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Monitoring of high alpine mass movements combining laser scanning with digital airborne photogrammetry

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ABSTRACT

Airborne- and terrestrial laser scanning are used in combination with digital airborne photogrammetry to monitor surface changes between 2009 and 2011 on rock glaciers and landslides at three mountain permafrost sites (Grabengufer, Schafberg and Flüela Pass) in the Swiss Alps. 3D surface changes detected through comparison of multitemporal laser scanning data, as well as horizontal creep rates determined using laser scanning data and digital airborne photogrammetry are analyzed. The methods applied allow comprehensive quantification of mass movements and volumetric changes, which are presented in 2.5D. GPS ground truths are used as reference data at the Grabengufer site. On the basis of this, a quality estimation is developed for the sites without GPS reference data. For changes with an extent of about 25 m^2, a level of significance of 3 cm was obtained for both horizontal and vertical displacements under optimal measurement conditions. The complex dynamics of creeping and sliding permafrost features are investigated through analysis of their surface kinematics.

1. Introduction

In areas with alpine permafrost, active rock glaciers and deep-seated landslides are common forms of mass movement. Rock glaciers are the visible expression of cumulative deformation by long-term creep of ice/debris mixtures under permafrost conditions (Berthling, 2011). They displace large volumes of rock debris–ice mixtures downslope at rates typically varying between several decimetres to metres per annum (Harris et al., 2009), with surges of up to several m a^{-1} (Roer et al., 2008). The dynamics of these ice-rich features have recently been investigated (e.g., (Kääb et al., 2007) and are of particular interest as they can be highly variable due to external meteorological forcing (Delaloye et al., 2008) and the internal composition and rheological characteristics of rock glaciers. Factors affecting rock glacier creep include temperature, contents of debris, ice, and in particular, water (Kääb et al., 2007) as well as the underlying topography. The temporally and spatially variable, and sometimes quite unforeseeable nature of rock glacier dynamics is particularly relevant in the triggering of rockfalls and debris flows from the snout (Lugon and Stoffel, 2010). In addition to rock glaciers, active, often deep-seated landslides also occur in alpine permafrost areas. Their dynamics have so far not been investigated in detail, although like rock glaciers, they act as sediment conveyors on mountain slopes.

Active rock glaciers and landslides from which further high-intensity sediment transfer processes such as rockfall and debris flows can occur must be monitored efficiently for successful hazard management. Three very common methods used to observe surface changes of mass wasting in unforested areas are digital airborne photogrammetry (DAP) and more recently, terrestrial- (TLS) and airborne lasers canning (ALS). Single point GPS measurements can be used to obtain precise reference data or to observe the kinematics of spatially limited areas (Lambiel and Delaloye, 2004). Photogrammetry is mainly used for the comprehensive detection of horizontal creep rates of rock glaciers over several decades (Kääb et al., 2003; Kellerer-Pirklbauer et al., 2007) but the detection of changes in surface elevation is also possible (Kääb, 1999; Kaufmann and Ladstädter, 2003). TLS/ALS make it possible to obtain information on vertical movements caused by subsidence, heave, slides and slumps etc. with a higher accuracy of up to a few cm. This type of 3D deformation data were obtained by Bauer et al. (2003) and Bodin et al. (2008) for rock glaciers using terrestrial laser scanning. Further analysis also makes it possible to extract creep rates from multi-temporal point clouds. A higher accuracy can thus be reached than via photogrammetry (Bauer et al., 2003; Schwalbe et al., 2008), which is of practical interest to decision-makers in hazard zones with mass movements.

To develop an accurate and reliable monitoring technique for use in potentially hazardous areas, we measured mass movements in three permafrost areas in the Swiss Alps using DAP, TLS and ALS and in one case GPS for the time period of 2009 to 2011. The aims of this study

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are: 1) to compare and optimize the analysis of the data obtained using the remote sensing methods DAP, TLS and ALS; and 2) to find solutions to combine the different measurement systems in order to develop an integrated 2.5D rock glacier/landslide monitoring technique.

In addition, geodynamic processes observed during the measurement campaigns are presented.

2. Site description and data sets

2.1. Grabengufer area, Randa

The Grabengufer site is located at the western foot of the Grabenhorn peak above Randa in the Mattertal, Valais (46°05′N, 7°48′E, WGS84, Fig. 1). It is characterised by very complex and dynamic terrain. The geometry of the mass movements and their kinematic behaviour were first detected by analysing satellite InSAR (Synthetic Aperture Radar Interferometry) data (Delaloye et al., 2007).

