Spectral analysis of seismic noise recorded on prone-to-fall compartments

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ABSTRACT

The dynamic response of four unstable rock compartments in the Alps has been studied using the ambient vibration technique, with the aim of identifying precursors to rockfalls. The test sites present various geological settings (limestone, argillite, and shale-sandstone series), failure mechanisms and volumes. The ambient vibration spectra measured on the unstable compartments systematically showed clear energy peaks at specific frequencies, in contrast with records made on the adjacent stable rock masses. These predominant frequencies were interpreted as resonant frequencies of the unstable compartments, in agreement with 2D modal analysis. In the horizontal plane, ground motion at the fundamental frequency was found to be systematically parallel to the slope face, and perpendicular to the main bounding fracture observed at most of the sites. The fundamental frequency of each prone-to-fall compartment shows reversible variations related to temperature fluctuations at different timescales, with a significant contrast in magnitude and phase-shift between sites. At the more fractured site, resonance seems to result from a contrast in internal rigidity between the compartment and the rock mass, rather than from decoupling along a rear fracture, which is the mechanism observed at the three other sites. No change in fundamental frequency resulting from damage processes was observed over the period of study.

1 INTRODUCTION

Medium-size rockfalls (10^3-10^5 m^3) draw attention to the need for appropriate monitoring techniques due to their large destructive power and relative high rate of occurrence (Frayssines and Hantz 2006). Passive seismic techniques, which consist of recording ambient vibrations, have been recently applied for monitoring prone-to-fall sites using two different approaches. The first approach consists in detecting an increase in the number of seismic events and/or a rise in seismic energy over a given period of time, which could indicate a destabilization of the unstable mass (Amitrano et al. 2005, 2010, Senfaute et al. 2009). The second approach is to process the seismic noise (i.e. periods without specific seismic events) to extract the dynamic parameters of a structure (Stubbs and McLamore 1973), in particular its resonant frequencies. This technique was recently applied to unstable crystalline rock slopes (Burjánek et al. 2010, 2012; Moore et al. 2011) or to limestone cliffs (Lévy et al. 2010). In the latter study, ambient vibration spectral monitoring allowed detecting the resonant frequencies of a prone-to-fall column, whose fundamental frequency (f_1) showed a clear drop a few weeks before the column collapsed. In the same study, f_1 was also shown to fluctuate reversibly over time under temperature forcing, similar to observations made on buildings (Clinton et al. 2006).

The ambient vibration technique, which provides information on the internal mass characteristics and on the boundary conditions of rock slope instabilities, offers the advantage of easy recording and simple processing, and may be used for damage monitoring if reversible and irreversible effects can be separated. Following the pioneering works applying ambient vibrations on unstable slopes, our works aims at testing the applicability of the technique in various rock mass configurations, characterized by different deformation and failure mechanisms. Four prone-to-fall medium-size rock compartments located in the Occidental Alps in various geological contexts (limestone, argillite and shale-sandstone series) were selected and instrumented. Ambient vibrations recorded on-site were analyzed, allowing us to retrieve the resonant frequencies of the rock compartments and monitor their fluctuations over time.

2 STUDY SITES

2.1 Description

The location and layout of the four study sites (Rubi, La Suche, La Praz and Les Arches) are shown in Figure 1. Figure 2 presents a simplified contour map for each site, along with the instrumentation set up. The unstable compartment is colored in grey and its rear limit shown by a thick barbed line. Geological information given in the following section is extracted from geological maps and field observations. Azimuths are given as clockwise from north.

