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Pierre-Allain Duvillard, Ludovic Ravanel and Philip Deline

Introduction

- 1 The Alps are particularly sensitive to global warming: it is two to three times more marked there than at the global scale while the cryosphere is very developed (Haeberli and Beniston, 1998). Alpine permafrost degradation (warming of permanently frozen ground) and glacial retreat cause geomorphological instabilities in rock walls or superficial deposits, which may lead to processes such as rock falls (volume > 100 m³), boulder falls (volume < 100 m³), landslides or subsidence (Harris *et al.*, 2009; Fischer *et al.*, 2006). In addition to indirect risks to people or infrastructures located in the path of a rock mass in movement, these processes may cause a direct risk of destabilisation for infrastructures built at high elevation (Duvillard *et al.*, 2015; Fabre *et al.*, 2015; Dall'Amico *et al.*, 2011; Ravanel, 2010; Bodin *et al.*, 2009).
- 2 An increasing amount of damage to infrastructures is clearly regrettable, and sometimes carries heavy social and economic implications. For example, the destabilisation of the Cosmiques hut (Chamonix, France) in 1998 by a large rock fall required reinforcement work at the foundation (Ravanel *et al.*, 2013). Another example is the subsidence of the Bellecombe chairlift arrival station (Les Deux Alpes, France), built on a rock glacier, which had to be raised during summer 2013 (Cadet and Brenguier, 2015). This paper focuses on the direct risks of infrastructure destabilisation in high mountains. The aim was to draw up an inventory of high mountain infrastructures and identify the most exposed sites to help prevent risks, associated with global warming, at high elevation in the French Alps, a very anthropised area. This study is an application, in a high mountain area, of previous works seeking to characterise the potential damage due to landslides (van Westen *et al.*, 2005; Leone *et al.*,

1996; Leone, 1996), by constructing a synthetic risk index. Risk prevention due to high mountain hazards is still an undeveloped research field, except for avalanches (Bründl and Margreth, 2015) and glacier lake outburst floods (Nussbaumer *et al.*, 2014; Schaub *et al.*, 2013).

- 3 An inventory of all the infrastructures was carried out using a Geographic Information System (GIS) with different data layers including the Alpine Permafrost Index Map (APIM; Boeckli *et al.*, 2012), representing the potential permafrost distribution, and glacier inventories since the end of the Little Ice Age (LIA; Gardent, 2014). The aim was to locate the infrastructures built in probable permafrost and/or glacier shrinkage areas. Then, in order to identify those most exposed, a risk index was compiled, combining hazard characterisation – geomorphological processes – and vulnerability diagnosis. Finally, a preliminary validation of the risk index was carried out using inventories of damage in different areas of the French Alps.

High mountain infrastructure

The French Alps

- 4 The French Alps are a mountain range between Lake Geneva and the Mediterranean sea, over 300 km long and covering more than 35,000 km². This territory contains 3.5 % of the French metropolitan population and is a very dynamic area thanks to tourism. The Rhône-Alpes region is the second most popular French destination in terms of number of overnight stays, while the French Alps have around 200 ski resorts.
- 5 Alpine tourism is thus largely oriented toward skiing: four generations of ski resorts have developed successively since the beginning of the 20th century. Moreover, infrastructures are being built at increasing altitudes in order to extend the opening period. According to the *Domaine Skiable de France*, there were 47 million day-skiers and 575 million people used the ski lifts over the 2012-13 winter. Approximately 105,000 jobs depend directly on the ski resorts in the French Alps.
- 6 These ski resorts have more than 3,000 ski lifts - 40 to 50 new infrastructures are built every year - in addition to tens of huts and other constructions (power lines, avalanche equipment, etc.). All of these are not located in high mountains, defined here as mountain areas characterised by permafrost and/or glacial shrinkage. Permafrost develops on around 700 km² in the French Alps (Boeckli *et al.*, 2012), which represents 10 % of the 6,800 km² located above 2000 m a.s.l. Glaciers cover about 4 % of this area, with less than 270 km², as 52 % of the glacial area disappeared between 1970 and 2009 and glacial shrinkage is accelerating (Gardent *et al.*, 2014).

