A FIRST ROCKFALL SUSCEPTIBILITY ASSESSMENT IN THE MONT BLANC MASSIF BASED ON ROCKFALL INVENTORIES

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ABSTRACT

In the last two decades, many rockfalls and rock avalanches occurred in high mountain areas throughout the world. We term rockfall the sudden collapse of a rock mass from a steep rockwall, with a volume exceeding 100 m^3. Among geomorphological phenomena affecting mountain regions, rockfalls and rock avalanches are the most unexpected ones because of their high speed, the large volume of rock involved, and the risks they generate: destabilization of infrastructures, danger for population and buildings along the path of the rockfalls, and in the valleys through cascading effects. Frequency of rockfalls rises in the Alps mainly due to the permafrost degradation controlled by the global warming, while vulnerability is increasing both at high elevation and at the bottom of the valleys. Our study presents a method for assessing the rockfall susceptibility in the Mont Blanc massif, based on the characterisation of rockfalls through the analysis of two types of inventories. Results are convincing and show that it is possible to assess rockfall hazard in high mountain.

Keywords: Rockfalls, hazard assessment, high mountain, Mont Blanc massif

INTRODUCTION

Due to their steep topography, mountains are affected by significant gravity-related transfers of materials. In peri- and supra-glacial areas, these transfers can result from rockfalls. A rockfall is usually an exceptional process, which corresponds to the sudden collapse of a rock mass from a steep rockwall, with a volume exceeding 100 m^3. Recently, many rockfalls and rock avalanches occurred in high mountain areas. Several of these phenomena implied rock and ice, with volumes exceeding 1×10^6 m^3: Mount Cook in New Zealand in 1991, 14×10^6 m^3; Kolka-Karmadon in the Caucasus in 2002, 100×10^6 m^3; Punta Thurwieser in Italy in 2004, 2.5×10^6 m^3; or Piz Cengale in Switzerland in 2011, 2-4 $\times 10^6$ m^3 for example. The failure mechanism differs according to the topographic and structural configurations. However, rockfalls and rock avalanches generally occur in hard rocks along pre-existing fractures. In high mountains, three major factors – possibly combined – can trigger those phenomena: (i) glacial debuttressing due to glacial retreat, (ii) seismic activity and (iii) permafrost degradation (Gruber and Haeberli, 2007), which corresponds to warming of the ground (i.e. substratum) that remains at or below 0°C for at least two years, thus generating physical changes of the potential interstitial ice (Haeberli et al., 1997).

Rockfalls are the most unexpected geomorphological phenomena affecting mountain regions because of their high speed, the large volume of rocks involved, the profound changes they may imprint to landscapes, and the risks they imply: infrastructures destabilization, effects on infrastructures and tourism flows located along the path of the rockfalls, and material/human risks for valleys through cascading effects.

The characterization of rockfall events and the understanding of their triggering are prerequisites to any response of management. However, data on rockfalls at high elevation are rare and it is difficult

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to interpret non-representative data (few isolated examples). That is why in the Mont Blanc massif (western Alps) we aim to systematically collect and process current data on rockfalls in order to better characterize these phenomena (triggering conditions, frequencies, and volumes), which occurrence can be increased due to global warming. To document present rockfalls, a network of observers (guides, mountaineers, and hut wardens) was initiated in the Mont Blanc Massif in 2005 and became fully operational in 2007. 139 rockfalls have thus been documented between 2007 and 2009. In addition, it was necessary to obtain exhaustive data on the large number of rockfalls that occurred during the 2003 summer heatwave. 182 rockfalls were identified from their supra-glacial deposits through the analysis of a SPOT-5 image taken at the end of the heatwave, which covers the entire massif.

This study presents a method for assessing the rockfall susceptibility in the Mont Blanc massif, based on the characterisation of rockfalls through the analysis of those two types of inventories. The data used to parameterize the rockfall susceptibility model are the one of 2003, 2007 and 2008. Rockfalls of 2009 are, in turn, used to validate the model.

TWO TYPES OF ROCKFALL INVENTORIES: METHODS AND DATA COLLECTED

Data on rockfalls at high elevation are scarce, although exhaustive and continuous spatial and time series are necessary to analyse these rockfalls. In this goal, two approaches have been developed: a network of observers for the current rockfalls and remote detection for 2003.

