High alpine geotechnical real time monitoring and early warning at a large imminent rock slope failure (Hochvogel, GER/AUT)

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Abstract. Monitoring and early warning systems based on process dynamics gain importance to cope with an increasing number of alpine hazards. The imminent Hochvogel rock slope failure (up to ca. 260,000 m³) is paradigmatic of natural carbonate slope failure dynamics and a benchmark site for developing an effective monitoring and early warning system. The analysis of process dynamics shows constant movement rates (12 mm/a) over the last 3 years but also a response of specific cracks to heavy precipitation events resulting in factor 5 higher movement rates during wet periods. Here, we show valuable lessons learnt during the development of a reliable monitoring system under challenging environmental conditions. The insights into pre-failure slope dynamics acquired at the Hochvogel will help to detect precursors of a final failure and to warn early.

1. Introduction

The increasing number of alpine hazards necessitates improved strategies for alpine communities to cope with them [1]. Monitoring and early warning systems based on process dynamics gain importance due to their lower cost compared to protective structures [2]. At the same time, reliable early warning requires a detailed and continuous monitoring of instable sites and their underlying processes [3; 4].

Landslide early warning systems at slope-scale are implemented and used all over the world (for a review see [5]). Actively monitored sites in Europe are for example Åknes (NO), Torgiovannetto (IT), Mannen (NO) or Preonzo (CH). Recent well-monitored case studies in metamorphic rock include Pizzo Cengalo (CH) [6], Marzellkamm (AT) [4] and Veslemannen (NO) [7]. But still, advances in rock slope early warning are reliant on more well-documented case studies from sites with different lithologies and overall settings.

The imminent Hochvogel rock slope failure (up to ca. 260,000 m³) is paradigmatic of natural carbonate slope failure dynamics and at the same time underlies very challenging high alpine conditions. Thus, it is a benchmark site for testing a multi-method risk assessment and developing an effective monitoring and early warning system. Our near real time monitoring is implemented in the AlpSense project (www.bgu.tum.de/landslides/alpsense) that aims at development and evaluation of a multi-method anticipation approach for climate change related natural hazards. Here we share valuable lessons learnt during the development of our system under challenging environmental conditions and a first analysis of precipitation-controlled movement rates.
2. Site Overview

The Hochvogel summit (2,592 m a.s.l.) is divided by a two- to six-meter-wide main fracture (figure 1a) and several lateral cracks into multiple instable blocks with a total volume of up to 260,000 m³ [8]. A detailed overview of the site at the German/Austrian border is given in Leinauer et al. 2020 [8]. The development and installation of the monitoring system at the site was challenging due to extreme alpine conditions which often lead to system disruption or damage.

With a topographic isolation of 5.4 km and a prominence of 572 m, the Hochvogel summit is an outstanding landmark in the Allgäu Alps. This leads to an exceptionally high frequency of lightning strikes into the summit area. During winter months, snow accumulates at the summit area and completely fills the decameter-deep main fracture (figure 1b). The closest weather station (8 km) at Nebelhorn (station 2075 m a.s.l.) is usually snow-covered between October and May reaching a maximum snow depth of over 2 m around March [9]. This implies high snow pressure in winter and no access to the site for at least seven months of the year. During the rest of the year, logistical operations mostly rely on helicopter service and good weather conditions. Alternative access for personal and light equipment is only possible through hiking 1,300 m of altitude difference. Additionally, the brittle dolomite rock with pronounced bedding is highly jointed which can make it challenging to find robust rock for the installation of measuring equipment.

3. Geotechnical monitoring system

3.1. Development of the system

We started to set up a monitoring system with wireless data transfer in summer 2018 and continuously improved the system. Originally, the system was installed with 2 crackmeters and 4 convergence meters (automatic vibrating wire instruments) which were connected to a central CR6 data logger with modem and GSM module via cable. Later in October, the system was extended with two more convergence meters, a rain gauge, and a webcam, all connected to the central logger with 5–30 m long wires.

