Influence of geological and meteorological factors on the frequency of rockfalls

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ABSTRACT: The processes leading to rock slope failures are poorly known as well as the influence of the geological conditions on the rockfall frequency. Terrestrial laser scanner has been used to detect rock falls and determine the rockfall frequencies in different geological conditions. It appears that thinly bedded limestone present rockfall frequencies (for rockfalls bigger than 0.1 m^3) more than 10 times higher than massive rocks. The influence of meteorological factors on rockfall occurrence has been studied for a thinly bedded limestone cliff. It appears that rockfalls bigger than 0.01m^3 are more frequent in the periods including freeze-thaw episods. For rockfalls bigger than 0.1 m^3, the rockfall frequency is respectively 4 times and 3 times higher during rainfall episodes and freeze-thaw episodes, than during periods without rainfall or freeze-thaw. These results could contribute to a better rockfall hazard assessment and a better knowledge of the processes leading to rockfalls.

1 INTRODUCTION

The processes leading to rock slope failures are poorly known as well as the influence of the geological conditions on the rockfall frequency. This study presents rockfall frequency measurements for different geological and climatic conditions, which have been carried out using annual terrestrial laser scanning. Moreover, for one of the investigated cliffs, the dates of the rockfalls have been determined using a continuous photographic survey, allowing studying the influence of meteorological factors on rockfall occurrence.

2 INFLUENCE OF GEOLOGICAL CONTEXT

2.1 Rockfall detection

Rockfall detection is carried out by comparison of 2 point clouds of the cliff acquired in 2009 and 2012 (Guerin et al. 2014). A mesh was built with the point cloud acquired in 2012. This mesh was superposed with the 2009 point cloud, and the deviations obtained were considered as rockfalls. Different thresholds were used depending on the precision of the scanning (Guerin et al. 2013). The point clouds defining a fallen compartment were meshed, allowing to calculate the volume of the compartment and to get dimensions and gravity center.

2.2 Rockfall spatial-temporal frequencies

Four sites were studied in the Grenoble area (Figure 1). Three sites are located in the Subalpine Chains (Gorgette, Saint-Eynard, Chabloz), one site is located in a metamorphic part of the Massif des Ecrins (Venosc). Geological and topographical information are given in the Table 1 for each site.

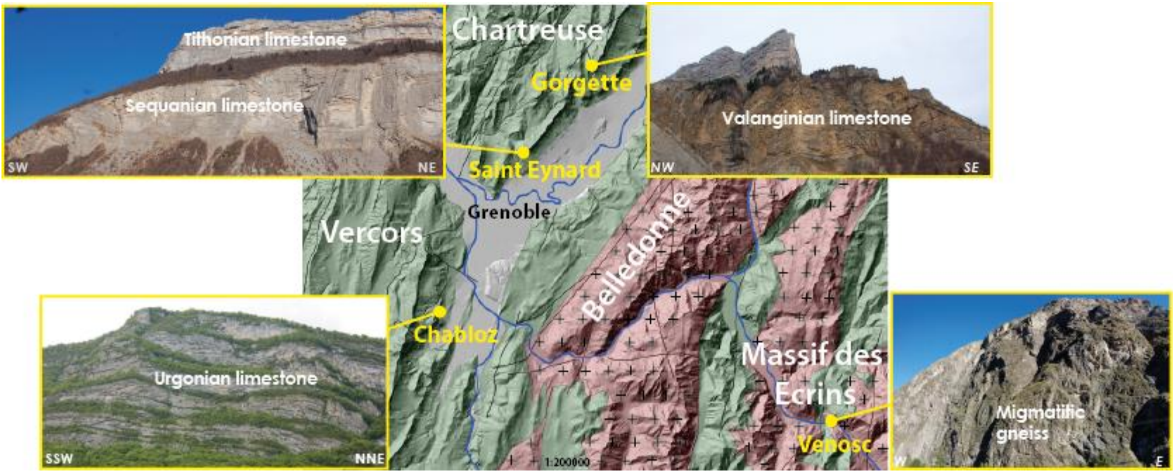

Figure 1: Location of the investigated cliffs (yellow points). Green: sedimentary rocks. Red and black cross: metamorphic and magmatic rocks. Black lines: major faults.