The network consists in dozens of guides, hut keepers and mountaineers sensitized to rockfalls observation thanks to posters put in the massif huts, and to a website (http://edytem.univ-savoie.fr/eboulements). Initiated in 2005, this network became fully operational in 2007. It was still in use in 2008 and 2009, focused on the central part of the Mont Blanc massif (57 % of the surface of the massif) due to heavy workload. The census was carried out with reporting forms, indicating the main features (volume, altitude, aspect, etc.) of the rockfalls and the conditions of the affected rockwall (presence/absence of ice/snow, weather, etc.). The network was reactivated every year through mountaineering forums, emails, radio, and press. As such network guarantees a very good representation of data but can not ensure perfect completeness of the inventories, important fieldwork was also conducted every fall in order to check the reported observations and to complete them. In particular, a check is conducted on the precise location of the scars, their altitude and volume. In 2007, a check of all the observations reported from the network was made by the analysis of aerial photographs, but only two rockfall deposits were not related by the network observations.

45 rockfalls were reported in 2007 (up to 15 000 m^3; Fig.1). They occurred between January and late September. Only three events took place out of the permafrost area. Year 2008 was characterized by a lower rockfall frequency: only 22 events were reported (Fig. 1), which occurred between June and September. The last one occurred at about 3470 m a.s.l. at Aiguille de Tré-la-Tête involving a volume of 33 000 m^3 of rocks (Fig. 2; Deline et al., 2008). It was the largest event of the 2007-2009. Among the 22 documented collapses, only one seems to have been triggered out of the permafrost area. Year 2009 was marked by a high number of small size rockfalls (up to 7000 m^3): 72 collapses were recorded (Fig. 1) between April and October, although morphodynamics really started in August. Only two rockfalls occurred out of the permafrost area.

Meanwhile, in order to get data on the exceptional morphodynamic of the 2003 summer heatwave, the 2003 rockfalls (n = 249) were identified from their supra-glacial deposits through the analysis of a SPOT-5 image taken at the end of the heatwave, which covers the entire massif.

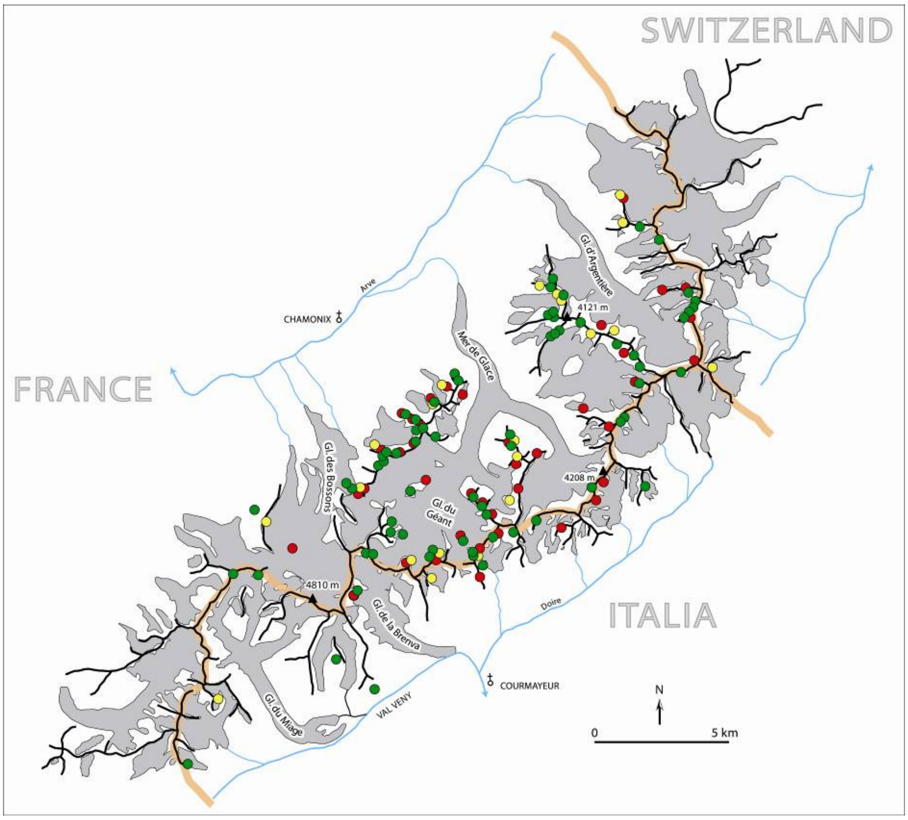

Fig. 1 Rock falls occurred in the Mont Blanc Massif in 2007 (red), 2008 (yellow) and 2009 (green).

