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Multi-parameter monitoring strategy applied to unstable rock slopes: the example of the Ruines de Séchilienne (Isère, 38)

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RÉSUMÉ. Les observations et les mouvements mesurés, depuis 1985, par le système de surveillance du CETE de Lyon sur le mouvement des Ruines de Séchilienne, montrent que les mécanismes de déformation et rupture du versant sont complexes. Pour progresser dans la compréhension de ces mécanismes, l'INERIS contribue depuis 2009 aux investigations menées sur le site par forages profonds. Un système d'observation multi-paramètres a ainsi été installé en bordure Ouest de la zone active. Il fait appel à une plateforme technologique intégrée qui combine des mesures microsismiques, géotechniques, hydrologiques, météorologiques et des mesures de déplacement tridimensionnel. L'article décrit les objectifs de la démarche et la méthodologie mise en œuvre par l'INERIS pour répondre aux exigences des systèmes d'alerte précoce multi-paramètres, appliqués aux mouvements de versants instables. Le site d'étude et les principales caractéristiques du dispositif sont présentés. Des considérations sur le calibrage du système et la qualification des données sont décrites et les premières données sont présentées.

ABSTRACT. Field observations and movements measured since 1985 by the Lyon CETE (Public works regional engineering office) monitoring system at the Ruines de Séchilienne show that the slope deformation and fault mechanisms are complex. To provide a deeper understanding of these mechanisms, INERIS has been investigating the site through the instrumentation of deep drillholes since 2009. An experimental multi-parameter monitoring system was installed on the western edge of the large active zone. It uses an integrated technology platform which combines microseismic, geotechnical, hydrogeological, meteorological and 3D displacements. The article outlines the objectives and the methodology applied by INERIS to meet the requirements of early warning multi-parameter systems applied to unstable rock slopes. The studied site and the main characteristics of the system are presented. Items dealing with the system calibration and characterization data are described and preliminary data are given.

MOTS-CLÉS : système d'alerte précoce, mesures hydrologiques et géotechniques, microsismicité, localisation 3D des foyers, versant rocheux.

KEYWORDS: early warning system, hydrogeological and geotechnical measurements, microseismicity, 3D location of event, rock slope.

1. Introduction

The prevention and the management of risks surrounding rock-slope movements – from tens of thousands to several million cubic metres – raise serious difficulties, given that these natural phenomena are both violent and difficult to study on account of the complexity of the mechanisms that govern them. Their evolution is effectively ruled by intrinsic characteristics (morphology, geology, condition of fracture, etc.) and by outside forces (precipitation, seismic activity, etc.) which further complicate studies and observations under real-life conditions (Harp *et al.*, 1996, Lollino *et al.*, 2006). Besides the possibility of carrying out protection work (stabilisation through plantations, support and sustaining structures, etc.) or work to reduce vulnerability (expropriation, road by-passes, etc.) to attenuate the effects of these rock-slope movements, one approach consists in implementing multi-parameter type early-warning systems (Ornstein *et al.*, 2007,) making it possible to observe and monitor as effectively as possible all the physical interactions likely to precede and trigger the feared phenomenon.

Many large-scale movements of rock slope are consequently coming under a multi-parameter approach, which however is still running into two major limitations. Firstly, the multi-parameter approach is often limited to observations and surface measurements for tracking displacements (by GPS, tachometer or extensometer) and forcing of a meteorological nature. Few systems are able to provide continuous perception of a mountain slope's evolution at any real depth. As a result, the integration of the microseismic monitoring of ruptures of rock compartments into early warning systems is a method with real promise (Senfaute *et al.*, 2003), extensively used in the monitoring of underground cavities to forestall the collapsing of gallery roofs (Senfaute *et al.*, 2000, Contrucci *et al.*, 2010). The microseismic monitoring of large rocky slopes is thus the subject of research programmes (Mertl *et al.*, 2008, 2010), but its input to an early warning system has yet to be clearly established. Indeed, the majority of networks are located on the surface, in terrain that is often both naturally very noisy and highly fractured, resulting in the attenuation of the microseismic waves. Secondly, the different measurement techniques deployed in early warning systems are seldom coupled in real time. This is due to the increased sophistication of measurements and the multiplication of independent data bases. Yet, the tracking of variables, all very different in nature, sampled at dissimilar frequencies and with a ratio of over 10^3 , applies huge stress on remote-measurement systems and on the information processing unit. In practice, tracking is possible only if it is managed automatically as part of a single process, and immediately so as to at once intelligently adjust acquisition strategies and promote expertise capabilities (Klein *et al.*, 2008).