Infrastructure inventory

- 7 The inventory was carried out using a GIS with 15 data layers divided into four main sets:
 - the identified infrastructures (points) positioned using topographic maps, IGN orthophotos and other documents (*Carte de Localisation des Phénomènes d'Avalanche*), ski resort maps, etc.);
 - glacier inventories in the French Alps (glacial extension in 2006-2009, 1967-1971 and at the end of the LIA), based on a digitalisation of glaciers from topographic maps or orthophotos and geomorphological field observations (Gardent *et al.*, 2014). In order to assess rock slope

failures (Oppikofer *et al.*, 2008) and landslides in the moraines (Ravanel and Lambiel, 2012) that may result from glacier shrinkage, buffers of 25 m were taken around the glacial extensions from 1967-1971 and of 50 m for the LIA glacial extension in the GIS;

- inventories of rock glaciers in the Southern Alps (Bornet *et al.*, 2014) and the APIM, which gives a probability index of permafrost presence in the whole Alps according to the type of terrain and geomorphological context (Mair *et al.*, 2011; Boeckli *et al.*, 2012). Being a thermal phenomenon, permafrost is not directly observable but can be detected by direct or indirect methods. The APIM was calibrated by reading geomorphological forms and processes associated with permafrost and/or by measuring permafrost indicators (temperature, geophysics, etc.);
 - general data like the administrative network of France, orthophotos and IGN topographic maps at 1:25,000, and the Digital Terrain Model (DTM) ASTER GDEM v.2 of 2011.
- 8 This inventory identified 1,769 infrastructures in areas probably located in the context of permafrost and/or potentially affected by glacial shrinkage. By applying the risk index, these can be classified and those that require special attention (studies, monitoring, geotechnical adjustments) can be recognised.

Construction of the destabilisation risk index

Quantifying the risk

- 9 To provide a risk level of destabilisation for high mountain infrastructures, a technical approach to the risk is required. Quantifying the risk enables an accurate ranking of the infrastructures according to their sensitivity. For a specific infrastructure (*e.g.* station, pylon, gas exploder), the risk of destabilisation corresponds to the specific risk (R_s). It can be interpreted as the probability of the occurrence of the event “infrastructure destabilisation”. Specific risk can be defined by the expression (Bell *et al.*, 2004; van Westen *et al.*, 2005; Leone, 1996; Figure 1):

10 $R_s = (PD (D*V))$

11 with:

- **PD**, the Probability of occurrence of a Destabilisation. The hazard is expressed by the probability of the occurrence of a destabilisation due to permafrost degradation and/or glacial shrinkage. PD is the product of the indexes corresponding to passive factors (F_p ; factors of “predisposition” that can prepare a destabilisation), and the probability of active factor development (P_a) sufficient to lead to an instability.
- **D**, the potential level of Damage. Vulnerability (*s.s.*) is assessed by the potential level of damage of the exposed element. This can be established using a scale of damage intensity and its consequences following slope movement.
- **V**, the index of the unitary value. The stakes are measured with an index of the unitary value, which reflects the economic operating value of an infrastructure. This analysis requires a hierarchy of the exposed elements in terms of financial (cost of acquisition/building) and/or operating (economic, functional, strategic) values.

Figure 1 - The different components of the risk of infrastructure destabilisation in high mountains

Hazard characterisation

- 12 Hazard refers to the probability of occurrence of a geomorphological process due to permafrost degradation and/or glacial shrinkage, in the short (a few years) or medium (from one to three decades) term. The process differs according to the slope and the type of terrain (Harris *et al.*, 2001). Those affecting the bedrock (*e.g.* large rock falls, boulder falls) are partially controlled by the slope and fracturing. In superficial deposits, processes (*e.g.* landslides, subsidence) are partially conditioned by the slope, the grain size and porosity. Hazard value considers the different passive factors (Fp) and the probability of active factors crossing a threshold, thus leading to destabilisation (Pa) (Figure 2).