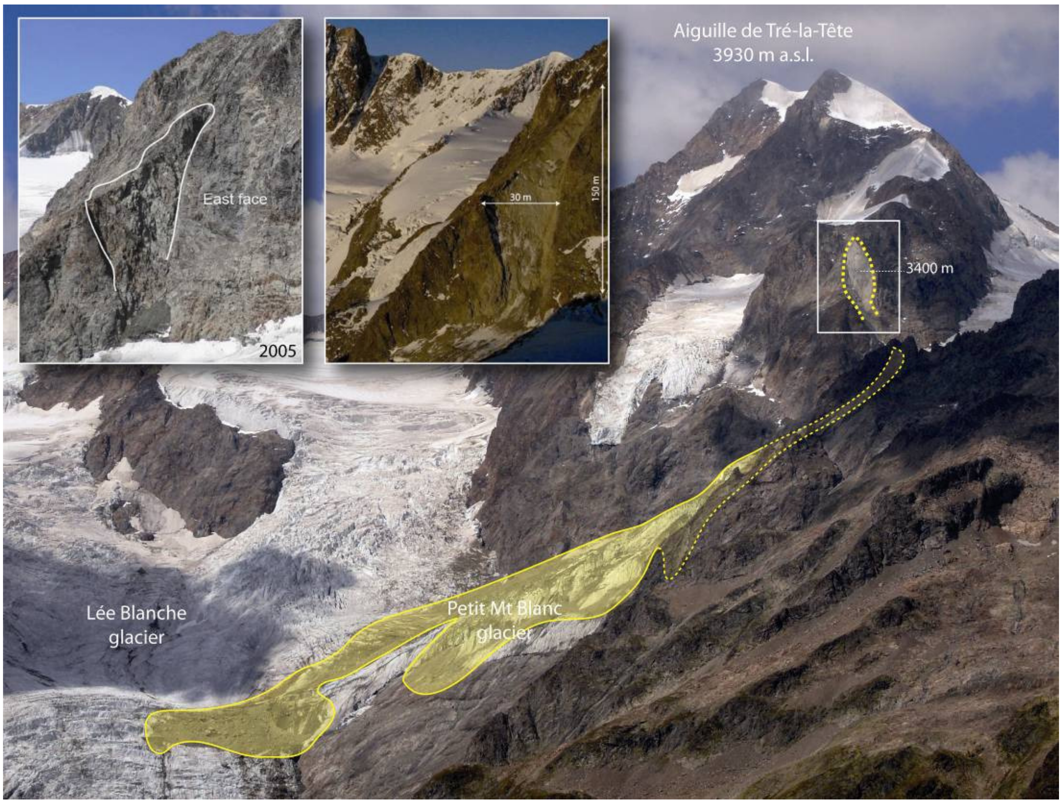

Fig. 2 The Tré-la-Tête rockfall of October 2008. Large photograph: scar on the East face of the eastern shoulder of Tré-la-Tête and runout path. Up left: comparison of the face before (in September 2005) and after the collapse (in October 2008**;** ph. M. Tamponi).

The 182 reported collapses were distributed fairly homogeneously throughout the massif (Fig. 3), with a slightly lower density south of the Mont Blanc. The most affected sector was the Mont Blanc du Tacul (4248 m a.s.l.) in the central part of the massif. All but two of the rockfalls occurred in rockwalls where models suggest the presence of permafrost.