This article presents a multi-parameter approach deployed experimentally on the slope of the *Ruines de Séchilienne* (France) to further our in-depth understanding of

the mechanical and hydrodynamic behaviour of the slope, while discarding the traditional limitations mentioned earlier. This approach utilises the 240-meter long horizontal gallery dug into the slope (Duranthon, 2006) and two vertical drill-holes of 80 m and 150 m, drilled in 2009 on the western edge of the most active zone. It brings into play an integrated technological platform which assembles microseismic, geotechnical, hydrogeological and meteorological measurements together with three-dimensional displacement measurements.

The first part of the article specifies the motivations and the methodology proposed by INERIS to meet the requirements of multi-parameter early warning systems applied to the question of rocky slopes. We then present the study site together with the main characteristics of the system. Finally, items dealing with the system calibration and characterization data are described and preliminary data are presented.

2. Monitoring strategy for major movements on rocky slopes

2.1. Reference items

Monitoring systems applied to major slope movements focus primarily on the measurements of surface movements acquired using different techniques and their correlation with exterior factors (climatic, seismic, etc.). The combination of different techniques is designed to provide a resolution in time and space that is compatible with the evolutionary speeds of phenomena and to quantify the 3-D kinematics of movements (Malet *et al.*, 2002). The emblematic sites at *Åknes* in Norway, *Randa* in Switzerland and *Séchilienne* in France, where some of the finest instruments are being used, are a perfect illustration of this approach. On the site at *Åknes* (Bitelli *et al.*, 2004), monitoring is carried out with one-off type measurements (GPS, extensometer, laser tachometer) and surface-type instruments (iconometry, radar interferometer or laser scanning). The site at *Randa* has been monitored through displacement measurements (geodesy, extensometer and laser tachometer) since the landslide of 1991 (Willenberg *et al.*, 2003). Likewise, the *Ruines de Séchilienne* site has been monitored since 1985 using a system that has been enhanced in pace with technological developments and which today pools displacement measurements by manual and automatic extensometry, clinometry, radar, laser tachometry and video photography (Duranthon, 2006). However, despite the geophysical reconnaissance campaigns conducted on the site for the past twenty years (Meric *et al.*, 2005) to evaluate the limits and volumes of rockslides and the monitoring system now in place, the mechanism and deformation kinetics that lie at the origin of this slope's instability, as they do with many others, have still not been clearly understood.

Our improved knowledge, particularly the in-depth response of rocky masses to hydrodynamic solicitations, focuses most notably on the study of interstitial pressure variations. Through hydro-mechanical couplings and the repeated effects of flows and cycles of ground water, these variations may indeed alter real stresses and con-

tribute to the instability of rocky slopes. This is why understanding of the in-depth response of masses has also led to the further installation of microseismic monitoring networks on large slopes where the risk is high. These networks are aimed at detecting and, if possible, localising at depth the active zones of rupture and deformation. The movement at *Åknes* is thus one of the rare sites that is being monitored in real time, since 2004, by a global system that includes a network of 8 three-dimensional probes placed on the surface (Roth *et al.*, 2006). However, monitoring of microseismic activity is confined primarily to the counting of events. At the other sites, microseismic monitoring is generally deployed experimentally by research laboratories. This is typically the case of the slope of *Ruines de Séchilienne*, which since 2007 has been equipped with 3 low-aperture seismological antennae placed on the surface around the most active zone, the readings of which are noted periodically independently of the monitoring system (Helmstetter *et al.*, 2010). However, this configuration has its limits: the measurement system is now highly sensitive and prone to permanent or recurring natural sources of noise and vibration on the surface (wind, rain, storms, lightning, etc.). Furthermore, the general condition of the fracture of rocky masses and the advanced deconsolidation of surface layers (where the probes are usually placed) seriously reduce the propagation of waves and complicate the processing and analysis of data (Spillmann *et al.*, 2007, Helmstetter *et al.*, 2010). The localisation of microseismic centres, when possible, is then very often marred by significant horizontal errors; the depth position is not often indicated as it is felt to be too unreliable (Mertl *et al.*, 2008, 2010).