For the Gorgette cliff, lower cliff of St Eynard, and Venosc rockwall the cumulative distribution function of the rockfall volume is well fitted by a power law:

$$N = aV^{-b} \quad (1)$$

Where V is the rockfall volume, N the number of rockfalls larger than V, *a* and *b* constants depending on the site. The constant *a* represents the number of rockfalls greater than 1 m^3 and *b* characterizes the distribution of the volumes. N and *a* depend on the size of the cliff and on the length of the observation period. The values obtained for the different sites are given in the Table 1.

No fitting has been made for the cliffs where less than 10 rockfalls have been observed. To compare the activities of the different cliffs, they have been characterized by the spatial-temporal frequency of rockfalls bigger than 0.1 m^3 (F_{st}(0.1 m^3)), which is the number of rockfalls per year and per hm^2. Assuming a Poisson's law for the time occurrence of rockfalls, a 95% confidence interval has been determined for N(0.1 m^3) and F_{st}(0.1 m^3) (Table 1).

The rockwalls can be classified in two classes: a) Thinly bedded rock walls (0.1-0.5 m beds), which present F_{st}(0.1 m^3) values higher than 1, and b values of about 0.6-0.8; b) Massive rock walls (2-10 m beds), which present F_{st}(0.1 m^3) values around 0.1 and b value of about 0.4.

3 INFLUENCE OF METEOROLOGICAL FACTORS

3.1 Rockfall databases and meteorological data

This study focuses on the lower cliff of the Mont Saint Eynard (MSE), consisting of thinly-bedded limestone, because of its higher rockfall activity. Rockfalls have been detected using annual terrestrial laser scanning. A photographic survey from 1 km to the cliff allows us to date the occurred rockfalls. It consists of high resolution photographs taken every 2-11 weeks (periodic survey) and lower resolution photographs taken every 10 minutes (continuous survey).

Table 1: Rockfall frequency parameters for different geological and topographical conditions.

Site		Gorgette	St-Eynard	St-Eynard	Chabloz	Venosc
Aspect		SW	SSE	SSE	E	SW
Elevation	[m]	1300-1500	850-1100	1150-1300	750-1050	1000-1800
Slope angle	[°]	55	70	80	65	65
Rock		Bedded limestone	Bedded limestone	Massive limestone	Massive limestone	Massive gneiss
Dip direction / dip	[°]	90 / 40	345 / 35	330 / 60	270 / 45	
Number of events > $0.1m^3$		64	233	3	2	12
95% conf. interval		[50-80]	[204-262]	[1-7]	[1-6]	[7-20]
Wall surface	[hm²]	5.14	12.96	7.72	10.46	36.57
$F_{st}(0.1\ m^3)$	$[hm^{-2}.yr^{-1}]$	3.85	5.57	0.12	0.06	0.10
95% conf. interval		[3.0-4.8]	[4.9-6.3]	[0.04-0.28]	[0.03-0.18]	[0.06-.017]
Exponent b		0.64	0.75	-	-	0.38
95% conf. interval		[0.55-0.73]	[0.67-0.83]			[0.16-0.60]

609 rockfalls have been detected between 16/11/2012 and 15/07/2014. Each rockfall has been checked on high-resolution photographs, and dated in 2-11 weeks long periods. They constitute the database 1 (DB1).

Among these rockfalls, 125 rockfalls have been dated more precisely thanks to the continuous photographic survey. They occurred between 1/2/2013 (installation of photographic survey) and 15/07/2014. They constitute the database 2 (DB2). Around 75% of DB2 rockfalls are dated in periods of 10 min to 20 h. Note that all the rockfalls detected (particularly the smaller ones) could not be precisely dated from low-resolution photographs (only 25% of the DB1 events were dated precisely).

The volume distributions for the 2 databases are given on Figure 2. The volumes of most of the rockfalls for the DB1 are between 0.01 and 0.1 m^3, whereas volume of most of the rockfalls for DB2 are above 0.1 m^3.

The meteorological data come from weather stations of Météo France network around the cliff, and since February 2014, from temperature sensors which have been placed on the upper cliff (1290 m ASL) and inside the rocks. Rainfall data are given by a rain gauge located 900 m from the cliff face, and valley temperature from a station located around 2 km from the cliff face at an elevation of 220 m. As we used temperatures from the valley and from the cliff crest, we interpolated the temperature at 900 m (average height of rockfalls).

