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Discussions

Brief communication
"Estimating rockfall frequency in a mountain limestone cliff using terrestrial laser scanner"

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Abstract

Using terrestrial laser scanner, 344 rockfalls larger than $0.05\,m^3$ have been detected for a period of 1180 days, in a thinly bedded limestone cliff of width 750 m and height 200 m. The complementary cumulative distribution of the rockfall volume is well fitted by a power law, with an exponent b of 0.75 ± 0.04. In order to compare the rockfall frequencies in different geological contexts, a rockfall activity parameter has been defined, which is the number of rockfalls larger than $1\,m^3$, which occur per century and per hm^2.

1 Introduction

Estimating rockfall frequency is needed to characterize a diffuse rockfall hazard (Hungr, 1999; Picarelli et al., 2005; Fell et al., 2005; Hantz, 2011). Up to now this frequency is determined from historical inventories. The minimal volume detected in these inventories can be relatively small when the rock blocks fall on a road or railway, but it is larger when they fall on a slope from a high rock cliff (Dussauge-Peisser et al., 2002). In the last years, terrestrial laser scanner (TLS) has been used to detect rockfalls by comparing digital cliff models obtained from successive datasets. It appears from these surveys that the spatial-temporal rockfall frequency (number of rockfalls per unit of surface and time) for a given minimal volume strongly depends on the geological and geomorphological contexts (lithology and structure of the cliff, erosion factors). The development of TLS allows to precise the frequencies corresponding to different contexts and further to determine the influence of the geological and geomorphological factors on the spatial-temporal frequency. In this paper, we study the rockfall frequency in a typical limestone cliff of the Subalpine Chains.

The Mont Saint-Eynard (1308 m) is located 4 km to the North of the Grenoble centre and towers above a residential area of the town. Its geological context has been described by Gidon (2013). The South-East face consists of, from top to bottom: a 120 m

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high limestone cliff (Tithonian and upper Kimmeridgian stages); a 100 m high forested slope of marl and marly limestone (Kimmeridgian stage); a 240 m high limestone cliff (Sequanian stage); a 300 m high forested talus slope, covering marl and marly limestone of the Oxfordian stage. This paper describes the results obtained for the Sequanian cliff.

The laser scanner technology is based on the acquisition of a point cloud using a time-of-flight distance measurement of an infrared laser pulse which reflects on the topography. The raw data consist of the x, y, z coordinates of each reflection point and the intensity of the reflected pulse. The survey station was located at the foot of the talus slope, on a protection embankment at an elevation of 580 m. The inclined distance to the cliffs ranges between 625 m and 900 m. Photographs and laser measurements were carried out on 27 August 2009 and 19 November 2012.

We have used two Optech systems: ILRIS-3D in 2009 and ILRIS-LR in 2012. The main characteristics of these systems are given in Table 1. It can be seen that ILRIS-LR has a higher repetition rate, allowing a greater number of points to be measured for a given period of time. In the distance range concerned, it can also measure surfaces having a lower reflectivity than ILRIS-3D. According to the distances given above and the accuracy given in Table 1, the expected accuracy of our distance measurements ranges from about 5 cm for the closest points to 7.5 cm for the farthest ones. Two scans were taken to cover a cliff width of about 750 m.

2 Data processing

The software 3DReshaper Application have been used to process the point clouds. Vegetation has a lower reflectivity than the rock making up the cliff. Thus, a reflectance threshold has been chosen to remove most of the points corresponding to vegetation. After cleaning, the point clouds consisted of 2.7 Mpt in 2009 and 12.8 Mpt in 2012. The average distance between the points ranged from 21 to 29 cm (according to the distance from the camera to the cliff) in 2009 and from 10 to 13 cm in 2012.

Georeferencing the LiDAR point clouds was made by registering these with a Digital Elevation Model (1 m × 1 m) using Lambert 2 extended (x, y) coordinates and NGF IGN 69 leveling (z). Then the coordinate system has been rotated in order to easily determine the width and the thickness of the fallen compartments. The width is defined horizontally, parallel to the cliff (new x direction), the thickness is defined horizontally, perpendicular to the cliff direction (new y direction) and the height is parallel to the z-axis (unchanged). The positive direction is inside the cliff for the y-axis and towards the East side for the x-axis.

The more recent point cloud (2012) has been transformed in a mesh, made up of 2.7 million of triangles and 1.3 million of vertex. The average distance between the vertex of the polyhedrons ranges from 26 to 36 cm (according to the distance from the camera to the cliff). The registration of the 2012 point cloud with the corresponding mesh gives information about the roughness of the rock surface at the scale of the triangles making up the mesh. It appears that about 50 % of the points are closer than 1 cm from the mesh, 90 % are closer than 3 cm and 99 % are closer than 7 cm.