The recent drilling of deep drill-holes, whenever possible like at *Randa* in 2001 (Willenberg *et al.*, 2003, Spillmann *et al.*, 2007), *Åknes* in 2009 (Blikra *et al.*, 2010) or more recently at the *Ruines de Séchilienne*, is evidently a solution to concentrate and enhance the performance of in-depth microseismic measurements by broadly filtering artefacts, monitoring sounder terrain and getting closer to the supposedly active zones of interest. These drill-holes, generally fitted with water table sensors, inclinometers and extensometers, usefully complement remote-measuring apparatus at the surface. They deliver additional data as to the internal dimension of the instability in order to get a finer take, qualitatively and quantitatively, on the relationship between the site's geology, faults, geomorphology and hydrology.

2.2 The integrated multi-parameter technology platform

The previous examples show that data is usually acquired then processed using multiple and independent measurement systems before being centralised with the system administrator. In addition, data is not always available in real time because it is gathered at regular intervals. This means that the different measurement systems provide little, if any, interoperability.

Today, the recent technological progress made in terms of portability, energy consumption and on-board data entry and processing software means we are able to

design modular and integrated early warning systems (Malet *et al.*, 2002, Klein *et al.*, 2008). The many different factors – aggravating, triggering, forerunning – that need monitoring imply having to install monitoring architecture with a networked architecture of acquisition probes and units so as to provide instrumentation for all the zones or points of interest with minimum compromise, all done while focusing data flows onto a master acquisition unit. Then, based on variables known as vigilance variables (often linked to the environment) and alarm variables (usually associated with forerunning signs and the actual hazard), this unit must be able to adjust automatically and instantly the frequencies for measurement acquisition for all – or part – of the probes, together with data transmission speeds and priorities to a central site. The many different factors being monitored also require resources and facilities with which to centralise and render accessible to the different players involved in monitoring all the data, measurements and information to promote expertise capabilities and decision support.

It is precisely to meet the monitoring requirements for this type of approach that INERIS has developed the e.cenaris integrated platform with which to simultaneously combine microseismic, geotechnical, hydrogeological and meteorological measurements with 3-dimensional movement measurements via a GPS-RTK network. The data collected on-site is automatically transmitted to the INERIS Surveillance Centre in Nancy, which boasts advanced capacities for hosting, storing and exploiting multi-parameter data via a dedicated web-monitoring platform. Faced with the growing complexity of warning systems, this platform sets out both to facilitate data access and sharing, and to promote expertise and decision support with attractive cost value in terms of benefits gained.

Since 2009, this integrated platform has been installed experimentally on the slope of the *Ruines de Séchilienne* to further our understanding of in-depth deformation mechanisms. This experimentation is being conducted in collaboration with the CETE in Lyon and with the support of the MEEDDM¹.

3. Monitoring of an unstable rock-slope – the example of Ruines de Séchilienne

3.1. Presentation of the rock-slope of Ruines de Séchilienne

The movement at *Séchilienne* (Isère department, 38) is located at the south-west tip of the crystalline highland of *Belledonne*. The deformation involves the whole of the southern slope of *Mont Sec* (1180 m above sea-level) and extends over an altitude drop of 900 m to reach the right bank of the *Romanche*. On the lower section, the mountain-side slopes very sharply at 35 to 40°; it is affected by past movements of considerable amplitude which appear to have increased in rate since the 1980s (Durville *et al.*, 2004). Observations and measurements show that the instabilities are to

¹ Ministry for Ecology, Energy, Sustainable Development and the Sea.

be found in the mica schist which – on account of its complex poly-phased tectonic history – is cut by different faults and fractures down to a depth of some 100 to 150 metres (Pothérat *et al.*, 2001). The highland’s progressive internal rupture is resulting in a disintegration of *Mont Sec*: the slope’s decompression is causing the opening of major discontinuities and fractures, the effect of which is to gradually cut it up into “vertical straps” separated by furrows (Pothérat *et al.*, 2009). The particularly active zone, the surface area of which is around 4 hectares (10 acres) comprises a volume estimated to be around 3 million cubic metres. It is characterised by a speed of displacement of between 0.15 m/year and 1 m/year (Pothérat *et al.*, 2009).

