parameters at exactly the same location point, instead of having to compare data gathered by different systems located at some distance from each other.

The hypothesis is that a displacement will be preceded by a build-up of pore water pressure. Subsequently, localized zones of soil compression as a result of displacements can lead to further, usually steep, increases in pore water pressure.

Comparing spatial and temporal trends of soil temperature at the different network nodes support analysis of the origin of water flow and infiltration, for example caused by snow melt. Infiltration can be one of possible causes for build-up of pore water pressure in deeper layers.

Near the top of the Super-Sauze mudslide a string of three modules was installed with positioning at the following depths with respect to the surface; Module GB1-1: -0,7m, GB1-2: -1,3m and GB1-3: -2,0m. Comparing the temporal trends of the different parameters through the spring period of 2010 shows evidence of solid correlation between pore water pressure build-up, displacement events and temperature changes (Fig. 3).

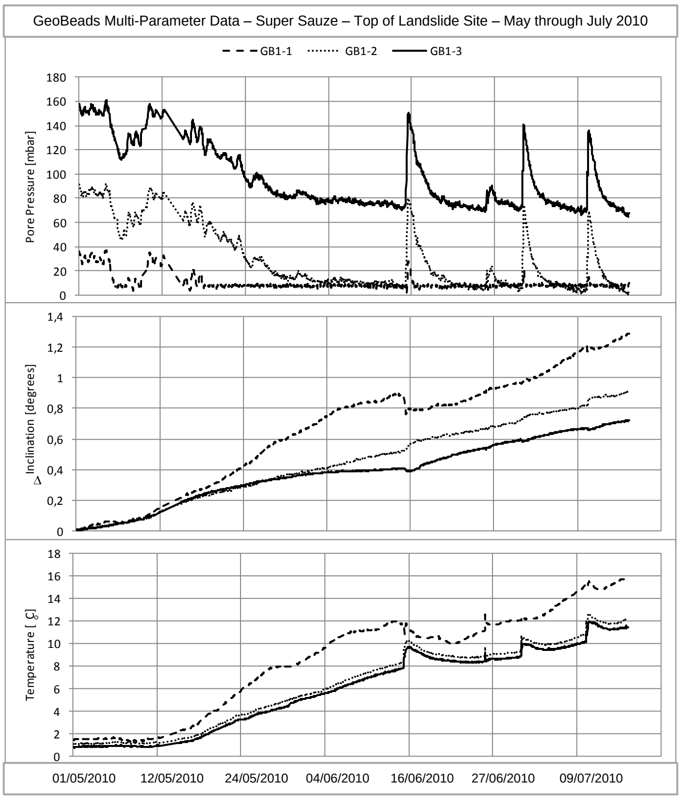

Figure 3. GeoBeads multi-parameter measurements from the installation at the top of the Super-Sauze mudslide over the period May to July 2010. From top to bottom graph, 1) pore water pressure [mbar], 2) delta inclination [degrees], and 3) temperature [°C]. Sharp pore water pressure peaks (top graph) coincide with observable inclination trend changes and temperature increases in the lower layers.

In early May there is an elevated pore water pressure at all installation depths from the snow-melt period and spring precipitation. This does not seem to cause sudden displacement events, although there is a more or less constant degree of background movement as evidenced by the constantly increasing inclination data (absolute value of the delta in inclination, regardless direction). The ground layers dry up as half of June 2010 is reached. An event on the landslide is triggered observed as abrupt changes in all three parameters.

Which mechanism is the cause and which is the effect is topic of further analysis and investigation. For, example, a ground layer displacement can cause soil compression leading to a pore water pressure increase. This pressure subsequently diffuses over a period of time to its surrounding, bringing the value back down to its original level. Also a displacement event can cause cracking of dry soil layers allowing more water infiltration from the surface thereby altering the temperature. In summertime, as observed in fig. 3, this would most likely lead to a temperature increase in the lower layers.

Alternatively, the order of events can be the reverse, meaning that increased infiltration can lead to elevated pore water pressures that trigger displacements. In this case, pore water pressure build-up would however be expected to take place in a more gradual manner than observed in the Super-Sauze data.