Experience gained in the summer of 2019 proved long wires converging in one central logger to be unfavorable, as high electric potential differences could generate in the system. In fact, lightning strikes caused damage to the system in 09/2018, 10/2018, 05/2019 and 06/2019 with consequent loss of data and laborious maintenance. Therefore, we decided to convert the system into a nodal based wireless system with individual logger nodes (LoRa) for each device. A GSM transmitter unit down in the valley communicates with each single node and forwards the measurements to our server [8]. Additionally, we made considerable effort to protect every crackmeter-logger combination against lightning (see section 3.2).
The second main challenge was snow, exerting massive loads and drag forces in the 10 m deep main fracture during subsidence. The convergence meters in the main fracture (protected by thin plastic pipes) failed in winter 2018 and those at the lateral cracks showed strong snow influence. Therefore, we installed wire displacement meters with 2 m range in the main fracture and smaller crackmeters in the lateral cracks. To further improve that situation, we plan on installing laser distance gauges and tiltmeters in summer 2021. Underestimation of snow accumulation also led to unfavorable positioning of solar panels (figure 1), hindering the recharge of the battery for the central unit. We acted on that by installing the new logger nodes which are individually powered by C-cell lithium-ion batteries and are not dependent on solar power supply.

3.2. Lightning protection
To protect each part of the system from repeated lightning damages, we implemented a lightning protection concept for the individual measuring nodes (figure 2). (i) Each measuring device is connected to its own datalogger through a surge arrester module. (ii) Cables are kept as short as possible to counteract high potential differences over great distances. (iii) Each crackmeter is connected to a piece of non-conductive glass-fiber plastic (~30 cm) at one side of the crack to obtain electrical decoupling. (iv) For equalization of electrical potential within one measuring node, the datalogger, the surge module and both rock bolts of the crackmeter are connected by a copper cable. This copper cable must lie on the ground of the crack or be long enough to avoid snow drag forces. This concept minimizes surficial potential gradients in the cables induced by nearby lightning strikes and so prevents from strong electrical currents in the system. Note that no lightning protection can protect from direct lightning surges.

Figure 2. Sketch of the lightning protected crackmeter installation and a photo from the site.
3.3. Active components of the monitoring system
Continuous near real time data are a requirement for early warning. The setup of the monitoring system at the Hochvogel provided only discontinuous measures in 2018 and 2019, due to repeated disruptions and damages. Strong improvements have been undertaken and since the switch into a node based LoRa system in October 2019, the system performs with high reliability under the challenging conditions of the site. Our system is now able to deliver such data even in winter, accompanied by other in-situ and remote sensing measurements from the AlpSense project. Table 1 gives an overview of all currently active components of the geotechnical monitoring system. Details about the data transmission technique are given in Leinauer et al. 2020 [8].

Table 1. Active components of the geotechnical monitoring system at the Hochvogel (data gaps not indicated).

| Instrument | Location | Installation/ Reinstallation |
|------------|----------|------------------------------|
| Manual tape extensometer sections | main + lateral cracks | 2014 |
| Vibrating wire crackmeter (150mm range) | 3 @ lateral cracks | Crack02: 09/2018, Crack05: 09/2018 and 10/2019, Crack06: 10/2018 and 10/2019 |
| Vibrating wire displacement meter (wire drum, 2m range) | main crack | 4427-1: 10/2019 |
| Rain gauge | summit | 10/2018 |
| Webcam | summit/ main crack | 10/2018; 07/2019; 06/2020 |
| Laser distance gauge | 2 @ main crack | Summer 2021 |
| Tiltmeter | 2 @ outer blocks, 1 @ stable side | Summer 2021 |

3.4. From monitoring to early warning
The above introduced near real-time monitoring system is designed to operate as an early warning system. This implies automatic data transmission, analysis and warning. These steps are executed on our safe server which sends out SMS and email warnings if certain alarm thresholds are exceeded (for details see [8]). In this early stage, to prevent from numerous false alarms, we evaluate the data before forwarding the alarms to the geological services, local authorities, hut operators and hiking clubs if necessary. By this it will be possible to ensure that no one remains in the summit area or the uninhabited runout zone in case of an expected rock slope failure. The most endangered hiking path beneath and on the instable masses is officially closed since 2014. For further improvement, we will also include a more complex automatic application of the inverse velocity method for real time prospective failure time forecasting in 2021.

