Quantifying sediment transfer between the front of an active alpine rock glacier and a torrential gully

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Abstract—**The present contribution describes results from the quantification of transferred sediment volumes between the front of an active rock glacier and a torrential gully. The focus is set on the methodological approach which combines terrestrial laser scanning (TLS) generated digital terrain models (DTM) and geodetic field surveys. The aim is to compare high resolution DTMs from different dates in order to calculate volume gain and loss in the system for different time intervals. As the object of the study is a fast moving landform, other sources of information such as geodetic measurements (GPS) were necessary to estimate the advance of the rock glacier during the same time intervals and to facilitate the interpretation of the TLS data. It was then possible to estimate sediment budgets in the whole scanned area for different time intervals. The results show an extensive erosion of the front (up to 5000 m^3/year) but also the presence of a temporary sediment storage area in the upper part of the torrential channel.**

I. Introduction

In alpine periglacial hillslopes, large volumes of rock debris originating from talus screes and moraines are transported downward by rock glaciers creep [1]. The movement of rock glaciers is a consequence of the deformation of the ice present in the porosity of the terrain under permafrost conditions. The ice content in the ground can be highly variable between sites. Active rock glaciers are usually delimited downward by a steep unstable front [2]. When located on steep slopes, the front of rock glaciers can act as the sediment source favoring the triggering of hazardous gravitational processes such as debris flows and rock falls [3]. Consequently, quantifying and monitoring the sediment transfer processes occurring at the front of active alpine rock glaciers could help the management of natural hazards in mountainous terrains.

In environmental sciences, terrestrial laser scanning (TLS) has been used to obtain high resolution digital terrain models (DTMs) since the beginning of the years 2000 [4]. The progresses made at a technical level over the years have induced an important increase in the amount of research projects using TLS in the last five years. Today, TLS devices offer the possibility to get high resolution terrain elevation data, allowing precise measurement and monitoring of geomorphological landforms to be made especially by the use of DTMs comparison techniques. There are only few applications of TLS on rock glaciers monitoring in the Alps (e.g.: [5]), and despite the influence of these landforms on the triggering of debris flow and rock fall, there are even less studies focusing on the sediment transfer dynamics at the front of rock glaciers [6]. However, while airborne methods tend to be costly (airborne LiDAR) or to show performance restriction linked to the steepness of the terrain (photogrammetry), TLS seems to be a suitable method to get high resolution DTMs in steep and remote mountain environments [7].

This contribution presents results from two years of TLS survey at the front of the Gugla-Bielzug rock glacier (western Swiss Alps). The aim is to discuss the interests and the limits of this method in the context of the monitoring of sediment transfer processes in such environments.

II. Study site

The Gugla-Bielzug rock glacier is located on the orographic right side of the Zermatt valley (western Swiss Alps, see Fig. 1). The front is directly linked to a torrential gully which shows traces of debris flow until the valley bottom. The rock glacier is currently in a destabilization phase, the surface velocities having drastically increased during the last ten years, reaching locally a maximum of 8 cm/day in June 2013. Another particularity of this rock glacier is the role it has been playing in the triggering of several debris flows in 2013 and 2014. The debris flows were

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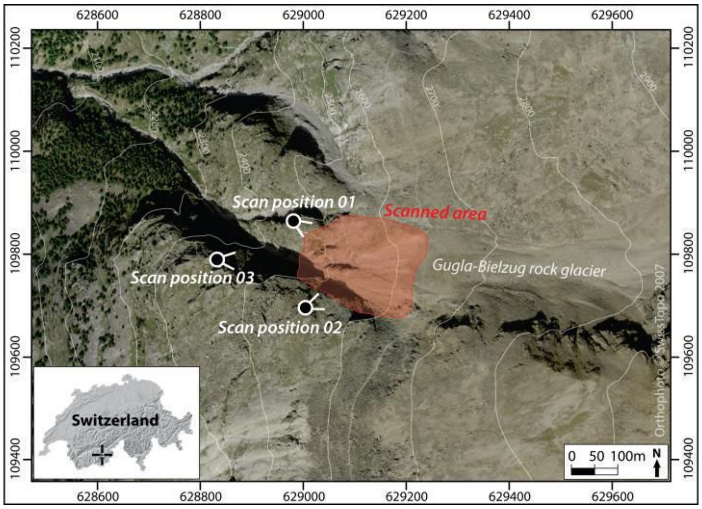

Figure 1. Location of the three scanning stations and the resulting scanned area at the Gugla-Bielzug rock glacier.

initiated beneath the front by snow-melt or rain fall events and reached the valley bottom near the village of Herbriggen (St Niklaus, VS, Switzerland).