Interesting observation in the Super-Sauze data is that the abrupt changes came in a series at a repetition of four distinct events in a one month time frame.

4 SET-UP OF EARLY WARNING SYSTEMS

4.1 Characteristics of the sensor network

Having the availability of an efficiently scalable sensor network that enables the continuous monitoring of several required stability parameters is a key element in the realization of an early warning system for mountain risks. A required condition for moving from observational monitoring to early warning is (near) real-time availability of decision supporting information.

Alert Solutions has built up extensive experience in coupling the sensor network to internet based communication technologies, both over cellular phone networks and internet infrastructure. A server stores the data in a structured database and a web-based application distributes the information worldwide.

Reliable, long-life autonomous power supply to each node of the sensor network is an additional requirement for the practical implementation of a permanently installed early warning system. Reduction of energy consumption by the measurement and communication systems is a continuous area of research and development. Current designs enable powering a network of approximately 20 sensor nodes including data communication on a single car battery for a one year period. The ongoing development program is targeted at achieving the same battery lifetime for such a system configuration on a D-cell size Lithium battery.

4.2 Value of long term monitoring

Real-time availability of measurement data is one ingredient. Putting the current measurements in perspective of historically gathered data sets strengthens the insight into the relevance of observed changes. This is a prerequisite for determining valid alert thresholds and calamity alarm conditions.

Qualitatively comparison to previous periods with similar meteorological circumstances or to other comparable landslide sites supports the judgment of the severity of a situation. Statistical methods can serve to determine the relevance of observations in a quantitative manner. At the Delft University mathematics department the application of change point analysis to the data series showed the potential to detect relevant events automatically (Mosterman, 2009).

4.3 Coupling to hydro-mechanical models

The next step is to evaluate monitored conditions with geophysical and ground mechanical analysis. Using measurement data as the dynamic input for geotechnical computational models directly presents a risk based assessment. Automatically recalculating the models at each new sample interval results into a trend of the stability factors of a certain site. Remotely altering the sampling frequency in case of threatening situations provides a more or less live update of the stability analysis.

The coupling of GeoBeads measurement data to ground mechanical models has already been realized for several levees in The Netherlands. The ongoing development of computational models for landslides should enable an analogous set-up of early warning systems for mountain risks.

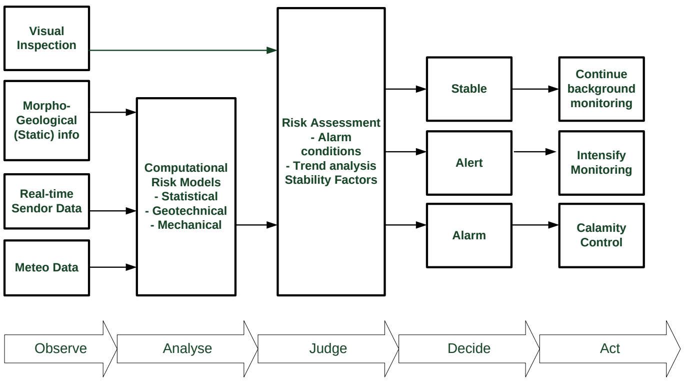

Figure 4. Flow diagram depicting elements of an early warning system applying real-time monitoring in order to continuously update stability calculations and assessment of alarm threshold conditions.

5 CONCLUSIONS

The GeoBeads multi-sensor network offers a scalable instrumentation solution for real-time monitoring of geotechnical ground stability over wide areas and in remote locations. Field installations of the sensor have been put in operation on landslide sites at Super-Sauze, La Valette and Villerville.

The measured parameters at each sensor node in the network are pore water pressure, inclination and temperature. These are each relevant parameters for mountain risks research. The combination of these parameters in single sensor nodes presents an unprecedented opportunity for correlation analysis. This may enhance insights into causes and conditions of landslide instability and displacement events.

The ongoing product development program at Alert Solutions is aimed at further optimization of the systems in terms of energy efficiency, robustness and ease of field deployment.

Besides these practical enhancements the coupling of monitoring data as input for computational stability models and statistical change analysis are seen as valuable elements in the realization of effective early warning systems for landslide risks.

6 ACKNOWLEDGMENTS

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