Figure 2 - Passive and active factors that may cause slope instability in high mountains

Passive factors (Fp)

- 13 Passive factors are continuously present parameters but, most of the time, they do not trigger destabilisation. There are two types:
- slope angle (P), computed from a DEM and/or assessed via the geomorphological context (e.g. rock walls). Four categories of slope were created: low ($P < 15^\circ$), intermediate ($15^\circ < P < 36^\circ$), steep ($36^\circ < P < 60^\circ$) and very steep ($P > 60^\circ$);
 - geological and geomorphological predisposition to instability according to the terrain type. There are two categories of terrain with different geomechanical properties: loose/superficial deposits, with more or less rough materials, and the bedrock, composed of more or less resistant and fractured rocks. A qualitative value characterises the potential instability of these terrains/rocks (Table 1).

Table 1 - Predisposition to instability of different superficial deposits and rocks

■ Forms and loose deposits		■ Bedrocks		Fracturing (density)		
Type of terrain	Predisposition	Rock type		Low	High	Destructuring
Backfills	Not very favourable		Clay sedimentary rocks	Rather favourable	Favourable	Favourable
Screed slope	Not very favourable		No clay sedimentary rocks	Not very favourable	Rather favourable	Favourable
Morain and/or tills	Rather favourable		Metamorphic rocks	Unfavourable	Rather favourable	Favourable
Rock glaciers	Favourable		Magmatic rocks	Unfavourable	Rather favourable	Favourable
Rock fall deposits	Not very favourable					

- 14 Quantitative assessment of all the passive factors is possible using a matrix crossing parameters (Table 2). The possibility of destabilisation with passive factors varies between 0 and 0.9 (0: impossible; 0.1: almost impossible; 0.2: unlikely; 0.4: implausible; 0.6: probable; 0.8: very likely; 0.9: almost certain).

Table 2 - Assessment matrix for passive factors (Fp)

		Geological and geomorphological predispositions			
		Unfavourable	Not very favourable	Rather favourable	Favourable
Slope (P)	Low	0	0.2	0.4	0.6
	Intermediate	0.1	0.4	0.6	0.8
	Steep	0.2	0.4	0.8	0.8
	Very steep	0.4	0.6	0.8	0.9

Active factors (Pa)

- 15 There are two active factors, possibly combined and both sensitive to global warming, which could lead to destabilisation:
- permafrost degradation, assessed by the Probability of a Destabilisation due to permafrost degradation (PDP). The estimation of permafrost presence is based on the APIM map. A value corresponding to the probability of destabilisation is associated with each type according to the supposed level of permafrost degradation (Table 3). The maximum values were placed in areas that may correspond to discontinuous permafrost because, due to generally not very negative temperatures, it is probably affected by current global warming (Ravanel and Deline, 2008). At higher elevation, continuous permafrost, which is colder, is

more conducive to slope stability (Magnin *et al.*, 2015). Therefore, recent slope movements and infrastructure destabilisations documented during the last few years were mainly observed in areas with discontinuous permafrost (*e.g.* Bellecombe chairlift in Les 2 Alpes; *Podin et al.*, 2009). Regarding permafrost at lower elevation (sporadic permafrost), caused by very specific geomorphological and topoclimatic conditions, this should be less sensitive to current global warming (Scapozza *et al.*, 2011). Only very limited destabilisation can occur.