As georeferencing with the DEM was not precise enough, the 2012 mesh and the point cloud acquired in 2009 have been registered (fitted) together in order to put them exactly in the same coordinate system. Ideally, the positive deviations between these objects (Fig. 1) should be due only to rockfalls occurred between 2009 and 2012. But in reality, there are other causes of deviations: (a) measurement inaccuracy; (b) the 2009 measurement points do not correspond to the 2012 ones and consequently, are not exactly on the triangles defined by the 2012 vertex (due to the curvature and the roughness of the rock surface); (c) the later cause is accentuated in areas where the triangles are large (this situation occurs particularly near the limits of the mesh); (d) vegetation element which has not been removed; (e) earth slide due to the impact of an overlying rockfall. Consequently, a deviation threshold has to be set for the detection of true rockfalls.

3 Rockfall frequency estimation

In a first stage, a deviation threshold was set to 0.2 m in order to make possible checking the rockfalls by comparing photographs taken in 2009 and 2012 (for a lower threshold, most of the rockfalls are not visible on photographs). A rockfall has been considered certain when a positive deviation is observed and the comparison of the 2009 and 2012 photos shows that a rockfall has occurred between these dates. When a positive deviation is observed and the comparison of the 2009 and 2012 photos shows that no rockfall has occurred, the deviation has been considered to be a false rockfall. The false rockfalls which have been obtained are due to the conditions (c) or (d) expressed in the later paragraph. When a positive deviation is observed and the photo comparison cannot conclude if a rockfall has occurred or not, the deviation has been considered to be an uncertain rockfall if the conditions (c) or (d) occur or a probable rockfall if these conditions don't occur.

At this stage of analysis, 169 events have been detected, out of which 2 false rockfalls and 5 uncertain ones. The minimal and maximal volumes detected are respectively of 0.018 m^3 and 81 m^3. For the 138 certain and 24 probable rockfalls detected, the volume has been calculated by creating a watertight mesh, starting from the 2009 and 2012 surfaces of the fallen rock compartment, which were not initially attached. This procedure is manual and time consuming. The complementary cumulative distribution function of the rockfall volume is shown in Fig. 2. A power law has been fitted to the data. It can be seen that the fitting is better when considering only the volumes greater than 0.1 m^3.

In a second stage, the deviation threshold has been lowered in order to detect smaller rockfalls, which cannot be checked with photographs. According to the accuracy expected, the deviation threshold has been set to 0.1 m. In this stage, 295 additional events have been detected, out of which 229 probable rockfalls. The complementary cumulative distribution function of the rockfall volume is shown in Fig. 3.

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The fitting to a power law is better when considering only the volumes greater than $0.05\,\mathrm{m}^3$.

4 Discussion

The distribution function of the rockfall volume has been studied by several authors (see reviews in Dussauge-Peisser et al., 2002, and Brunetti et al., 2009). Most of them found that the complementary cumulative distribution function is well fitted by a power law:

$$N = aV^{-b} \tag{1}$$

where V is the rockfall volume, N is the number of rockfalls larger than V occurring in a given rock wall during an investigation period, a and b are constants. The constant a represents the number of rockfalls whose volume is greater than $1\,\mathrm{m}^3$ (assuming the law is valid for this volume range). It depends on the size of the cliff, the length of the investigation period and the geological and geomorphological context. On the contrary, the exponent b only depends on the geological and geomorphological context. Its value has been determined for some different contexts (Dussauge-Peisser et al., 2002). For the particular contexts studied up to now, it ranges from 0.4 to 0.72. Its standard deviation has been estimated in some cases (Dussauge-Peisser et al., 2003) using a maximum likelyhood method:

$$\sigma = b \Big/ \sqrt{N_0} \tag{2}$$

where N_0 is the number of events considered and b is the exponent value in Eq. (1).

Figure 2 shows the volume distribution function for the rockfalls detected in this study using a threshold of 0.2 m, most of which having been checked visually. It can be seen that the distribution function is well fitted by a power law for volumes greater than $0.2\,\mathrm{m}^3$, with an exponent of 0.69 ± 0.07 and a correlation coefficient of 0,983. But the

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volumes lower than $0.2\,m^3$ are underrepresented, probably by under-sampling. This is confirmed by Fig. 3, which shows the volume distribution function for a threshold of 0.1 m. This function is well fitted by a power law for volumes greater than $0.05\,m^3$, with an exponent of 0.75 ± 0.04 and a correlation coefficient of 0,994. Now the volumes lower than $0.05\,m^3$ are underrepresented. This underrepresentation can be due to the limited resolution of the investigation method or reflects the real distribution of the rockfall volume. The fact that the exponent value is not significantly changed by passing from the visually checked rockfalls (Fig. 2) to the numerically detected ones (Fig. 3), suggests that the obtained inventory is exhaustive for volumes greater than $0.05\,m^3$.