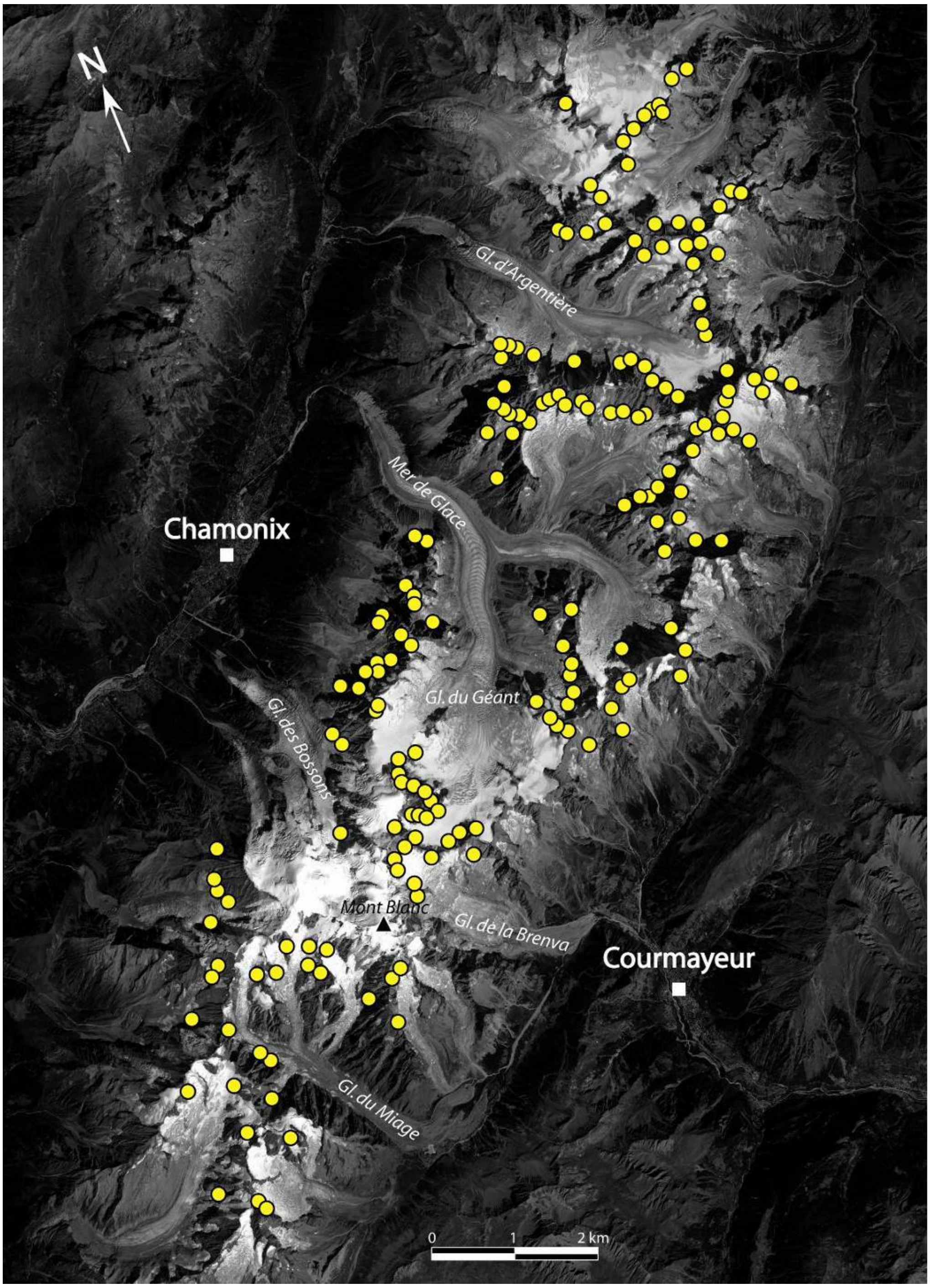

Fig. 3 The Position of the 182 rockfalls of 2003 on a sector of the panchromatic SPOT-5 satellite image 051/257 of the 23 August 2003 (10:50 GMT).

The characteristics of each collapse (and deposit for 2003) were determined using several methods. The altitude of scars, slope/orientation of the affected rockwalls, and the surface of the deposits were calculated from a GIS (ArcGIS; Fig. 4) working on several DEM assembled and sometimes enhanced. Without any direct measurements of the scars, the surface of the deposits was multiplied with an estimate of their thicknesses in order to assess the collapsed volumes (uncertainties may reach 50 %). Beyond topographic parameters, several other parameters are needed to study rockfalls predisposing or triggering factors but are not necessary for this study. Results of 2003, 2007 and 2008 have been published: see respectively Ravanel et al. (2011), Ravanel et al. (2010) and *idem*. Results of 2009 are summarized in Tab. 1.