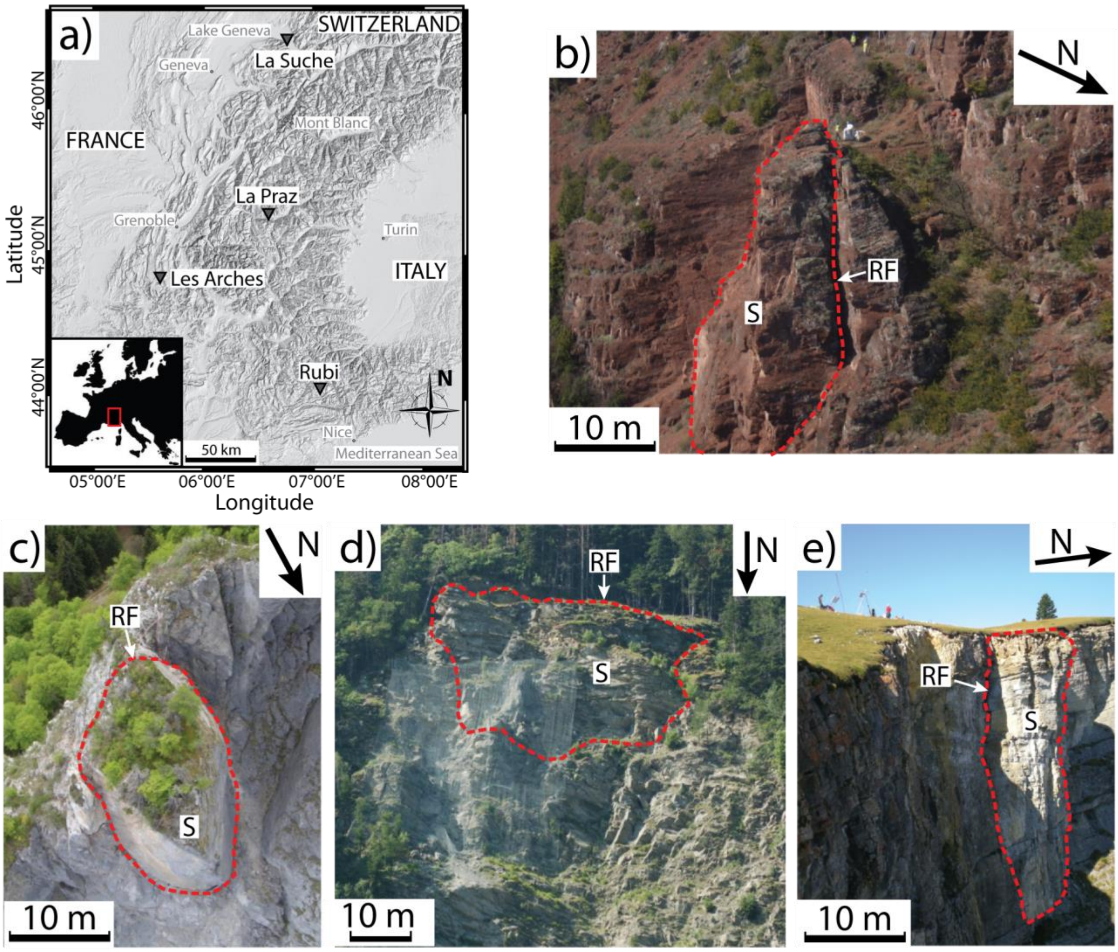

Figure 1. a) Map of the western Alps with location of the four study sites. b to e) Photographs of Rubi, La Suche, La Praz and Les Arches study sites, respectively. The limits of the unstable compartments are delineated by red dashed lines, RF arrow shows the main rear fracture separating the unstable compartment (S) from the rock mass.

The Rubi site lies on the downstream right-bank of the Cians River, in the maritime Alps (France) at about 800 m in altitude (fig. 1a). The steep slope is composed of fine-grained, thinly-bedded red argillites of Permian age, belonging to the Barrot dome (Faure-Muret and Fallot 1957). The daylighting bedding is oriented parallel to the slope (065°) with a dip of about 20° to SE. The 4,500 m^3 unstable column (figs. 1b and 2a) is delineated by a 065° oriented, meter-wide near-vertical discontinuity on the entire height of its rear side. Two near-vertical sets of discontinuities (dip ranging from 80 to 90°) bisect the rock mass, striking 020-030° and 100-120°, respectively. The morphology and rock mass structure suggest toppling and/or basal sliding as the failure mechanism. During the last 10 years, regular measurements of the column displacement were carried out and showed a cumulative 13 cm of motion in the 160° direction with a plunge of 30°.

The second site, La Suche, is located at an elevation of about 1,400 m on the downstream left-bank slope of the Rhône valley (fig. 1a) in the canton Valais, Switzerland. The cliff consists of sub-horizontal limestone layers of Lower Jurassic to Paleocene age (Badoux 1965). The studied unstable column is approximately 70 m high, 28 m wide and 15 m thick, with a volume of about 30,000 m^3 (figs. 1c and 2b). On its southeastern side, the column is separated from the rock mass by a complex network of open and near-vertical fractures, while an open fracture striking 120-135° is visible on the southwestern side. The column toe is affected by a discontinuity oriented 110° and dipping 70° to the NNE, which creates a preferential basal sliding plane. The activity of this site is evidenced by regular rockfalls occurring since the 60's, with four significant events between 1969 and 1999. Extensometer monitoring conducted by CREALP (Centre de Recherche en Environnement ALPin - Guardaval Network) since 2005 has revealed a northwestward opening at rates up to 3 mm/year.