For comparing the rockfall activities of cliffs in different geological and geomorphological contexts, it is necessary to consider the number of rockfalls per unit of time and space (spatial-temporal frequency). For this purpose, we introduce the rockfall activity parameter A_{st}, which is a (from Eq. 1) divided by the cliff surface and the length of the observation period. In order to calculate this parameter for the Mont Saint-Eynard lower cliff, a mean height of 200 m and a width of 750 m have been considered, which give a value of 0.85 rockfalls per year and per hm^2, using the a value of 41 given in Fig. 3.

Hantz et al. (2003) analyzed the cumulative distribution of rockfall volumes between 10^2 and $10^7\,m^3$, occurred in the 120 km long limestone cliffs of the Grenoble area, which include the Mont Saint-Eynard cliff. They found that a power law well describes the distribution, with an exponent of 0.55 ± 0.11 and a rockfall activity of 0.0047 rockfalls per year and per hm^2. It appears that both parameters b and A_{st} are significantly different for the two considered rock fall populations: $b = 0.75 \pm 0.04$ and $A_{st} = 0.85$ for the Mont Saint-Eynard; $b = 0.55 \pm 0.11$ and $A_{st} = 0.0047$ for the Grenoble area. As the power law parameters for the two inventories were determined from volumes ranging respectively from $0.05\,m^3$ to $100\,m^3$ and from $100\,m^3$ to $10^7\,m^3$, it is more pertinent to compare the rockfall activities by using the numbers of rockfalls larger than $100\,m^3$, which occur per century and per hm^2. These numbers are respectively of 2.7 and 0.037, giving a ratio of 72. Several reasons can be proposed to explain this strong

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discrepancy: (a) The rockfalls for the Grenoble area were known from a historical inventory which is probably not exhaustive. (b) Most of the rockfall volumes for the Grenoble area were estimated from historical sources, with more uncertainty than for the Mont Saint-Eynard. (c) The cliffs of the Grenoble area consist of different calcareous rocks of Jurassic and Cretaceous age, including mostly massive limestones (metric to decametric thickness), whereas the cliff studied consists only of thinly bedded limestone of Sequanian stage (thickness of 20–50 cm).

5 Conclusions

Terrestrial laser scanner can be used to detect rockfalls which occur in high rock walls from a survey station located up to 900 m from the cliff. Using a threshold of 0.1 m in term of distance variation, 344 rockfalls larger than 0.05 m^3 have been detected for a period of 1180 days, in a rock wall of width 750 m and height 200 m.

The complementary cumulative distribution of the rockfall volume is well fitted by a power law, with an exponent b of 0.75 ± 0.04 and a rockfall activity parameter A_{st} of 0.85 rockfalls per year and per hm^2. These parameters characterize the rockfall frequency in a thinly bedded limestone cliff of the Subalpine Chains.

They are significantly different from those which have been obtained from a historical rockfall inventory covering 120 km of cliff consisting mostly of massive limestone: For this inventory, the b value is 0.55 ± 0.11 and the theoretical number of rockfalls larger than 100 m^3, which occur per century and per hm^2, is 0.037 instead of 2.7 for the thinly bedded limestone. Terrestrial laser scanning of large cliff surfaces of massive limestone in the Subalpine Chains is needed to better investigate the rockfall frequency in these cliffs.

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Table 1. Main characteristics of the laser scanners used.

Parameter	ILRIS-3D	ILRIS-LR
Range 80 % reflectivity	1200 m	3000 m
Range 10 % reflectivity	400 m	1330 m
Minimum range	3 m	3 m
Laser repetition rate	2500 to 3500 Hz	10 000 Hz
Efficiency	100 %	100 %
Raw range accuracy	7 mm @ 100 m	7 mm @ 100 m
Raw angular accuracy	8 mm @ 100 m	8 mm @ 100 m
Field of view	40° × 40°	40° × 40°
Minimum step size	0.001146° (20 µrad)	0.001146° (20 µrad)
Maximum density	2 cm @ 1000 m	2 cm @ 1000 m
Rotational speed	0.001 to 20 $^\circ s^{-1}$	0.001 to 20 $^\circ s^{-1}$
Beam diameter	22 mm @ 100 m	27 mm @ 100 m
Beam divergence	0.009740° (170 µrad)	0.014324° (250 µrad)
Laser wavelength	1535 nm	1064 nm
Integrated camera	3.1 MP	3.1 MP