As mentioned earlier, this site, where the issues at stakes are quite considerable, has been monitored since 1985 by the CETE in Lyon. The monitoring system – which has evolved considerably since it was first set up – is based primarily on the remote measurement of surface movements (extensometers, laser tachometer, radar), GPS reports and meteorological parameters (Duranthon, 2006). Since 2007, the Grenoble-based LGIT (Laboratory of Internal Geophysics and Tectonophysics) has headed the monitoring of a seismic probing network consisting of 3 low-aperture antennae positioned around the most active zone (Helmstetter *et al.*, 2010).

Given that these systems are unable to fully perceive the hydro-mechanical behaviour of the slope at any real depth, drill-holes were drilled on-site in 2009 and 2010. Four drill-holes of between 80 and 150 metres were made on the western edge of the active zone. Two are dedicated to periodic clinometric measurements by the CETE in Lyon. The other two were instrumented by INERIS for continuous hydrogeological and clinometric measurements and for in-depth seismic monitoring (Figure 1).

3.2. Description of the integrated multi-parameter system

The system has been configured around “underground” structures available on the western edge of the active zone, i.e. the sub-vertical drill-holes SD and SP, respectively 80 m and 150 m in depth, and a sub-horizontal gallery which is 240 m in length. The system, powered by batteries and solar panels, comprises 2 measurement stations – GALERIE and PISTE – the composition of which is described in Table 1 (see also Figure 1). It includes:

- 8 high-resolution microseismic probes including 4 three-dimensional probes positioned at depth in the mountain (in the reconnaissance gallery and in the SD drill-hole at depths of 40 m and 80 m), each equipped with a bi-axial inclinometer and an orientation station,
- 1 piezometer and 1 conductivity-temperature probe placed in the SP drill-hole dedicated to hydrogeological measurements,
- 2 GPS-RTK stations, one measurement station placed level with the drill-hole area, another, a reference station, is placed on the reputedly stable opposing slope (*Mont Falcon*),

– 1 meteorological station (air and ground temperatures, rainfall) set up on the opposite slope (*Mont Falcon*). Measurement data is transmitted to the PISTE acquisition unit by radio link via the GPS reference receptor which also serves as a radio transmitter.

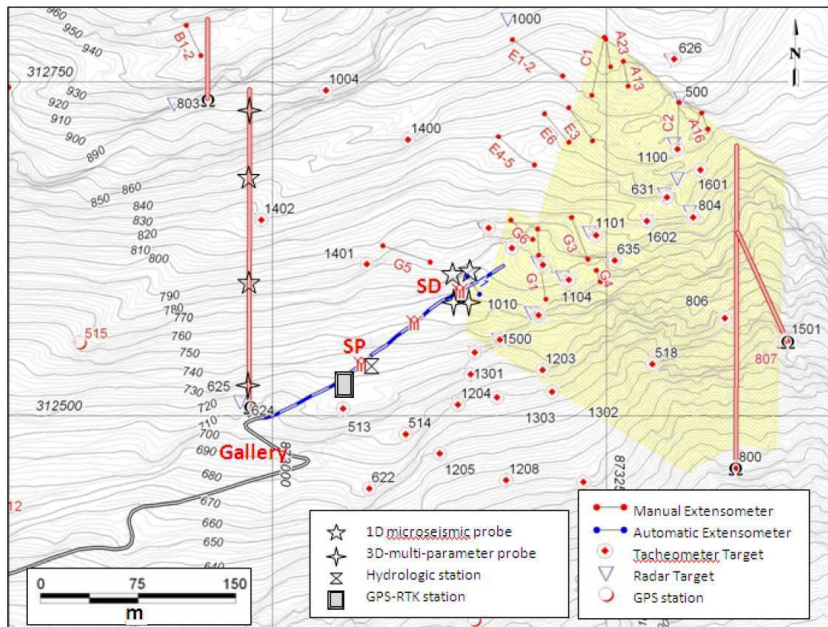


Figure 1. Plan of the site showing the positions of equipment set up by CETE and INERIS along with the location of the drill-holes (illustrated by red pit-heads) and galleries (illustrated by red rectangles) on the site. The most active zone is given in yellow, the access trail to the 3 drill-hole platforms is in blue.