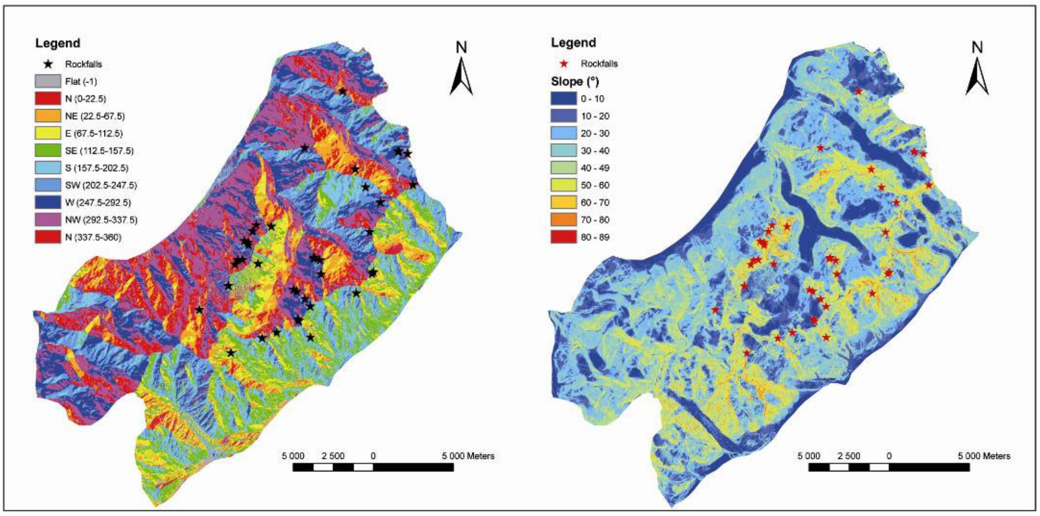

Fig. 4 Aspect and slope angle of the sides of the Mont Blanc massif. Stars indicate the location of the rockfalls of 2007.

Tab. 1 Characteristics of the 72 rockfalls of 2009 in the Mont Blanc massif. R: the date of the rock fall, F: the date of the first observation of the rockfall deposit.

Site	Date	Coordinates (ext. Lambert II étendu)	Elevation of the centroid of the scar (m a.s.l.)	Slope angle (°)	Aspect (°)	Volume ($\times 10^3$ m^3)
Aig. des Pélerins	23/07 R	X 0954.239 Y 2109.770	3180	75	348	7 ± 2
Aig. Grds Montets	17/08 R	X 0958.312 Y 2116.079	3120	43	332	6 ± 1.8
Rognon du Plan	13/09 F	X 0954.266 Y 2108.760	3325	69	295	6 ± 1.2
M.B. du Tacul	22/08 R	X 0953.945 Y 2105.563	3485	37	90	5 ± 2
Evêque	14/06 R	X 0958.558 Y 2113.222	3355	52	297	2.5 ± 0.8
Aiguille de Talèfre	25/08 F	X 0962.248 Y 2110.590	3345	57	131	2 ± 0.5
Dent du Requin	21/08 R	X 0955.370 Y 2109.000	3300	73	341	1.3 ± 0.4
Aig. de Bionnassay	13/09 F	X 0948.241 Y 2102.786	3865	60	126	1.1 ± 0.5
Evèque / Enf. d.C.	02/09 R	X 0958.604 Y 2113.261	3425	51	313	1 ± 0.2
Petites Jorasses	24/08 R	X 0961.768 Y 2108.543	3440	54	266	1 ± 0.4
Aiguille Mummery	30/08 F	X 0962.403 Y 2113.143	3585	62	206	0.8 ± 0.25
Aig. de Saussure	22/08 R	X 0951.835 Y 2106.457	3050	38	318	0.8 ± 0.3
La Vierge	28/08 F	X 0956.331 Y 2105.359	3185	48	10	0.8 ± 0.3
Tour Ronde	20/08 R	X 0954.732 Y 2104.196	3565	67	304	0.8 ± 0.15
Piton des Italiens	23/08 R	X 0949.319 Y 2102.904	3965	50	203	0.8 ± 0.3
Aiguille du Tacul	07/08 R	X 0958.885 Y 2109.243	3115	45	351	0.7 ± 0.25
Pointe Farrar	17/08 R	X 0958.985 Y 2115.249	3275	51	57	0.7 ± 0.2
Aig. du Midi	09/08 R	X 0953.710 Y 2108.580	3160	53	335	0.7 ± 0.2
Pointe Kurz	24/08 F	X 0963.992 Y 2115.098	3495	52	291	0.6 ± 0.2
Pt. Aig. R. Dolent	05/09 F	X 0964.238 Y 2115.384	3545	38	302	0.6 ± 0.15
Aiguille du Tacul	31/08 R	X 0958.423 Y 2109.060	3060	40	275	0.6 ± 0.3
Aig. du Diable	28/08 F	X 0953.844 Y 2105.338	3645	46	69	0.6 ± 0.2

