Stability Monitoring of High Alpine Infrastructure by Terrestrial Laser Scanning

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Abstract

Rock mass movements are dominant in the morphodynamics of high Alpine rock slopes and are at the origin of significant risks for people who attend these areas and for infrastructures that are built on (e.g. huts, cable cars). These risks are increasing because of permafrost degradation and glacier retreat as consequences of the global warming. These two factors may affect slope stability by changing mechanical properties of the interstitial ice and modifying the mechanical constraints in these rock slopes. The monitoring of rock slopes is thus an essential element for risk management. Our study focuses on two particularly active areas of the Western Alps: the lower Arête des Cosmiques (3613 m a.s.l., Mont Blanc massif, France) on which is located the very popular Refuge des Cosmiques, and the Col des Gentianes (2894 m a.s.l., Valais, Switzerland) where is located a cable car station. Discussed on the basis of geophysical and glaciological data, the evolutions monitored by terrestrial laser scanning probably result from the combination between permafrost activity/degradation and glacier shrinkage.

Keywords

High alpine infrastructure • Landslides • Permafrost • Glacier • Hazards

32.1 Introduction

High mountain environments became true markers of the climate warming, particularly through the glacier retreat and the permafrost degradation (Harris et al. 2009) i.e. the warming of any lithospheric materials that remain at or below 0 °C for at least two years. Both processes—and combination -, are often pointed out to explain the current upsurge of gravitational hazards (rockfalls, landslides) in high mountains (Ravanel and Deline 2011) by changing mechanical properties of the interstitial ice and modifying the mechanical constraints in the rock slopes.

Such instabilities are becoming of increasing concern (Haeberli et al. 1997). It is especially true since high alpine mountains are more and more visited (tourist flows) and well endowed with infrastructure (refuges, railways cable cars and associated buildings). In the recent years, an increasing number of damage occurred on structures, both in context of bedrock and sedimentary formations.

Our study focuses on the case of two highly anthropised areas (Fig. 32.1). The first one is the lower Arête des Cosmiques (LAC hereafter, 3613 m a.s.l., Mont Blanc massif, France) on which is located the very popular Cosmiques hut. Since 1998, when a rockfall threatened a part of the refuge, observations allowed to identify several detachments. Since 2009, this area is yearly surveyed by terrestrial laserscanning (TLS) to obtain high-resolution 3D

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Fig. 32.1 **a** The lower Arête des Cosmiques with the Cosmiques hut (3613 m a.s.l.) on it; **b** the inner side of the Gentianes moraine (2894 m a.s.l.) with its lower Mont Fort cable-car station

models. Their diachronic comparison shows few important rock detachments between 2009 and 2011. The second one is the Col des Gentianes (2894 m a.s.l., Valais, Switzerland) where is located a cable-car station. Since the early 1980s the moraine is unstable: its inner slope has retreated for several meters. Since 2007, the moraine is monitored by TLS: 8 campaigns were conducted between July 2007 and October 2011. The comparison of the high resolution 3D models obtained allowed the detection and quantification of mass movements that have affected the moraine over this period.

32.2 The TLS Method

In the case of the LAC, the presence of refuge keepers attentive to the mountain evolution has yielded a quasi-complete data collection of rockfalls since 2003 (Ravanel et al. 2013). Prior this date, a rockfall in 1998 had however attracted the attention of keepers and risk managers in Chamonix. It affected the slope immediately under the refuge, requiring closure of the refuge and important works of consolidation. These observations were then completed in 2011 by TLS measurements in order to characterize the affected areas and to compute the fallen volumes.

These topographic measurements have been carried out using a terrestrial laser scanner. This is an active acquisition device that emits electromagnetic energy in the form of laser beams and records back the amount of energy that is reflected by the object being scanned. The high degree of accuracy of the measurement of the time-of-flight and of the angle attitude of each pulse provides quickly high resolution point clouds (Oppikofer et al. 2008; Ravanel et al. 2010).

The first TLS campaign at the LAC was carried out in October 2009. Two others were carried out the two following years (Oct. 2010, Sept. 2011). The first TLS measurements at the Gentianes moraine were carried out in July 2007 (Ravanel and Lambiel 2013). Since this date, the moraine has been scanned one (2009), two (2007 and 2008) or three times (2011) a year, with a break in 2010. The device used is an *Optech* ILRIS 3D (wavelength: 1500 nm; acquisition speed: 2000 pts. per sec.; effective range: 600 m). According to the manufacturer, the acquisition accuracy of a point at 100 m is 7 mm in distance and 8 mm in position. Initialization and setup of the scanner are controlled by a driver. After the determination of shooting windows and the point spacing, the acquisition is automatic.