Table 3 – Assessment of destabilisation probability due to permafrost degradation

Index of permafrost presence			PDP	
Colours			Value	Signification
APIM	Class	Signification		
		Permafrost in nearly all conditions ¹	0.4	Not very likely
			0.6	Likely
		Permafrost mostly in cold conditions ²	0.8	Very likely
			0.6	Likely
			0.4	Not very likely
		Permafrost only in very cold conditions ³	0.2	Unlikely

¹Continuous permafrost; ²Discontinuous permafrost; ³Sporadic permafrost.

- glacial shrinkage, assessed by a Destabilisation Probability due to Glacial shrinkage (PDG) in the recently deglaciated areas, but also in areas affected by glacial debuttressing. The assessment of the probability of these “paraglacial” destabilisations (Ballantyne, 2013) is based on several glacial buffers since the end of the LIA to the current period (Figure 3). For example, a 25-m buffer around the glacial extension of 1967-1971 was used to consider the possible instabilities triggered by the glacial retreat. It should be noted that the infrastructures currently located on glaciers are adapted to their movements.

Figure 3 – Assessment of the probability of “paraglacial” destabilisation

- 16 In the case of the combination of these two processes, PDP and PDG are crossed using a matrix (Table 4).

Table 4 – Matrix for active factors (Pa) crossing Destabilisation Probability due to permafrost degradation (PDP) and the Destabilisation Probability due to glacial shrinkage (PDG)

		PDP				
		Almost impossible	Unlikely	Not very likely	Likely	Very likely
PDG	Almost impossible	0.1	0.2	0.4	0.6	0.8
	Unlikely	0.2	0.2	0.4	0.6	0.8
	Not very likely	0.4	0.4	0.4	0.6	0.8
	Likely	0.6	0.6	0.6	0.6	0.8
	Very likely	0.8	0.8	0.8	0.8	0.8

Diagnosis of vulnerability

- 17 Infrastructure vulnerability following slope movement can be characterised by considering the potential level of damage (vulnerability s.s.) and the economic or financial value of these elements (stakes).

Vulnerability s.s. (D)

- 18 The potential damage rate (or vulnerability) expresses the interaction between a process and an element at risk in terms of mode and level of damage (Leone, 1996). This damage (D) can be established with a scale of damage intensity (ID) by assessing the sensitivity of the infrastructure to instability, and its consequences.

Figure 4 – Relationship between the sensitivity and consequences of the infrastructure in the case of instability (Boomer *et al.*, 2010 modified)

- 19 In a diagram crossing sensitivity and consequences (Figure 4), infrastructures at risk are classified according to a scale of damage intensity (ID) from I to IV. These quadrants reflect the different levels and modes of damage to infrastructures exposed to the processes resulting from permafrost degradation and/or glacial shrinkage (Table 5). Quantification of damage modes is based on the damage level (*i.e.* the degree of potential loss of the infrastructure) with a value ranging from 0.2 to 0.8.

Table 5 – Typology of damage modes and potential damage level for the infrastructure

ID	Damage modes	D
I	Weak non-structural damage (intact structure) Stability preserved	0.2
II	Cracking Stability preserved (non-essential works)	0.4
III	Cracking of the structure Stability affected Partial destabilisation	0.6
IV	Fracturing of structure General stability affected Major destabilisation	0.8

ID : Scale of damage intensity
D : Damage level (degree of loss)

(Leone *et al.*, 1996, modified).

Stakes (V)

- 20 The vulnerability analysis requires a hierarchy of the exposed elements (or stakes) in terms of financial (cost of acquisition or building) and operating (economic, strategic,

functional) values to determine the infrastructure weight for operators. An index of unitary value *V* of the exposed elements allows a comparison of infrastructures. The knowledge of the financial value of an infrastructure or an estimate of its capacity enables the operating value of a similar infrastructure to be assessed more precisely. Nevertheless, the construction of this index generally results from a subjective evaluation (Table 6).