Fig. 2 shows a detailed overview of the individual terrain structures described below. There is an extensive deep-seated landslide feature at the foot of the rock slabs of the Grabenhorn west face (blue in Fig. 2) which is henceforth referred to as the Grabengufer landslide. On its orographic left border, the landslide collapses over a steep rock band, and during the observation period, voluminous erosion occurred from this failure scar (green in Fig. 2). Most of the material was deposited on the underlying Grabengufer rock glacier (red in Fig. 2). In 2009 this rock glacier showed extreme creep rates attaining up to about 100 m a^{-1} in its frontal part (Delaloye et al., 2010). Our terrestrial geodetic surveys show large seasonal fluctuations of the velocity and a decreasing trend of the velocity since the paroxysm of the surge in late 2009. Debris released by the rock glacier and some of the larger boulders issued from the upper failure scar fall into the large Grabengufer gully (yellow in Fig. 2) below the rock glacier front. Debris flows originating from here transport significant volumes of sediment through the Grabengufer and Dorfbach gullies and can be hazardous for the village of Randa (Bühler and Graf, 2012).

In 2010 and 2011 TLS and helicopter-borne ALS measurements were carried out. The TLS scan position and the spatial extent of the measurements can be seen in Fig. 2 including its inset, and details on the nature and timing of the measurements are given in Table 1.

2.2. Rock glacier complex Foura da l' amd Ursina, Pontresina

Foura da l'amd Ursina is a complex of three rock glacier features located in a cirque above Pontresina in the upper Engadin valley (46°29′N, 9°55′E, WGS84, Fig. 1). The site is surrounded by the peaks Las Sours to the north, Piz Muragl to the east and a rocky ridge called Muot da Barba Peider to the south (Fig. 3). The rock glacier in the orographic right sector of the cirque (red in Fig. 3) has a steep front located above the Val Giandains gully. Mass movements from this zone would be hazardous for two popular hiking trails crossing the upper part of Val Giandains. Pontresina is protected by a large avalanche and debris-flow retention dam at the base of the gully.

Terrestrial laser scanning was carried out from two different scan positions; on an avalanche protection wall west of the steep rock glacier front to observe the latter and on the ridge of Muot da Barba Peider to capture the remaining rock glacier complex (Fig. 3 and Table 1).

2.3. Rock glacier Schwarzhorn, Flüela Pass

The Schwarzhorn rock glacier has its root zone beneath the eastern sector of the north face of Flüela Schwarzhorn and its front reaches down to around 20 m from the Flüela Pass road (46°44′N, 9°56′E, WGS84, Fig. 1). The rock glacier can be divided into three parts: an extensive terrace-like upper part, a narrow and steep central part and a tongue-shaped lower part.

Terrestrial laser scanning was carried out from a slope opposite to and to the north of the rock glacier. From there the central and lower parts of the rock glacier could be observed, but only fragments of the upper part. Fig. 4 shows an overview of the measurement site, and Table 1 gives measurement details.

3. Data acquisition methods

3.1. Terrestrial laser scanning (TLS)

TLS was carried out using a Riegl LPM321 Long Range Scanner. This instrument provides a single point accuracy of 25 mm @ 50 m + 20 ppm. The laser wavelength of 905 nm is suitable for rock as well as snow and ice. The scan process was managed over a laptop by the scanner software RiProfile. Data referencing was carried out using at least six geometrically and optimally distributed reflecting targets (Kenner et al., 2011). Coordinates of these targets were defined using a Leica total station. To reduce the influences of poor long term stability of the measurement setup, the instrument was reoriented regularly using the targets. A zone of stable terrain was always included within the scan area for accuracy analysis.

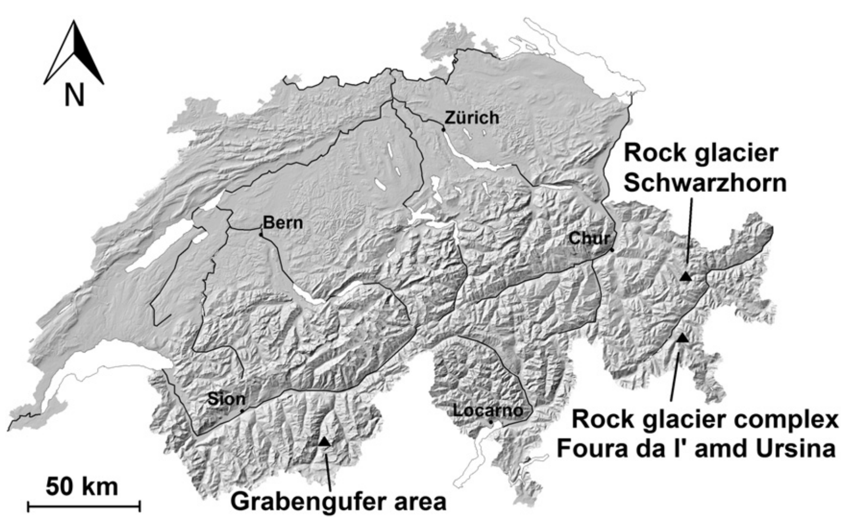

Fig. 1. Map showing the location of the study sites within Switzerland (Relief © Swisstopo (JA100118)).