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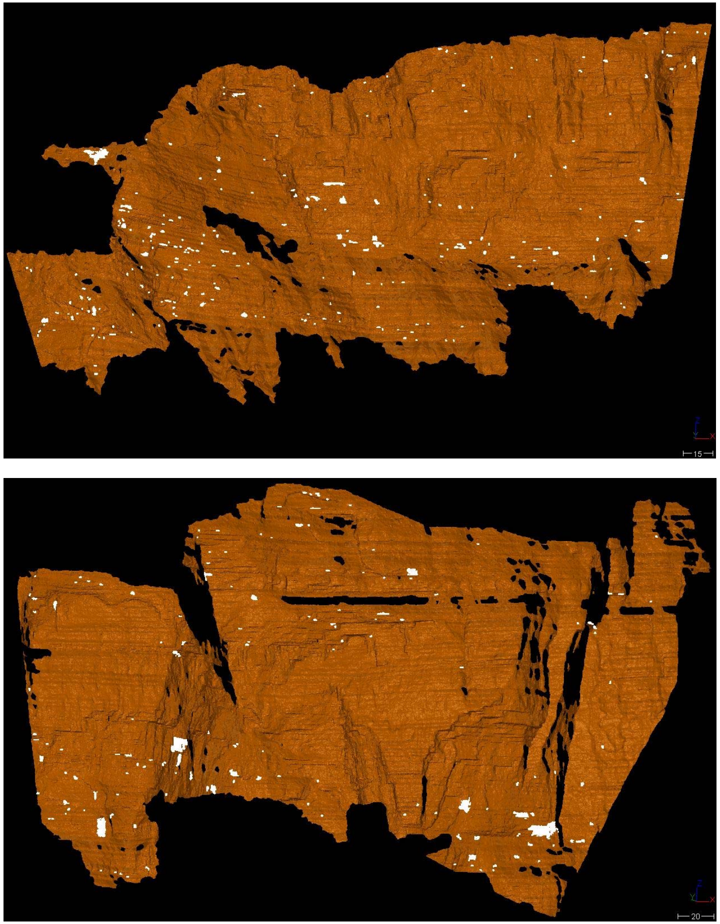

Fig. 1. Upper: mesh for the left scene 2012 and rockfall detected (white spots). Lower: mesh for the right scene 2012 and rockfall detected (white spots).

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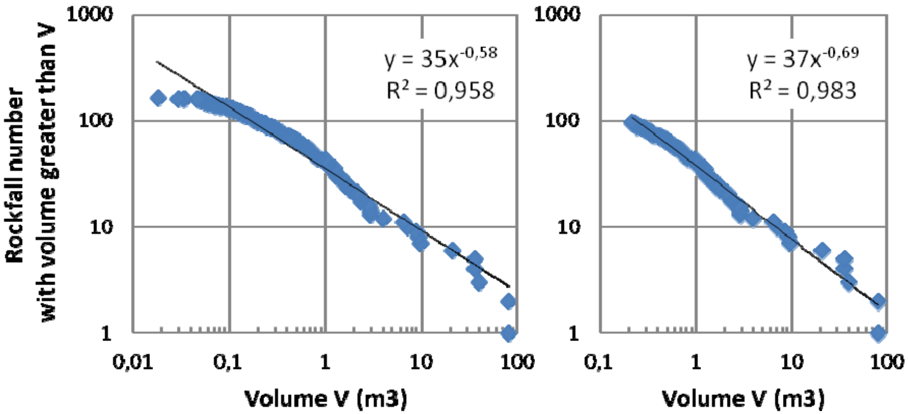

Fig. 2. Distribution function of the rockfall volume for a deviation threshold of 0.2 m. Left: volume > 0.01 m^3 (162 events). Right: volume > 0.2 m^3 (96 events).

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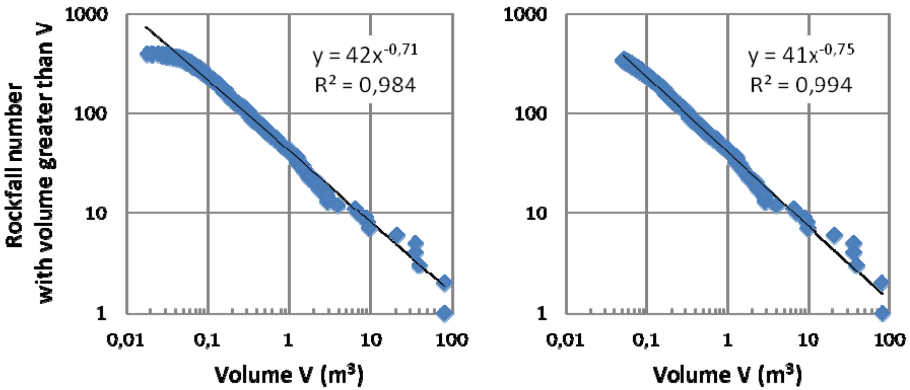

Fig. 3. Distribution function of the rockfall volume for a deviation threshold of 0.1 m. Left: volume > 0.01 m^3 (391 events). Right: volume > 0.05 m^3 (344 events).

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