Table 6 – Determination of the index value of different infrastructures

Elements exposed		Financial value ¹ (k€)	Operating value ²	V
Ski lifts	Detachable chairlift	7 500	Major	0.8
	Chairlift	3 000	Considerable	0.6
	T bars or rope tow	500	Minor	0.2
	Gondola	8 000	Major	0.8
	DMC; Funitel; 3S (big gondola lift)	13 000	Exceptional	0.9
	Cable car	-	Exceptional	0.9
	Funicular	-	Exceptional	0.9
Buildings	Elevator lift	-	Considerable	0.6
	Hut < 30 people dormitory	-	Considerable	0.6
	Hut > 30 people dormitory	-	Major	0.8
	Hut > 100 people dormitory	-	Exceptional	0.9
	Restaurant	-	Considerable	0.6
	Shelter	-	Minor	0.2
Defence and protection systems	Chalet / Building	-	Intermediate	0.4
	Gas exploder - Explosive carrier	80	Intermediate	0.4
	Snow avalanche barrier	0.7 / m	Minor	0.2
	Wind structure	0.5 / m	Minor	0.2
	Gallery / Road tunnel	30 / m	Considerable	0.6
	Stop wall / Dike	0.01 / m ³	Minor	0.2
	Brakeman structure for snow avalanche	0.25 / m ³	Minor	0.2
Networks	Road - Overhead power line pylon	-	Exceptional	0.9
	Communication antenna	-	Considerable	0.6

¹Average duty-free cost for ski lifts in 2012 (Mountain Leaders, Jan/Feb2013) and equipment and structures against snow avalanche in 2004
²Economic, strategic, operational

Specific Risk assessment

- 21 Crossing hazard characterisation and vulnerability diagnosis allows the construction of a risk index reflecting the degree of risk of destabilisation (Table 7). Infrastructures were classified according to their degree of risk, from low to very high. This index was completed by a qualitative stability definition for infrastructure, from rather stable to possible generalised destabilisation.

Table 7 – Risk index of infrastructure destabilisation in high mountains

		Hazard ¹					
		0.01	0.04	0.16	0.36	0.64	0.81
Vulnerability ²	0.01	0.0001	0.0004	0.0016	0.0036	0.0064	0.0081
	0.04	0.0004	0.0016	0.0064	0.0144	0.0256	0.0324
	0.16	0.0016	0.0064	0.0256	0.0576	0.1024	0.1296
	0.36	0.0036	0.0144	0.0576	0.1296	0.2304	0.2916
	0.64	0.0064	0.0256	0.1024	0.2304	0.4096	0.5184
	0.81	0.0081	0.0324	0.1296	0.2916	0.5184	0.6561

¹ Result of the probability of occurrence of a destabilisation due to permafrost degradation and glacial shrinkage (PD).
² Result of the potential damage level (D) multiplied by the index of unitary value (V).

Specific Risk (Rs)	Definition of risk	Recommendation
Low [0.0001 - 0.0016]	Infrastructure stable	No analysis needed.
Limited]0.0016 - 0.0256]	Possible weak destabilisation	Qualitative analysis recommended ³ .
Marked]0.0256 - 0.1296]	Possible partial destabilisation	Realization of qualitative analysis ³ : expert opinion, ground reconnaissance and quantitative analysis if no comparable project exists.
High]0.1296 - 0.4096]	Possible considerable destabilisation	Restricted quantitative analysis ⁴ : assessment by an engineer, monitoring of the foundations and quantitative analysis if no comparable project exist.
Very high]0.4096 - 0.6561]	Possible generalized destabilisation	Compulsory monitoring of the structure : detailed quantitative analysis ⁴ of the foundations in the field and in the lab., independent expert assessment.

³ Qualitative analysis : analytic modelling of impacts of ground instability on the structure.
⁴ Quantitative analysis : detailed numerical modelling.