III. Methodology

Five TLS campaigns were carried out at this site using a Riegl VZ-6000 long range scanner. The results are high resolution point clouds representing the surface of the terrain. We used three scanning positions to enhance the surface coverage and increase point clouds density (Fig. 1). Concerning the coregistration, we applied an Iterative Closest Point (ICP) algorithm on the RiscanPro software. Assumed stable areas (rock walls) were used to register point clouds from different dates. After the coregistration, the root-mean-square error (RMSE) in assumed stable areas is about 0.013m, and the resolution of the resulting point clouds is 0.1m. Given the high density of the point clouds we used a simple GIS natural neighborhood interpolation for the creation of DTMs [8].

In the context of sediment transfer studies, the interest of this method is to produce several high-resolution DTMs corresponding to different dates. It is then possible to compare the DTMs to calculate and map the vertical surface changes in the area:

DTM (date 2) – DTM (date 1) = vertical surface changes

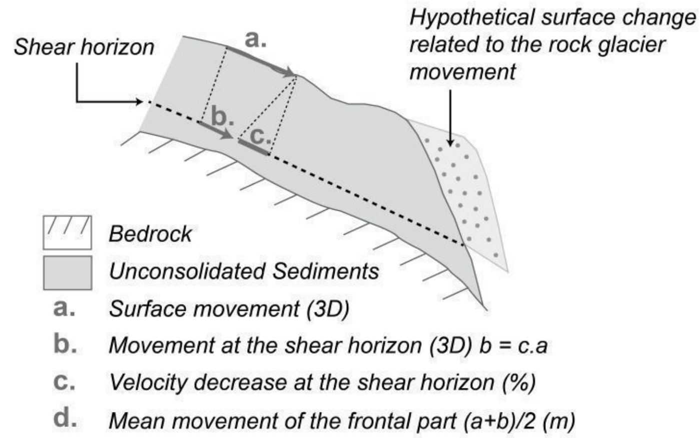

Figure 2. Schematic drawing explaining how the rock glacier movement impacts the volume gain and loss calculation. At Gugla-Bielzug, c. is assumed to be important (estimated at 50%) because of the presence of three shear horizons.

In our scanned area, two different zones can be distinguished (Fig. 4). The first zone is the gully where volume gain and loss calculated from the DTMs comparison can be interpreted respectively as accumulation and erosion of sediments. The second zone is the front of the rock glacier, located at the top of the gully and acting as the sediment source to the system. There, volume gain and loss results from erosion/accumulation processes but also from the movement of the rock glacier (Fig. 2). As the aim of the study is to quantify accumulation and erosion processes, it was important to remove the effect of the rock glacier movement on the calculated volumes. In order to complete that, movements measured by GPS on the surface of the rock glacier were used as explained hereafter:

1. First, the area affected by the rock glacier movement was delimited using the vertical difference map produced by DTMs comparison for a 2 week interval (Fig. 3).
2. In a second step, the position of several boulders was measured by GPS on the surface of the rock glacier at the dates of the scans. Boulders located near the front were selected to calculate for each time interval the mean 3D displacement at the surface of the rock glacier.
3. As the rock glacier velocity decreases in depth, a mean displacement for the whole frontal part was calculated using the formula described in Fig. 2 (point d.). The velocity at the shear horizon was estimated to be significantly lower than the surface velocity (about 50%) because of the presence of at least three different shear horizons, favoring the velocity decrease in depth.

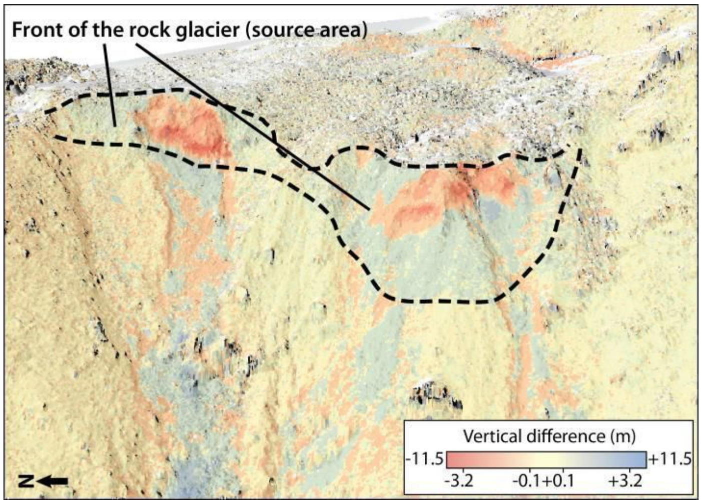

Figure 3. Limits of the front area detected on the surface changes between the 25.06.2013 and the 10.07.2013.