The detection and acquisition of transient signals are based on threshold overstep criteria in amplitude; the system uses a 16-bit A/D converter with sampling frequency adjusted at 8 kHz. The deep-ground implantation of probes fitted with geophones allows low noise levels (less than $3.10^{-4} \text{ mm.s}^{-1}$), the measurement score (outside overload) being $\pm 2 \text{ mm.s}^{-1}$. The probe fitted with accelerometers is intrinsically more sensitive and consequently noisier.

Hydrogeological, meteorological and clinometric measurements are made 4 times a day with digitisation precision of 15 bits. GPS-RTK measurements are made twice a day according to measurement cycles of 30 minutes based on comparisons of signal phases in real time. Consequently, no post-processing is required. Measurement data and state of functioning variables are transmitted, via the high-speed mobile net-

work, to the INERIS Surveillance Centre in Nancy for processing, analysis and hosting in a data base.

Station	Probe	Type	Sensors(s)	Installation
GALERIE	SGa	3D	Accelerometer, Inclinator	Short drill-hole
	SGp1	1D	Geophone 28 Hz	Wall
	SGp2	1D		
	SGg	3D	Geophone 28 Hz, Inclinator	Short drill-hole
PISTE	S80	3D	Geophone 28 Hz, Inclinator	SD drill-hole
	S40	3D	Geophone 28 Hz, Inclinator	SD drill-hole
	SPp1	1D	Geophone 28 Hz	Wall
	SPp2	1D		
	Piezo	-	Pressure, Conductivity, Temp.	SP drill-hole
	GPS	-	GPS RTK	-
	Weather	-	Rainfall meter, Temp., Pressure	<i>Mt Falcon</i>

Table 1. Measurement equipment set up at the GALERIE and PISTE stations.

The whole system underwent preliminary tests and setting adjustments for several weeks after installation to validate the proper functioning of the measurement chain and to make adjustments to acquisition parameters. With the exception of micro-seismic data, data validation during this phase was quick, as reading and analysis are virtually immediate. Consistency with measurements by CETE in Lyon was also verified. By contrast, for the microseismic facilities, functioning tests were confined to manual solicitation with a sledge-hammer. To appreciate the resolution and calibrate the microseismic monitoring network for the localisation of microseismic events, two further actions were carried out. They are described hereinafter.

3.3. Resolution and calibration of the microseismic monitoring network

3.3.1. Sensitivity study for the localisation of microseismic events

Given that the implantation of microseismic probes was conditioned by the availability of “low-noise” underground structures (gallery and drill-hole), the system’s geometry is not optimal for analysis of events coming from the active zone (expected in principle at ~ 50 m to the east of the system). As a result, to figure the system’s resolution, a numerical simulation study was carried out. The principle is as follows: it consists in generating, from a theoretical microseismic centre positioned on-site in

the likely zone of activity, synthetic data (arrival time of P & S waves and angles of polarisation for 3-D waves). The network simulation consists in degrading this synthetic data (by introducing noise to generate large quantities of data) then in introducing this data to the localisation module: the resulting centres thus calculated are compared, in terms of spatial distribution tendency and discrepancy, with the original theoretical centre. This numerical simulation approach gives a quantitative appreciation of the sensitivity of the localisation of microseismic events.

For this study, the theoretical centres considered are positioned to the east of the network, on the western edge of the active zone of the *Séchilienne* rock-slope. Note that for this study, a homogeneous single-layer model is considered ($V_P = 2750 \text{ m.s}^{-1}$ and $V_S = 1588 \text{ m.s}^{-1}$). The localisation module is based on the global research method “Oct-Tree” (Lomax *et al.*, 2001); a full description is given in Contrucci *et al.* (2009).