Risk index application

- 22 The 1,769 infrastructures in the French Alps were classified by applying the risk index. They are mostly located in the Vanoise (59 %), Ecrins-Oisans (19 %) and Mont Blanc (5 %) massifs, and are mainly concentrated in the high-altitude ski resorts: Val d'Isère, Val Thorens, Tignes, La Plagne; Les Arcs, les Deux Alpes, Alpe d'Huez; La Grave and Chamonix, respectively (Figure 5). 75 % of these infrastructures are ski lifts. 10 % of them are characterised by a high risk of destabilisation. No infrastructure is currently characterised by a very high risk.

Figure 5 – Location of the infrastructures at risk in the ski resorts of the French Alps

Preliminary validation of the risk index

- 23 The risk index of infrastructure destabilisation was compared to three detailed inventories of damage in Les Ecrins, Val Thorens and Les Arcs. Field observations in La Plagne, Val d'Isère and Tignes were also considered. This allowed an initial assessment of the reliability of the risk index. It was validated by 10 infrastructures characterised by a high risk, presenting damage and requiring work. However, some more detailed inventories of damage are needed to confirm the index.
- 24 Among the most risky fifteen infrastructures (characterised by a high risk of destabilisation) are the pylon and arrival station of Bellecombe chairlift (Les Deux Alpes), and the Cosmiques hut and the top station of the Aiguille du Midi cable car (Chamonix). The case of the Cosmiques hut (Figure 6) confirms the index because its foundations were destabilised in 1998 due to a large rock fall event (Ravanel *et al.*, 2013).

Figure 6 – a: Infrastructures of the Aiguille du Midi area (3848 m a.s.l.). b: Large rock fall under the Cosmiques hut in August 1998 (A. Sage)

Discussion

- 25 This study has identified many infrastructures potentially at risk in the French Alps. Nevertheless, this work has various methodological limitations that future research should solve.
- 26 For example, the risk index could be improved through a better interpretation of the hazard. The assessment of the local distribution and thermal state of permafrost are unclear. The APIM layer is the result of permafrost modelling over the whole Alps. Its reliability is imprecise and is, therefore, a source of errors in the evaluation of PDP. The ASTER GDEM v.2 could lead to an overestimation of the gentle slopes and an underestimation of the very steep slopes due to its resolution of about 27 m in the Alps. The use of a more precise DTM could refine these slope angles to improve the characterisation of passive factors.
- 27 The diagnosis of vulnerability (*s.l.*) should be completed by taking into account possible reinforcement works or geotechnical solutions. This approach should assess the response capability of managers, and thus the resilience.

Concluding remarks

- 28 This study is part of a programme of prevention and monitoring of the impacts of global warming in the French Alps.
- 29 1,769 infrastructures were identified and, by applying the risk index of destabilisation, they were classified according to their degree of risk ranging from low (159 infrastructures) to high (185), or very high (0, currently). A first validation of the index based on inventories of damage and observations was undertaken. The realisation of new inventories of damage will determine whether the index underestimates or overestimates the risk.
- 30 An improvement would be to take into account the geomorphological evolution of the terrain on which the infrastructures are located, in order to specify risk levels together with the magnitude and consequences of potential destabilisations in the context of global warming.

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ABSTRACTS

Due to ongoing global warming, high alpine environments are affected by significant changes, such as glacial retreat and permafrost warming, which can trigger mass movements in rock slopes or superficial deposits. These processes generate a risk of direct destabilisation for high mountain infrastructures (huts, cable cars, etc.). To help prevent such risks, an inventory of all the high mountain infrastructures in the French Alps was carried out using a Geographic Information System. This combined several data layers, including the Alpine Permafrost Index Map and glacier inventories since the end of the Little Ice Age. 1,769 infrastructures were identified in areas probably characterised by permafrost and/or possibly affected by glacier shrinkage. An index of destabilisation risk was constructed to identify and rank infrastructures at risk. This theoretical risk index includes a characterisation of hazards and a diagnosis of vulnerability. 10 % of the infrastructures were characterised by a high risk of destabilisation.

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Keywords: high mountain infrastructure, risk index, permafrost degradation, glacier shrinkage, French Alps

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