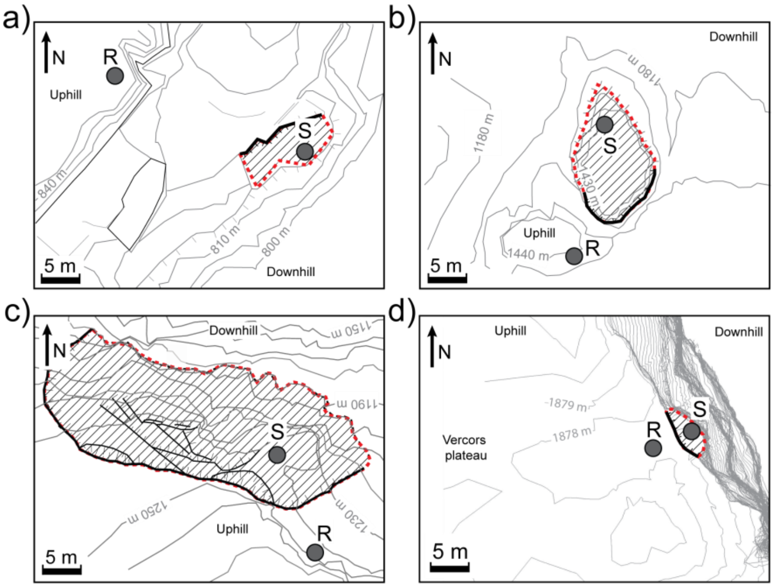

Figure 2. Site maps of Rubi (a), La Suche (b), La Praz (c) and Les Arches (d). The unstable rock compartment is filled with black hatches and circled with the dashed red line. The boundary separating the unstable compartment from the stable rock mass (RF or RS in Figures 1 and 3) is delineated with a black barbed line. The location of the sensor (S) on the prone-to-fall compartment and the reference sensor (R) on the stable rock mass are shown with grey dots.

The third site, La Praz, is located in the middle part of the Maurienne Valley (Savoie, France; fig. 1a). It lies on a north-facing slope at about 1,230 m in altitude. It is composed of a succession of highly fractured sandstone beds and dark mica-rich shale layers of Carboniferous age (Debelmas et al. 1989), (fig. 1d). The rock mass is cut by a major fracture set nearly parallel to the slope, while the bedding shows inward dip. This discontinuity pattern creates an unstructured mass of rock blocks (with volumes up to 10 m^3 in sandstones) separated from the adjacent stable part by a 10 m high rear fracture, generating compound sliding of fractured material (fig. 2c). The volume of the unstable compartment is estimated at about 13,000 m^3, with a thickness varying from 7 m to locally 15 m, from morphological observations and active seismic profiles (not shown). Rockfall volumes up to 1,000 m^3 were generated at this site during the 20^{th} century, while three recent rockfalls between 2002 and 2009 produced volumes of a few hundred cubic meters. This site was equipped with nine extensometers in 2006, and displacement measurements show large spatial variability resulting from the discontinuous structure of the material, from a few mm to locally more than 40 mm per year.

The final site, Les Arches, is located at an elevation of about 1,900 m in the southern part of the carbonate Vercors massif (Isère, France; fig. 1a). The eastward facing cliff is composed of sub-horizontal meter-thick bedded bioclastic limestone in its upper part (upper 100 m) and of decimeter-thick layers of marly limestone in the less steep lower part (Arnaud et al. 1974, Lévy et al. 2010). The unstable column is decoupled from the neighboring rock mass by a rear open fracture oriented 145°, visible in figure 1e. The unstable rock compartment is about 30 m high, 15 m wide and 5 m thick at its crown, resulting in a total volume of about 1,000 m^3 (fig. 2d). Regular water seepage is observed at the toe of the column. The column geometry and discontinuity pattern suggest toppling and possible basal sliding as failure mechanisms. In such a geological context, the main factor controlling failure is the proportion of rock bridges along the potential rupture surface, as shown by Frayssines and Hantz (2006) in their study of 25 rockfalls that occurred in steep limestone cliffs in the French Alps.

All four study sites represent a large variety in terms of geological materials, morphology, failure mechanism and unstable volume. A summary of the study site characteristics is given in Table 1.

Site	Rock type	Shape	Failure mechanism	Volume (m^3)	Rear fracture azimuth (°)	f_1 (Hz)	Vibration azimuth at f_1 (°)
Rubi	Argillites	Column	Toppling/basal sliding	4,500	065	5.2	160
La Suche	Limestone	Column	Toppling/basal sliding	30,000	undefined	2.2	015
La Praz	Shale-sandstone series	Heavily fractured rock mass	Compound sliding	13,000	090-100	5.8	016
Les Arches	Limestone	Column	Toppling/basal sliding	1,000	145	6	054

Table 1. Characteristics of the four prone-to-fall compartments along with their fundamental frequency (f_1) and corresponding azimuth of vibration. Azimuths are given in degrees clockwise from north.

2.2 Ambient vibration recording technique

At each site, two short-period three-component seismometers were installed on the unstable compartment (S) and on the stable rock mass (R), respectively (see locations in fig. 2). The seismometers were oriented northward, with ± 5° accuracy. At all sites, the studied resonant frequencies were within the flat response range of the seismometer and no record deconvolution by the instrument response was performed. Seismometers were operated in continuous recording mode for seven months with a 250 Hz sampling frequency. A meteorological station was set up at each site, except for Les Arches where a previously installed station is located about 3 km southwest of the site and 120 m lower in altitude. Air temperature and rainfall were recorded every 15 minutes. Seismic and meteorological recordings are both referenced with respect to the Coordinated Universal Time (UTC).