The obtained point clouds are assembled in the software *InnovMetric* PolyWorks to get a full single high resolution 3D model of the rockwall (Rabatel et al. 2008). The comparison of 3D models allows measuring morphological changes. As result of this comparison is a difference map where each point of the 3D model “data” is coloured depending on its distance from the nearest point on the 3D model “reference”. The operator can then identify rockfalls or landslides using this difference map and the corresponding colour scale—once remove the differences resulting from changes in ice/snow cover and shifts in measuring stations. Then, the volume of identified rockfalls can be computed.

32.3 Results

32.3.1 A Very Active Cosmiques Rock Ridge

The first important collapse occurred in 1998, immediately below the refuge (600 m^3). No evidence of instability has been collected for the following 5 years. In 2003, a rockfall (140 m^3) occurred a hundred meters SW of the refuge. In 2004, two rockfalls occurred. One mobilized a rock volume of 200 m^3 in the immediate vicinity of the scar of 2003, whereas the second one (20 m^3) reshaped the SW margin of the 1998 scar. A new deposit was formed on the Glacier du Géant due to a rockfall of 85 m^3 that occurred in July 2006 on the crest line, just above the 2003 scar. Another rockfall detached in the same area in July 2007 (180 m^3), reshaping the crest line. Another rockfall (40 m^3) affected again the ridge. No significant destabilization occurred until August 2009 when a rockfall (200 m^3) detached, mobilizing blocks that formed the crest of the LAC.

The first TLS comparison (Oct. 2009–2010; Fig. 32.2) shows two unstable areas. The first, fairly recurrent, was the most active area between 2003 and 2009. Three new ones affected it in 2010: a fractured block of 256.2 m^3, a block of 0.7 m^3 and a pile of blocks of 52 m^3. The second unstable area recognized during the period is a couloir. A minimal volume of 111.7 m^3 of rock detached in the lower part of the couloir. Two unstable areas were identified for the second period (Oct. 2010–Sept. 2011). A massive block of 40.1 m^3 detached about 10 m downstream the most active area. A second unstable area is the couloir. In its lower part, three events occurred: the instability documented in 2010 continued mobilizing 48.7 m^3, a column slightly tilted, and another detachment (4.4 m^3).

32.3.2 Evolution of the Gentianes Moraine

TLS data acquired between 2007 and 2011 have provided opportunities for 7 diachronic comparisons (Ravanel and Lambiel 2013). The first comparison (July–Oct. 2007) reveals several evolutions. The most directly visible one is a landslide of 198 ± 6 m^3. Positive volume changes appear on both sides of this landslide, related to deposits of anthropogenic origin. Finally, about twenty meters downstream from the cable-car station, a 40-m-wide and 15-m-high area is characterized by gravitational movements of blocks. Between Oct. 2007 and July 2008, morphodynamics is reduced. The third comparison (July-Oct. 2008) is evidencing a new landslide occurred just south of the 2007 one, mobilizing 111 ± 6 m^3 of material. Two other areas were affected by movements of blocks. The following comparison (Oct. 2008–Sept. 2009) reveals new deposits probably of anthropogenic origin. Three areas have been affected by movements of blocks. Two juxtaposed landslides occurred,