4. Analysing process dynamics
During the last three years (2018–21), the main crack opened with movement rates of 1–2 mm/month. Similarly, the main lateral crack showed an expansion of 31 mm in 2.5 years (~1 mm/month). On a multi-annual scale, movement rates stay constant, not indicating any obvious acceleration.

On a shorter scale, movement rates are not constant over time. Especially in summer during heavy precipitation events, some cracks show higher movement rates than during dry days. This pattern is
most distinctive at the transect Crack06. Figure 3 shows a plot of crackmeter and rain data from summer 2020. Periods with enhanced opening rates coincide with strong precipitation (orange rectangles). During all highlighted periods, precipitation exceeded 20 mm/2 days, except for the first period in June. Here, during early summer, snow melt seems to significantly contribute to the hydrostatic pressure. This is not the case around July 27, when similar precipitation amounts did not accelerate the movement.

The average rate measured at Crack06 during high precipitation events reaches 0.2 mm/d which is five times higher than the 0.04 mm/d recorded during dry summer periods. Not all lateral cracks as well as the main crack show the same precipitation-dependent behaviour which supports our hypothesis of a consecutive failure of single blocks.

![Figure 3. Response of Crack02 to rain. Orange rectangles indicate timeslots with higher movement rates which coincide with strong precipitation events. In June, snowmelt is contributing to the hydrostatic pressure.](image)

5. Discussion and Outlook

Continuous and reliable sensor readings are a crucial requirement for typical early warning systems [10]. As the failure event approaches, the availability of high-frequency continuous data is crucial for real-time decision-making and in time response to protect affected people and property. Unfortunately, standard monitoring solutions do not always perform satisfactorily in rough inaccessible high-alpine environments. By continuously improving our setup, we created a reliable monitoring system that delivers high-frequency data all year round. The most important change to reduce outage is to operate a wireless system with individual lightning protected nodes and to locate the central unit of the system outside the danger zone.

Apart from real-time early warning, continuous and accurate high-frequency measurements also allow a detailed analysis of underlying process dynamics. This process understanding in turn is crucial when it comes to interpretation of accelerations, understanding trigger mechanisms and setting alarm thresholds. The preliminary analysis shown here indicates an overall secondary creep status of the instable mass [11] while hydrostatic pressure plays an important role. A future change in the process dynamics of particular cracks can indicate a change of the site’s stability status.

Climate change leads to an increased frequency of high precipitation events in the alps [12] possibly influencing the acceleration behaviour of the instable mass. This very likely makes the Hochvogel and many similar rock slope instabilities climate change related. Still, to confirm this hypothesis there is the need for multi-year data sets. To achieve this, and for a reliable early warning, we will extend our monitoring system and improve its redundancy within the next years. A joint
interpretation with corresponding on-site and remote measurements [e.g. 13] that are simultaneously collected at the Hochvogel will also help to gain insights into rock slope failure dynamics. This will help to timely detect precursors of a final failure and so to warn early.

**Acknowledgements**

The monitoring system at the Hochvogel is part of the projects AlpSenseBench and AlpSenseRely which are funded by the Bavarian Ministry of Economic Affairs, Regional Development and Energy and the Bavarian Ministry of the Environment and Consumer Protection. Thanks also to all project partners, the helicopter pilots of Helix, the helpers in the field and Peter Biebl (lightning engineer).

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