3 VIBRATION STUDY

3.1 Field data analysis

The spectral content of ambient vibrations in the horizontal plane was computed from the N and E components by calculating Fourier spectra for each azimuth at 1° angular increments. The resulting polar plots for the Rubi, La Suche, La Praz and Les Arches sites are displayed in figures 3a, b, c and d, respectively, both for the unstable compartment (top) and the stable rock mass (bottom). Azimuths are displayed clockwise with respect to north, while the radial direction is the frequency axis. Results are shown in the 1-5 Hz or 1-10 Hz range, and the amplitude of the polar plots is normalized to 1 for each site. For all prone-to-fall compartments (figs. 3a to d, top) polar plots exhibit clear peaks at specific orientations and frequencies. In contrast, no significant peak in amplitude or directionality is observed on the plots for the stable rock mass (fig. 3 a to d, bottom), except for the La Suche site. Notably, the reference sensor (R) at La Suche had to be set up relatively close to the unstable column (fig. 2b) and the data likely reflect part of the column vibration explaining the spectral peak between 1.8 and 3 Hz (fig. 3b, bottom). For Rubi (fig. 3a), La Suche (fig. 3b) and Les Arches (fig. 3d), the greatest spectral amplitudes are observed at the lowest peak in frequency, in agreement with results from previous studies (Lévy et al. 2010, Burjánek et al. 2012). At higher frequency, another peak is clearly distinguishable at these three sites, showing a direction of vibration nearly perpendicular to the fundamental mode. In contrast, no such clear relation between spectral peaks is observed at La Praz (fig. 3c, top). The three first peaks are oriented in nearly the same direction, while the fourth is orthogonal to the others. These results suggest a different response of the La Praz site, as compared to the other three prone-to-fall compartments.

Comparing the polar plots (figs. 3a to d) with the site maps (figs. 2a to 2d), the motion of the predominant vibration appears to be oriented perpendicular to the main rear limiting crack separating the unstable compartment from the stable rock mass (Table 1), especially at Rubi, La Praz and Les Arches. These observations are consistent with the results of Burjánek et al. (2010, 2012) and Levy et al. (2010), who found that ambient vibrations were predominantly oriented perpendicular to open fractures. At La Suche, the fracture pattern is more complex (Figure 2b), with at least two fracture sets delineating the rock column. At this site, the 015° striking vibration is oriented roughly in the line of slope. As shown in a similar study (Lévy et al. 2010), the frequency peaks measured on the prone-to-fall compartments could be associated with their resonance modes. This hypothesis is supported by the absence of similar peaks in the spectra measured on the stable rock mass, and is explored in the following section.

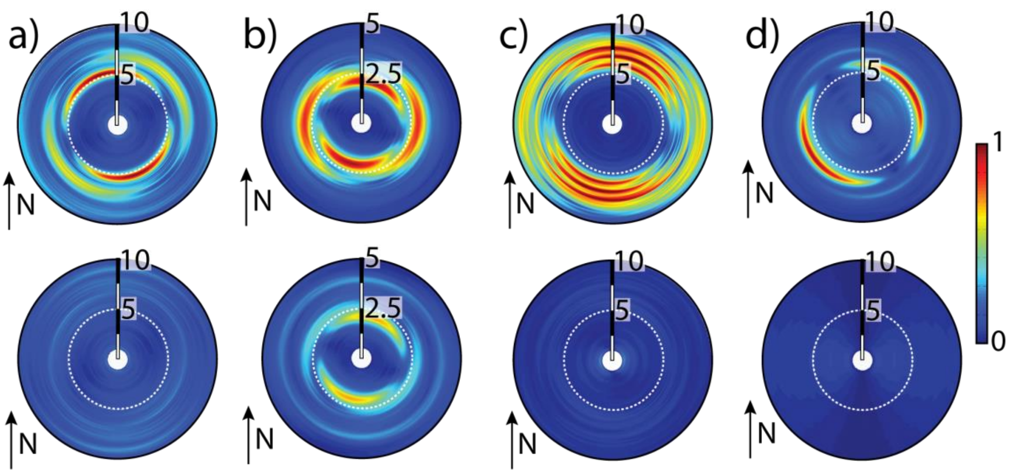

Figure 3. Polar plots of normalized Fourier spectra, computed from 1-hour long records, for Rubi (a), La Suche (b), La Praz (c) and Les Arches (d). Frequency is shown on the radial axis and the azimuth is given clockwise with respect to north. The color scale corresponds to the amplitude of the Fourier spectrum, normalized to 1 for each site. Top row: unstable compartment, and bottom row: stable rock

mass. Notice that the frequency scale in (b) is different from the others.