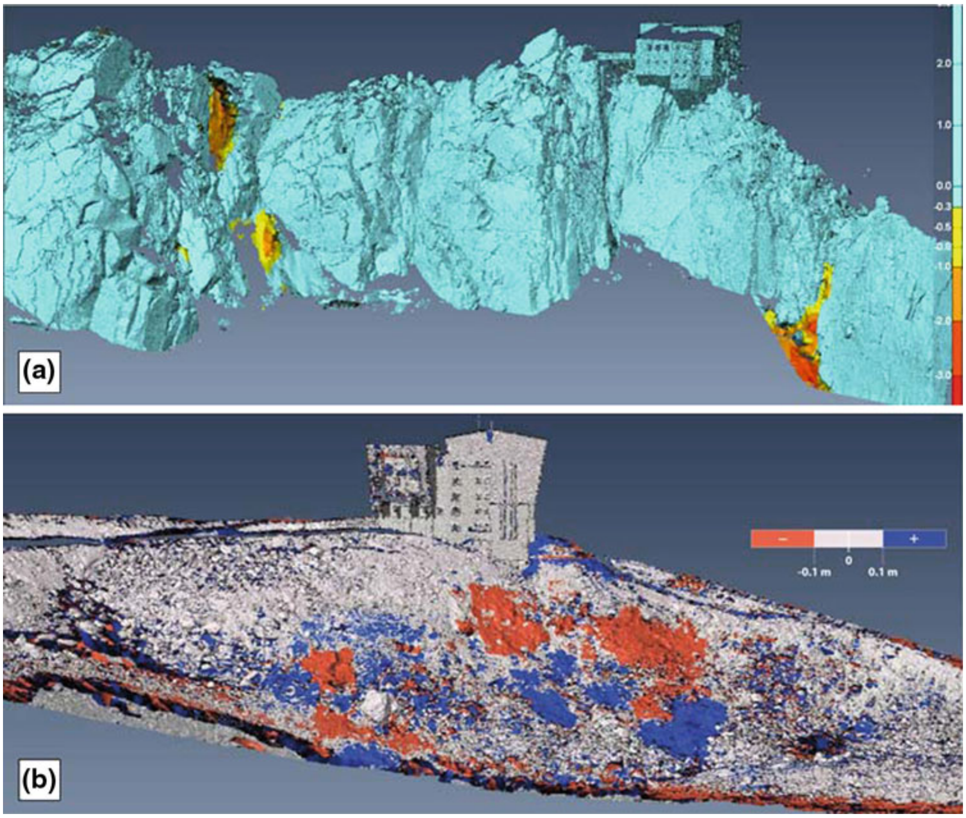

Fig. 32.2 **a** 3D model comparison of Oct. 2009 and Oct. 2010 of the LAC (4 identified rock detachments; scale is in m); **b** comparison of July 2011 and Aug. 2011 of the Gentianes area

with a total volume of 1138 ± 47 m^3. The following comparison (Sept. 2009–July 2011) indicates that the two main areas of individual movements of blocks continued to evolve. Between these two sectors, a significant loss of volume was recorded (874 ± 61 m^3). The absence of deposit at the foot of the moraine suggests that this loss is due to ice melting. The activity of the summer 2011 (early July–late Aug.) is arguably the most important of the study period (Fig. 32.2). Beyond the anthropogenic establishment of a small deposit and the continuation of the movements of blocks, three landslides have affected the moraine (270 ± 12 m^3, 217 ± 14 m^3 and 546 ± 20 m^3). The last comparison (Aug.–Oct. 2011) shows that three areas continued to be affected by block movements. A new landslide, whose volume is estimated around 115 m^3 finally affected the area.

32.4 Discussion and Conclusions

At the LAC, rock temperature data suggest the presence of temperate permafrost from the first meters to depth in the SE face, and cold permafrost in the NW face. The presence of permafrost has been corroborated by the observation of massive ice in several rockfall scars, emphasizing the role of ice in the slope stability. As suggested by the occurrence of rockfalls mainly during or at the end of hot periods in summer, degradation of the ice has likely participated in the triggering of a large part of these rockfalls (see: Gruber and Haeberli 2007).

The evolution of the glacier also directly interferes with the stability of the LAC. It is indeed striking to note that the rockfall of 1998 has affected a slab whose base was located under the ice until that year. The glacier mass balance of the hydrological year 1997–1998 is the lowest of the 8 years that have been measured, which caused a strong lowering of the glacier and the snow cover below the refuge. Similarly, 2010 and 2011 rockfalls in the couloir located east of the refuge were possible because of the lowering of the glacier in the recent years. Before, the glacier exerted a stop-effect prone to stabilize the potential instability determined by the geological structure.

The diachronic comparisons of 3D models at the very probably ice-cored Gentianes moraine also showed a significant general instability trend that can be mainly explained by the combination of the loss of glacier thickness and the permafrost activity/degradation, both allowed by a series of hot summers. The annual thaw of the active layer (measured) seems to promote rearrangements of rock material (block movements) and, when this active layer reaches the ice present in a part of the moraine, landslides are initiated. Two main scenarios are then possible: (i) the buttress exerted by the sediment located just below is sufficient to stop the phenomenon, or (ii) a landslide occurs. The latter scenario, which has been reproduced 7 times over the study period, is largely induced by the loss of thickness of the glacier (locally reaching 11.3 m, which corresponds to a local ablation in the order of 2.25 m per year) and certainly by the increase of the slope angle.

Given those results, the TLS method appears as a very relevant method for monitoring the evolution of those highly anthropised and vulnerable area.

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