3.2 *Meteorological data treatment*

In order to link the meteorological factors to the occurrence of rockfalls, a particular approach has been used. The fact that rockfalls are more precisely dated than in historical inventories for example, allows us to consider meteorological factors more precisely. We have considered rainfall and freeze-thaw episodes, defined precisely.

A rainfall episode begins with the rain. It ends if no rainfall has occurred during 24h. This value has been chosen from field observation and considering the cliff height: we assumed that after 24h, the rain has no more direct effect on the rock mass.

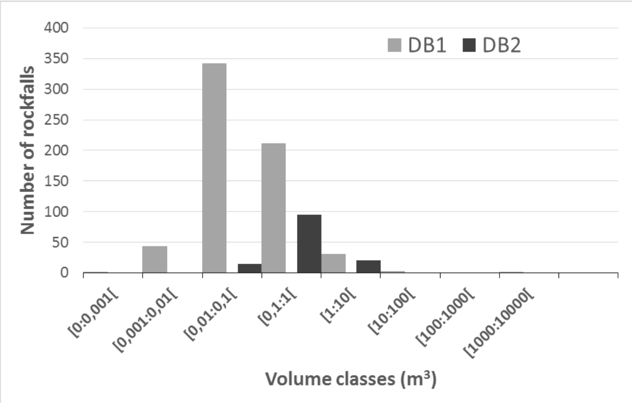

Figure 2: Volume distribution for the 2 rockfall databases

The presence and quantity of ice in the rock mass (defining a freeze-thaw episode) can be approached using the freezing potential (FP) (Montagnat et al. 2010), defined by:

$$FP = \int_{t0}^{t} \big(Ti - T(t)\big) dt \qquad (2)$$

A freeze episode begins when the temperature becomes negative ($t = t_0$), and ends when it becomes positive again. A thaw episode begins when the temperature becomes positive (the FP is necessarily positive), and ends when the temperature becomes negative again (new freeze period) or FP reaches 0 (the ice has melt).

The influence of ice on rockfall occurrence can be explained by the pressure it exerts in rock discontinuities, either when the ice forms in a confined environment (joints, cracks or pores), and either when it dilates during heating episodes. In order to investigate these processes, the freeze-thaw episodes have been divided in three types of periods: cooling periods (when temperature decreases), warming periods (when temperature increases but remains negative) and thawing periods (when temperature is positive).

3.3 Results

3.3.1 DB1: Rockfall frequencies during periods of the year

For each period, the number of rockfalls is known, as well as the duration of rainfall or freeze-thaw episodes (Figure 3). It appears that the 6 periods with the highest rockfall frequencies are the periods which have the highest freeze-thaw relative duration. But they don't correspond to the periods with the highest relative rainfall duration. For periods without freeze-thaw, the lowest rockfall frequency corresponds to the lowest relative rainfall duration.

3.3.2 DB2: Influence of rainfall and freeze-thaw

Each rockfall in the DB2 has been associated with a precise rainfall and/or freeze-thaw episode (Table 2). Compared to the mean rockfall frequency for the complete period of the DB2, rainfall and freeze-thaw periods present a higher rockfall frequency. Rainfall seems to be the more important triggering factor for the DB2, which consists mainly in volumes greater than 1 m^3, contrarily to DB1, which includes a lot of smaller volumes (Figure 2). Nevertheless, both meteorological factors have a significant impact on rockfall triggering.