3.2 Numerical simulations

To validate the interpretations deriving from analysis of field data, a simple numerical modal analysis of Les Arches, Rubi and La Suche sites was conducted using the 2D finite element code RDM6 (http://iut.univ-lemans.fr/ydlogi/rdm_version_6.html). Each unstable compartment was modeled as a simple 2D rectangular column attached at its toe, using the mechanical parameters given in Table 2. At Les Arches, the dynamic characteristics of the limestone were measured in-situ using seismic prospecting (Lévy et al. 2010), yielding an elastic modulus of 6.9 GPa. A seismic refraction profile conducted on the rock mass at Rubi showed a P-wave velocity (Vp) of about 2,000 m/s at 10 m depth, in good agreement with the value given by Lavergne (1989) for soft sedimentary rocks (marls and shales). According to this same source, Vs was taken as 800 m/s, leading to an elastic modulus of 4.5 GPa. Such investigation was impossible on the steep terrain at La Suche. Using characteristics given in the literature for similar fractured limestone (Marclay et al. 2010), elastic modulus values were bracketed in the range between 15 and 25 GPa. Computed fundamental resonance frequencies, which correspond to the first flexural mode, are compared to the measured values in Table 2. Despite the strong assumptions regarding the column geometry and boundary conditions, as well as uncertainties in the mechanical parameters, the simulations yield results within the same order of magnitude as our field measurements. This supports the hypothesis that the spectral peaks measured on-site are related to resonance of the unstable compartments. The origin of this resonance will be addressed in the discussion section.

Site	Density ρ ($kg.m^{-3}$)	E (GPa)	Poisson ratio ν	f_1 (Hz)	
				F.M.	N.M.
Rubi	2,500	4.5 (1)	0.40	5.2	4.9
La Suche	2,650	15 (2) 25 (2)	0.31	2.2	2.1 2.7
Les Arches	2,650	6.9 (3)	0.43	6	6.4

Table 2. Mechanical parameters used for 2D resonance modeling (see text for details). f_1 is the fundamental resonance frequency, while F.M. and N.M. refer to Field Measurements and Numerical Modeling, respectively. Elastic modulus values come from (1) seismic refraction profile, (2) laboratory and dilatometer tests (Marclay *et al.* 2010) and (3) previous seismic surveys (Lévy *et al.* 2010).

4 RESONANT FREQUENCY MONITORING

The fundamental resonant frequency at each site was monitored over the acquisition period. First, the seismic signal in the direction of fundamental vibration was obtained by rotating the horizontal components, then cut into one-hour long segments and clipped to mitigate the effects of transients. The averaged Fourier spectrum was computed for each time block and normalized to 1. This processing brought out the fundamental frequency (f_1) for monitoring its changes over time (fig. 4, top); displayed along with air temperature and rainfall rate (fig. 4, bottom).

All sites exhibited variations in f_1, but with very different magnitudes; the standard deviation ranging from 9 % at Les Arches (fig. 4d) to 0.5 % at La Praz (fig. 4c) over the entire monitoring period. Such changes are observed at two different time scales: long-period changes (a few days to a few weeks, see figure 4) and daily cycles (figure 5, enlargement of figure 4 during August 2011). Both frequency and temperature curves exhibit this same characteristic, suggesting that reversible changes in f_1 are caused by thermal effects. At Rubi, La Suche and Les Arches, the two parameters are to be strongly correlated, and in phase at both time scales (figs. 4 and 5; a, b and d respectively). Similar behavior was also observed by Lévy et al. (2010) and Lévy (2011) on an unstable limestone column. The rise in resonant frequency with temperature was there interpreted as resulting from rear fracture closure induced by rock thermal expansion. On the contrary, the f_1 data at La Praz (figs. 4c and 5c), which shows little variation, is negatively correlated (i.e. out of phase) with air temperature. This difference in the thermal response of the shale and sandstone series could result from the failure mechanism. Indeed, the absence of deep open fracture makes the potential rupture surface less sensitive to temperature variations. These small changes in f_1 may result from temperature-dependency of the Young's modulus (E) (Xia et al., 2010). As temperature decreases, E increases at the rock surface and causes slight f_1 augmentation. This effect is probably not noticeable at the other sites where the influence of contact in the rear fracture prevails. During the first two months of this study, the fundamental frequency at Les Arches exhibited a linear decrease (fig. 4d). This long term trend likely results from ice melting in the rear fracture during spring which generates a progressive decrease in f_1 during warming, as proposed by Lévy (2011). Over the entire period of monitoring, no clear irreversible changes in resonant frequency that might indicate damage were observed.