Tour d'Entrèves	25/08 R	X 0956.044 Y 2103.614	3125	63	88	0.6 ± 0.25
Aig. Grds Montets	27/07 R	X 0958.178 Y 2115.946	3130	46	305	0.5 ± 0.15
Pointe Kurz	05/09 F	X 0964.190 Y 2115.194	3595	62	303	0.5 ± 0.2
Pointe Michelle M.	26/08 R	X 0957.698 Y 2113.958	3025	69	317	0.5 ± 0.2
Petit Dru	02/09 R	X 0957.990 Y 2113.946	3450	56	230	0.5 ± 0.12
Grands Charmoz	01/08 R	X 0955.313 Y 2111.130	3040	58	39	0.5 ± 0.2
Aiguille de Talèfre	25/08 F	X 0962.388 Y 2110.580	3320	69	136	0.5 ± 0.1
Aig. du Peigne	23/08 R	X 0953.895 Y 2109.860	2945	54	325	0.5 ± 0.15
La Noire	30/08 F	X 0957.284 Y 2106.832	3405	67	269	0.5 ± 0.25
Dent du Géant	28/08 F	X 0958.084 Y 2105.556	3340	66	134	0.5 ± 0.1
Aig. de Rochefort	28/08 F	X 0958.898 Y 2106.008	3640	53	151	0.5 ± 0.18
Aiguille du Gouter	26/08 R	X 0948.704 Y 2105.178	3435	40	14	0.5 ± 0.2
Aiguille de Toule	02/09 F	X 0956.032 Y 2104.426	3375	50	140	0.5 ± 0.1
Doigt de l'Etala	01/09 F	X 0955.075 Y 2111.378	2765	69	44	0.4 ± 0.15
Mont Gruetta	13/09 F	X 0963.738 Y 2108.633	3100	74	75	0.4 ± 0.18
Aig. du Midi	23/08 R	X 0953.298 Y 2108.520	3075	53	353	0.4 ± 0.1
Gros Rognon	30/08 F	X 0954.720 Y 2107.112	3285	60	18	0.4 ± 0.1
Pointe A. Rey	25/09 F	X 0954.530 Y 2105.233	3305	55	8	0.4 ± 0.15
Mt R. de Peuterey	14/08 R	X 0954.806 Y 2099.329	2225	59	79	0.4 ± 0.18
Aiguilles Marbrées	27/09 F	X 0957.395 Y 2104.948	3445	51	252	0.4 ± 0.15
Aig. du Chardonnet	27/08 F	X 0961.498 Y 2118.068	3455	49	159	0.3 ± 0.1
Pointe Kurz	23/08 R	X 0964.079 Y 2115.150	3535	60	327	0.3 ± 0.08
Pointe Eales	19/08 R	X 0962.614 Y 2112.818	3495	68	188	0.3 ± 0.1
Pointe Isabelle	19/08 F	X 0962.508 Y 2112.366	3335	60	300	0.3 ± 0.07
Aiguille du Plan	22/08 R	X 0954.573 Y 2109.437	3575	75	85	0.3 ± 0.07
Dent du Géant	23/08 R	X 0957.877 Y 2106.107	3500	43	297	0.3 ± 0.1
Pte de l'Androsace	20/10 R	X 0953.058 Y 2104.328	3820	60	204	0.3 ± 0.08
Eperon Brenva	16/09 R	X 0953.140 Y 2103.043	3610	38	141	0.3 ± 0.15
Punta Innominata	13/09 F	X 0952.705 Y 2100.020	3125	62	254	0.3 ± 0.15
Col du Chardonnet	27/08 F	X 0962.303 Y 2117.805	3490	51	284	0.25 ± 0.11
Aig. du Chardonnet	22/04 R	X 0960.615 Y 2117.610	2955	56	127	0.2 ± 0.05
Aig. de Blaitière	30/08 R	X 0954.612 Y 2110.468	2955	56	294	0.2 ± 0.08
Aig. du Plan	23/08 R	X 0954.268 Y 2109.294	3140	63	289	0.2 ± 0.04
Aiguille du Midi	12/09 R	X 0953.180 Y 2107.765	3765	58	211	0.2 ± 0.08
Arête inf. Cosmiques	30/08 F	X 0952.965 Y 2107.164	3590	47	298	0.2 ± 0.04
Col sup. de la Noire	25/08 F	X 0957.719 Y 2106.443	3490	59	207	0.2 ± 0.1
Pte Aig. Glaciers	14/09 F	X 0947.728 Y 2095.290	3025	51	65	0.2 ± 0.07
Evèque	23/08 R	X 0958.567 Y 2113.259	3355	67	302	0.2 ± 0.08
Dôme de Rochefort	18/08 R	X 0959.655 Y 2106.540	3585	71	82	0.2 ± 0.08
Signal Vallot	13/08 F	X 0959.915 Y 2114.085	3700	45	246	0.2 ± 0.05
Le Tour Noir	05/09 F	X 0964.035 Y 2116.087	3505	47	262	0.2 ± 0.06
Tour Ronde	22/08 R	X 0955.071 Y 2104.095	3535	50	85	0.2 ± 0.05
Pte de l'Androsace	17/08 R	X 0953.229 Y 2104.433	3805	51	61	0.15 ± 0.05
Aiguilles Marbrées	27/09 F	X 0957.380 Y 2105.032	3440	44	205	> 0.1
Les Courtes	21/08 F	X 0961.572 Y 2113.408	3395	48	181	> 0.1
Brêche du Domino	05/09 F	X 0963.820 Y 2112.990	3555	38	16	0.1 ± 0.025
Grand Flambeau	02/09 F	X 0956.289 Y 2104.374	3320	63	209	0.1 ± 0.02
Les Drus	07/08 R	X 0957.986 Y 2114.078	3645	66	183	0.1 ± 0.03
M.B. du Tacul	23/07 R	X 0952.578 Y 2106.248	3500	50	351	0.1 ± 0.025
Aiguille du Midi	26/09 R	X 0953.085 Y 2107.450	3570	60	135	0.05
Moyennes			**3365**	**55**	**202**	**0.8 ± 0.26**
Totaux (72)						**> 57 ± 18**