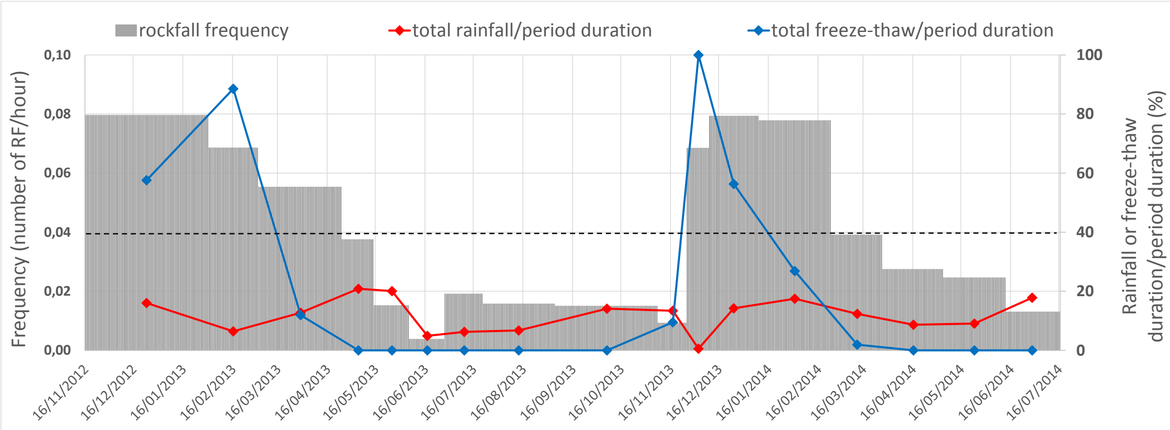

Figure 3: Rockfall frequencies for each period of datation, and rainfall and freeze-thaw relative duration during these periods. Black dashed line: average frequency on the investigation period.

Table 2: Rockfall frequencies of DB2 considering the different meteorological situations.

	Duration (hours)	Number of rockfalls	Rockfall frequency
Complete period	12,696	125	0.0098
Rainfall periods	3211	62	0.0193
Freeze-thaw periods	1851	26	0.0140
Cooling periods	*767*	*9*	*0,0117*
Warming periods	*312*	*6*	*0,0192*
Thawing periods	*772*	*12*	*0,0155*
Rain and freeze-thaw	204	1	0.0049
No meteo. factor	7430	36	0.0048

3.3.3 DB2 : Influence of freeze-thaw

The influence of ice on rockfall occurrence can be explained by the pressure it exerts in rock discontinuities, either when the ice forms in a confined environment (joints, cracks or pores), and either when it dilates during heating episodes. In order to investigate these processes, the freeze-thaw episodes have been divided in three types of periods: cooling periods (when temperature decreases), heating periods (when temperature increases but remains negative) and thawing periods (when temperature is positive). The rockfall frequencies for each type of period have been compared in Figure 4, where the uncertainty has been represented. For the three cases, it appears that the frequency is higher than for the periods with no meteorological perturbation, but it is difficult to conclude about the more influent factor.

4 CONCLUSION

In order to better assess rockfall hazard, rockfall frequencies have been studied regarding geological and meteorological contexts. It appears that thinly bedded limestone present rockfall frequencies more than 10 times higher than massive rocks. For a thinly-bedded rock wall, the influence of rainfall and freeze-thaw has been highlighted. It appears that rockfalls bigger than 0.01 m^3 are more frequent in the periods including freeze-thaw episodes. For rockfalls bigger than 0.1 m^3, the rockfall frequency is respectively 4 times and 3 times higher during rainfall episodes and freeze-thaw episodes, than during periods without rainfall or freeze-thaw.

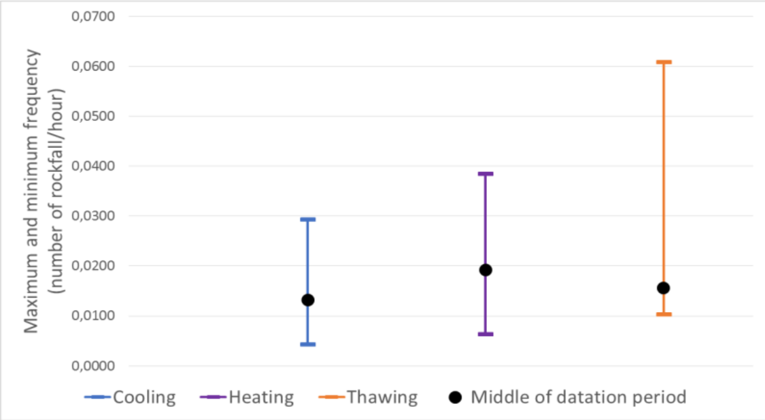

Figure 4: The bars represent the maximum and minimum frequency considering the datation intervals. The black dots indicate the frequency considering the middle of the intervals (most probable date).

ACKNOWLEDGEMENTS

The authors would like to thank the Région Rhône Alpes, and the Federation VOR (Vulnérabilité des Ouvrages aux Risques).

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