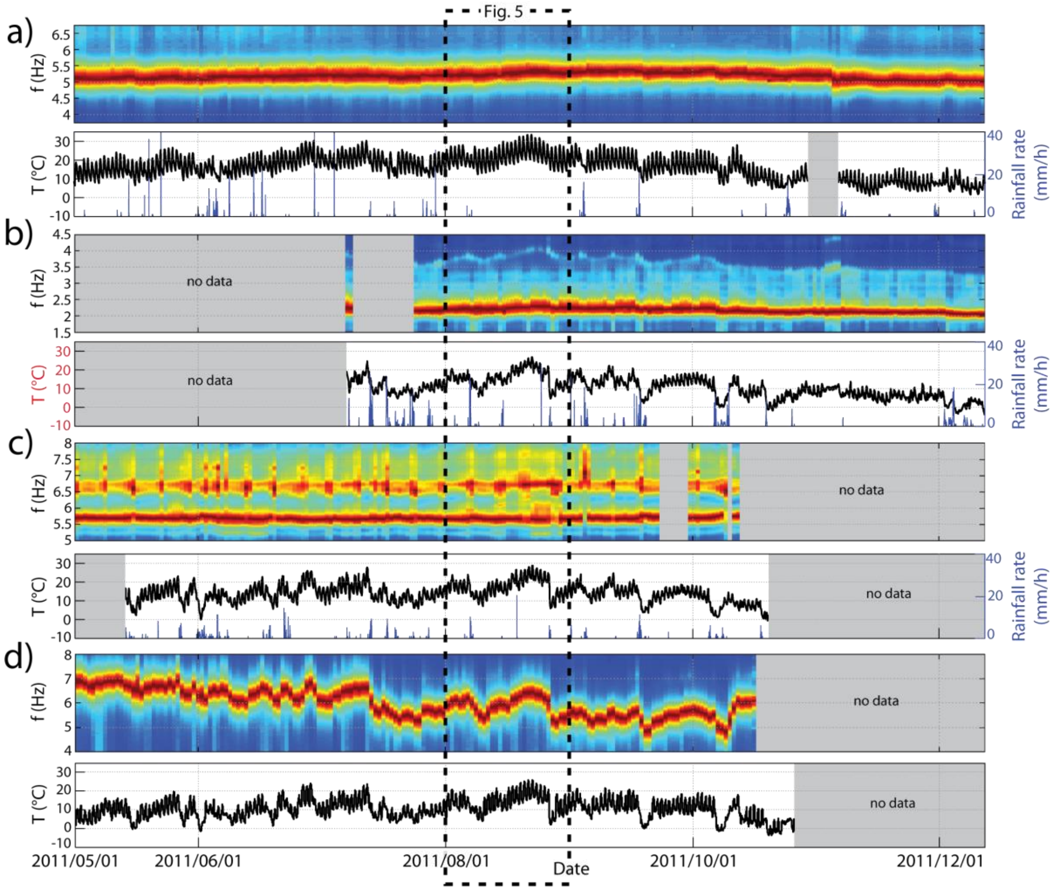

Figure 4. (Top) Averaged seismic noise spectrum, (bottom) air temperature (in black) and rainfall rate (in blue) over time, for Rubi (a), La Suche (b), La Praz (c) and Les Arches (d) study sites.