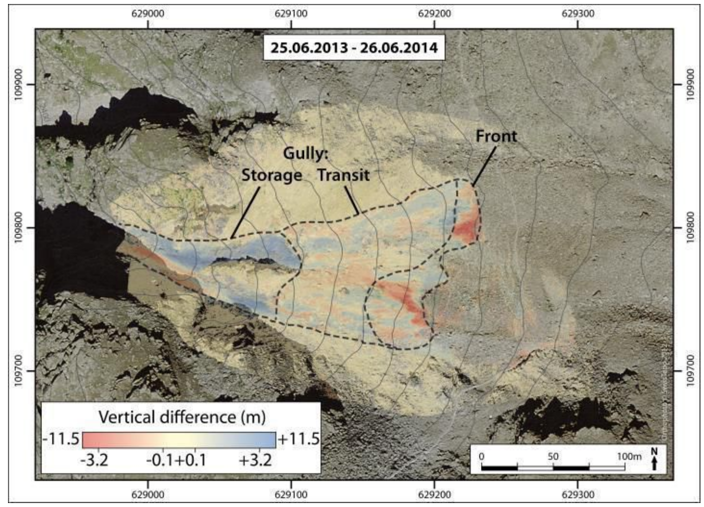

Figure 4. Example of a surface changes map for a one year period between June 2013 and June 2014.

4. Knowing the mean slope angle of the front (σ, calculated from the DTMs) and the mean horizontal (d_{xy}) and vertical (d_z) displacement (decomposition of the mean 3D displacement), the vertical differences related to the rock glacier advance (ΔH) were estimated for each time interval covered by the scans:

$$\Delta H = (\tan \sigma \, . \, d_{xy}) - d_z$$

The vertical differences (ΔH) related to the movement of the rock glacier were then subtracted from the vertical differences calculated by the DTMs comparison for the whole front area in order to obtain estimations of accumulated and eroded volume in this sector.

IV. Results

Five scanning campaigns were carried out at the Gugla-Bielzug rock glacier between the 25th of June 2013 and the 9th of October 2014, each campaign including three scanning positions. The results are five high resolution DTMs (0.1m) which were compared to obtain an overview of the evolution of sediment transfer processes in the system.

Fig. 4 presents an example of a surface changes map produced by DTMs comparison. The erosion areas are represented in red and the accumulation areas in blue. Changes too small to be significant are represented in pale yellow. The image shows a good coverage of our zone of interest, which is the interface between the front of the rock glacier and the upper part of the gully. The analysis of these maps shows that most of the erosion occurred at the front during the period covered by the scans. An important accumulation area is present in the lower part of the scanned area. These two sectors seem to be separated by a transit area, characterized by smaller eroded and accumulated volumes (Fig. 4).

Based on in situ observations of permafrost outcrops, the ice content of the rock glacier should not exceed by much the general porosity of the terrain, and is about 50%. This allows us to make a correspondence between the volumes eroded from the front (approximately 50% of sediments and 50% of ice) and the volumes accumulated in the gully (approximately 50% of sediments and 50% of air), and then to calculate a total sediment budget (the sum of volume gain and loss) in our entire scanned area. Budgets were also calculated separately for the two zones (the front and the gully). The results are presented in Table 1. They show plausible values given the velocity of the rock glacier and the geometry of the front. Important amounts of sediment were eroded from the front during the investigated period, and most of it was transported further down, sometimes after having been stored for a certain lapse of time in the gully.

V. Discussion

The methodology seems appropriate to the object of the study. It brings important information about the spatial behavior of the sediment transfer processes and especially quantitative data about erosion and accumulation. The repetition of the

TABLE I. CALCULATED VOLUMES (SEDIMENTS ONLY) FOR THE DIFFERENT TIME INTERVALS

Time interval	Budget at the front (m^3)	Budget in the gully (m^3)	Total budget (front & gully) (m^3)	Erosion rate at the front (m^3/day)
25.06.2013-10.07.2013 *(15 days)*	-394	*352*	42	26
10.07.2013-04.10.2013 *(86 days)*	-1163	1065	-98	14
04.10.2013-26.06.2014 *(265 days in which 124 days where the front is covered with snow)*	-2437	582	-1855	18
26.06.2014-09.10.2014 (105 days)	-2304	-2207	-4511	22

measurement supplies temporal variability data. However, the results need to be analyzed carefully. The methodology used to correct the influence of the rock glacier movement implies some simplifications and the calculated volumes give therefore an order of magnitude more than exact numbers. In addition, the interpretation of the surface changes map can be difficult depending on the time between two scanning campaigns. There is then a need for other sources of information. In this study, webcam images were used to link surface changes with the occurrence of sediment transfer processes.

There are also some limits associated to the measurement itself. For example, it is difficult to find stable terrains for the coregistration. This could induce some uncertainties that we did not quantify. In addition, the presence of snow in the gully between November and June reduces the potential scanning period. Finally, the method asks for a good coverage of the whole area of interest, which implies to have access to good scan positions at reasonable distances.

VI. CONCLUSION

TLS seems to be a well suited method the get quantitative data about surface changes and sediment transfer processes in steep and remote environments where aerial and satellite data are known to have performance restrictions [4]. However, the application of such a method on rock glacier fronts asks for additional data such as GPS measurements and images to help the interpretation of the results. In the case of the Gugla-Bielzug rock glacier, the combination of geodetic measurements, observations from high temporal resolution photographs and TLS have been proven to be a coherent method to get precise spatial and temporal information about the evolution of this system.

VII. ACKNOWLEDGEMENT

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