SUSCEPTIBILITY ASSESSMENT: METHOD AND VALIDATION

Rockfall reported in 2003, 2007 and 2008 are not only a basis for studying the fresh upsurge of rockfalls in high mountains but also an analytical basis for determining the susceptibility of rock walls to be affected by instabilities. Although the period taken into account – three years – is rather short, it allows observing a wide variety of responses of rock walls depending on the weather.

In Chamonix, Météo France data indicate that the years 2003, 2007 and 2008 – of which the rockfalls will be used to parameterize the model – were respectively the 3th, 8th, and 9th warmest years since 1934, - and probably since the end of the Little Ice Age. Summers 2003, 2007 and 2008 have been respectively the 1st, 12th and 25th warmest since 1934 these dates. In the Mont Blanc region in 2003, after a mild late winter and early spring, temperatures have increased to high values. In June, sun and high temperatures have dominated. In both July and August, the heatwave prevailed with unprecedented value. Finally, the summer of 2003 was the warmest ever recorded by weather stations in Chamonix, in the Alps and also in Europe (Beniston, 2004). In 2007, the spring was particularly wet, as in July and August and summer temperatures have remained relatively low. In 2008, the weather was very varied. In July, rainfall was excess with quite mild temperatures. August was more consistent with normality. September was first wet, then dry and very cold.