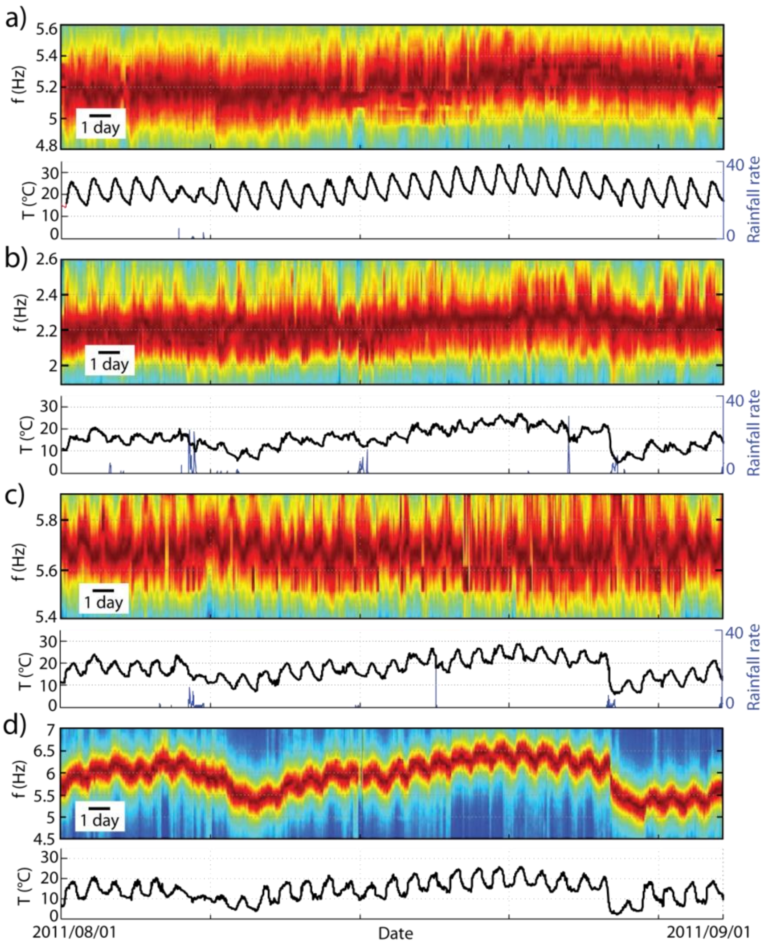

Fig. 5. Zoomed view of Figure 4 during August 2011. (Top) Fundamental frequency f_1, (bottom) air temperature (in black) and rainfall rate (in blue) variation over time, for Rubi (a), La Suche (b), La Praz (c) and Les Arches (d).

5 DISCUSSION

All unstable rock compartments exhibited clear fundamental resonant frequencies (f_1) ranging from 2.2 to 6 Hz for volumes between 1,000 and 30,000 m^3. The resonance of a simple oscillator is given by:

$$f_1 = \frac{1}{2\pi}\sqrt{\frac{K}{M}} \qquad (1)$$

where K is the spring stiffness and M is the mass.

Using this simple equation, the resonant frequency should decrease with compartment volume. Such decrease is observed for Les Arches, Rubi and La Suche (see Table 1). In contrast, the La Praz site exhibits an unexpectedly high resonant frequency (5.8 Hz) with respect to its volume of 13,000 m^3, suggesting the influence of another parameter. Other factors controlling the resonant frequency of an unstable compartment are its Young's modulus and the stiffness of the contact linking the compartment to the stable rock mass (Lévy et al. 2010). For stiff and homogeneous rocks such as limestone, the failure process (toppling or sliding) develops through rock bridge breakage along a bounding fracture (Frayssines and Hantz 2006) and the predominant factor influencing the resonant frequency change is the contact stiffness. This explains the in-phase change of f1 with temperature, resulting from the thermal expansion which closes the rear fracture. On the contrary, the resonant frequency of the heterogeneous La Praz compartment, which is controlled by compound sliding with no deep rear fracture, is less sensitive and anti-correlated with temperature variations through the Young's modulus dependency on temperature. The Vp profile obtained at La Praz (not shown, see Bottelin et al. 2013 for more details) shows the presence of a superficial low velocity layer (< 1,000 m/s) across the identified unstable zone. This seismic structure is likely to generate spectral amplification, similar to site effects widely appreciated in earthquake engineering (Bard and Riepl 1999). Such effects result from trapping of shear and surface waves in the low-velocity layer, generating resonance. Assuming a constant Poisson's ratio of 0.33 in the rock, Vp values were converted into Vs values and the first resonant frequency was estimated using the simple relation for a single infinite layer overlying a half-space:

$$f_1 = \frac{V_s}{4\,H} \qquad (2)$$

where H is the layer thickness, and Vs is the mean shear wave velocity in the layer. Application of this simple formula to the La Praz site (mean computed Vs = 314 m/s; H = 12 m) yielded a f1 value of 6.5 Hz, relatively close to the observed first resonant frequency of 5.8 Hz. Despite the strong simplification of 1D medium, these results suggest that the resonance phenomenon observed at La Praz, in contrast with the other sites, is most likely generated by the contrast in rigidity between the unstable fractured compartment and the parent rock.

6 CONCLUSIONS

This study of the dynamic response of four prone-to-fall rock compartments exhibiting diverse morphology, failure mechanism, geological context and volumes allowed us to draw conclusions on the applicability of ambient vibration monitoring. All sites exhibited well-defined spectral peaks, both in specific orientations and at distinct frequencies. A predominant peak was systematically measured at the lowest peak in frequency, which has been interpreted as the first resonant frequency f_1 of the unstable compartment, in accordance with 2D modal analysis performed at three sites. The dominant vibration direction at f_1 is oriented perpendicular to the rear limit of the unstable compartment in the horizontal plane, at the three sites exhibiting a deep open rear fracture. This feature is consistent with numerical modeling results and suggests that the first vibrational mode is bending. These results attest that spectral analysis of ambient vibrations can provide valuable information on the dynamic behavior of unstable compartments in various geological contexts. Secondly, monitoring f_1 during a few months did not reveal any irreversible f_1 variations linked to damage. In contrast, all sites exhibited reversible f_1 fluctuations related to temperature variations. At Rubi, La Suche and Les Arches, the two parameters are in phase, in contrast to La Praz where they are out of phase with smaller f_1 variations. Furthermore, the value of f_1 at La Praz is not consistent with the other sites, with respect to the relative volumes. These results indicate that the mechanical behavior of the La Praz compartment, which is composed of fractured and heterogeneous layers, is different from the other sites that are characterized by a deep near-vertical open rear fracture. Resonance at the La Praz site results from a contrast in internal rigidity within the rock mass, similar to site effects observed in seismology, rather than from decoupling from the rock mass along a bounding fracture. Whatever the origin of the resonance phenomenon, an irreversible decrease in f_1 can be interpreted as resulting from damage along the contact interface or within the compartment. For sites with toppling and basal sliding failure mechanisms, a decrease in f_1 may be related to breakage of rock bridges and the decrease in friction along the sliding plane, respectively. In the case of compound sliding (e.g. at La Praz), a decrease in f_1 could result from gradual disintegration of the rock compartment, which lowers its elastic modulus. These results highlight the benefit of monitoring f_1 on unstable rock compartments, provided that reversible fluctuations and irreversible effects can be discriminated.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

Amitrano D., Grasso J. R. and Senfaute G. 2005. Seismic precursory patterns before a cliff collapse and critical point phenomena. Geophys. Res. Lett. 32, L08314.

Amitrano D., Arattano M., Chiarle M., Mortara G., Occhiena C., Pirulli M., and Scavia C. 2010. Microseismic activity analysis for the study of the rupture mechanisms in unstable rock masses, Natural Hazard and Earth System Sciences, 10, 831-841, doi:10.5194/nhess-10-831-2010.

Arnaud H., Meloux M. and Montjuvent G. 1974. Notice explicative de la carte géologique de la France au 1/50 000ème, feuille XXXII-37 Mens (844), BRGM.

Badoux H. 1965. Notice explicative de la carte géologique de la France au 1/50 000ème, feuille XXXV-28 Thonon-Châtel, BRGM.

Bard P.Y. and Riepl J. 1999. Wave propagation in complex geological structures and local effects on strong ground motion, in Wave motion in earthquake engineering: WIT Press, Series "Advances in Earthquake Engineering" 38–95.

Bottelin P., Jongmans D., Baillet L., Lebourg T., Hantz D., Lévy C., Leroux O., Cadet H., Lorier L., Rouiller J-D., Turpin J., Darras L. In prep. Spectral analysis of prone-to-fall rock compartments using ambient vibrations. Near Surface Geophysics.

Burjánek J., Gassner-Stamm G., Poggi V., Moore J. R. and Fäh D. 2010. Ambient vibration analysis of an unstable mountain slope. Geophys. J. Int. 180, 820-828.

Burjánek J., Moore J. R., Yugsi Molina F. X. and Fäh D. 2012. Instrumental evidence of normal mode rock slope vibration. Geophys. J. Int. 188(2), 559-569.

Clinton J.F., Case Bradford S., Heaton T.H. and Favela J. 2006. The Observed Wander of the Natural Frequencies in a Structure. Bulletin of the Seismological Society of America 96(1), 237-257.

Debelmas J., Desmons J., Ellenberger F., Goffé B., Jabre J., Jaillard E. and Pachoud A. 1989. Notice explicative de la carte géologique de la France au 1/50 000ème, feuille Modane (775), BRGM, 53 p.

Faure-Muret A. and Fallot P. 1957. Notice explicative de la carte géologique de la France au 1/50 000ème, feuille XXXVI-41 Puget-Théniers, BRGM.

Frayssines M. and Hantz D. 2006. Failure mechanisms and triggering factors in calcareous cliffs of the Subalpine Ranges (French Alps), Eng. Geol., 86, 256–270, doi:10.1016/j.enggeo.2006.05.009.

Lavergne M. 1989. Seismic methods. Editions Technip, Paris. 192 p.

Lévy C., Baillet L., Jongmans D., Mourot P. and Hantz D. 2010. Dynamic response of the Chamousset rock column (Western Alps, France). J. Geophys. Res. 115, F04043.

Lévy C. 2011. Etude instrumentale et numérique de la réponse dynamique d'une écaille potentiellement instable. PhD Thesis. Université de Grenoble, France.

Marclay R., Hohberg J.M., John M. and Marcher T. 2010. The new Linth-Limmern hydro-power plant - design of caverns under 500m overburden. Rock Mechanics in Civil and Environmental Engineering: Proceedings of the European Rock Mechanics Symposium (Eurock) 2010, Lausanne, Switzerland, 15-18 June 2010. CRC Press. 4p.

Moore J.R., Gischig V., Burjánek J., Loew S., and Fäh D. 2011. Site Effects in Unstable Rock Slopes: Dynamic Behavior of the Randa Instability (Switzerland). Bulletin of the Seismological Society of America 101(6), 3110–3116.

Senfaute G., Duperret A. and Lawrence J. A. 2009. Micro-seismic precursory cracks prior to rock-fall on coastal chalk cliffs: a case study at Mesnil-Val, Normandie, NW France. Nat. Hazards Earth Syst. Sci. 9, 1625–1641.

Stubbs I.R. and McLamore V.R. 1973. The ambient vibration survey. Proc. of the Fifth

World Conference on Earthquake Engineering, Rome, 286-289.