The year 2009, which rockfalls are used to validate the model of susceptibility, is the 4th warmest year in Chamonix since 1934. The summer was the 3rd warmest summer since that date. After a spring almost summer, precipitations in July were abundant. The sunshine of August was very high, with warm temperatures or heatwaves. In September, rainfalls were very low and the heat remained high.

As a first approximation, the rockfall susceptibility is determined by the three fundamental topographic parameters that are elevation, slope angle and aspect. The 249 collapses of 2003, 2007 and 2008 are used to assign an index for each class of values. Given this total number of rockfalls, the ideal number of classes – according to Huntsberger or Brooks and Carruthers (Beguin and Pumain, 2000) – would be 9. But since we have 8 different possible aspects, we opted to build 8 classes for each parameter. Arbitrarily, the index is based on the distribution of 5 points for each parameter based on the number of collapse for each class. This index can be weighted by the area of the class (in %, where 100% is the whole investigation area) to get comparable values (Tab. 2).

Tab. 2 Index of susceptibility (unweighted index UI and weighted index WI) calculated from the number of rockfalls identified for different classes of elevation, slope angle and aspect.

Elevation	**Classes (m a.s.l.)**	**2200-2449**	**2450-2699**	**2700-2949**	**2950-3199**	**3200-3449**	**3450-3699**	**3700-3949**	**3950-4200**
	# rockfalls	0	1	10	35	89	81	28	5
	UI	**0**	**0**	**0.2**	**0.7**	**1.8**	**1.6**	**0.6**	**0.1**
	Area (%)	14,4	14,5	15,9	16,7	18,1	12,3	6	2,1
	WI	0	0,01	0,14	0,49	1,15	1,55	1,1	0,56
Slope	**Classes (°)**	38-42	43-47	48-52	53-57	58-62	63-67	68-72	73-77
	# rockfalls	15	27	45	52	34	30	17	5
	UI	**0.3**	**0.6**	**1**	**1.2**	**0.8**	**0.7**	**0.4**	**0.1**
	Area (%)	18,2	19,7	19	16,7	12,4	7,90	4	1,60
	WI	0,19	0,32	0,55	0,72	0,64	0,88	0,98	0,72
Aspect	**Aspect**	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
	# rockfalls	31	29	23	29	33	28	27	33
	UI	**0.7**	**0.6**	**0.5**	**0.6**	**0.7**	**0.6**	**0.6**	**0.7**
	Area (%)	10,5	10,1	10,9	13,3	14,5	15,4	14,7	10,6
	WI	0,77	0,75	0,55	0,57	0,59	0,47	0,48	0,82

Thus, according to the unweighted index, a rockfall would most likely occur between 3450 and 3449 m a.s.l., on a N-, S- or NW-facing rockwall with a slope angle between 47 and 51° (as calculated from the DEM used and not measured on the field). All parameters are considered equivalent. It is to note that some values of slope (24) and aspects (16) are missing.

An overall level of susceptibility based on the unweighted index can finally be calculated for the rockfalls of 2009 by multiplying the three levels previously obtained in order to verify the model of susceptibility. Indeed, quantifying the relationship between levels of susceptibility and rockfalls of 2009 (72 events) allows the validation the model. Most of the rockfalls of 2009 occurred between 3200 and 3449 m a.s.l., often on NW-facing rockwalls, what tends to validate the model. It should be noted that this preferential distribution does not match the one of the rockwalls. Table 3 shows the correlation between the model and the data of 2009: more than 90 % of the collapses have a correlation higher than 50 %, and nearly 50 % of these events have a correlation above 80 %.

Tab. 3 Number of rockfalls of 2009 according to the correlation (in %) with the susceptibility model (unweighted index).

Correlation	0 - 10	10 - 20	20 - 30	30 - 40	40 - 50	50 - 60	60 - 70	70 – 80	80 - 90	90 - 100
# rockfalls	0	0	0	2	5	14	7	10	23	11

CONCLUSION

Two methods were developed in the Mont Blanc to identify rockfalls occurred in 2003 and between 2007 and 2009. The results of the first three years were used to build a susceptibility model based on three topographic parameters (elevation, slope angle and aspects). This model, validated by the data of 2009, is a first in high mountains and must now be supplemented by other parameters influencing the stability of high rock walls (see for example Fischer et al., 2006) to get a reliable tool for the management of rockfall hazard in these areas often more and more frequented and inhabited.

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