The results from the different simulations are presented in Table 2. They show that the synthetic events seen by the two stations are globally speaking well localised. As might be expected, the best results are obtained when arrival times for P & S waves are used, because they alone restrict the source-to-station distance. These good results were foreseeable given the geometry of the network (4 x 3D probes and 3 x 1D probe), which gives two stations deployed virtually normally, one in relation to the other.

Data used	PISTE Station	PISTE & GALERIE Stations	GALERIE Station
Points P & S, azimuths, dip	68%	100%	38%
Points P, azimuths, dip	31%	77%	15%
Points P, azimuths	27%	78%	4%
Points P, dip	3%	76%	16%
Points P & S	14%	100%	1%

Table 2. Percentage of events localised at less than 20 metres from the theoretical centre ($X = 873200 \text{ m}$, $Y = 312629 \text{ m}$ and $Z = 718 \text{ m}$), according to the data used from either of the two stations.

By contrast, results deteriorate when events are seen only by one of the two stations (Table 2). For localisation made from probes at the PISTE station only, angles of polarisation – particularly the azimuth – are decisive. Localisation is then accurate at depth. For the unlikely configuration where an event from the east of the network would be detected only by the probes at the GALERIE station, resolution deteriorates very significantly. In what would appear to be the most positive case (P arrival time, azimuths and dip are used), only 15% of events are localised at less than 20 m

from the theoretical centre (Table 2). This is explained primarily by the centre being rather far-removed from the GALERIE station. In this configuration, the dip is moreover decisive and localisation is specified along axis Y.

The simulations also show that the accuracy of localisation varies according to the depth position of the theoretical centre. For a centre on the surface (or sub-surface), 80% of events are localised at less than 20 m from the theoretical centre, versus 95% for a centre at depth (Figure 2).

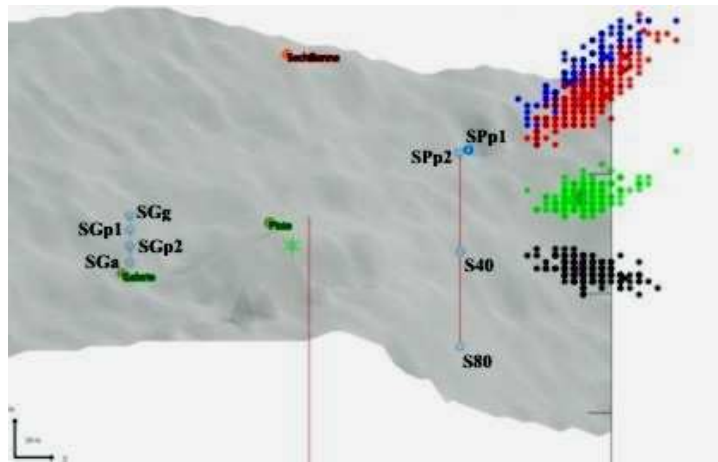


Figure 2. Illustrations of simulation results, carried out from theoretical centres located at different depths for a given position (X, Y) – using P arrival time, azimuths and dip measured with the probes at the GALERIE and PISTE stations. The blue and red show the simulations conducted at or near the surface; the green and black denote simulations at depth.

Thus, despite non-optimal implantation of probes, the localisation of microseismic events from the active zone should be relatively accurate in the positive case where events are detected by the two stations with a correct signal to noise ratio. These theoretical results also show the importance of angles of polarisation in the quality of localisation. The processing and analysis of a series of calibration blasts should help to evaluate the confidence with which these angles can be measured and do so in a more complex environment than that considered in this theoretical approach.

3.3.2. Calibration of the microseismic network via surface blasts

Calibration data was obtained in June 2010 when high-resolution seismic profiles were made on the north-western edge of the active zone (Figure 3). Although the

position of the blasts that were then carried out was not optimal regarding the geometry of the microseismic system (it provides little azimuthal and energy variability), the collected data is analysed hereinafter in such a way as to:

- assess the quality of the coupling of the sensors with the rock mass as well as the system's detection capacities regarding the geological medium encountered,
- set the data processing parameters by determining a simplified seismic wave velocity model, making it possible to best relocate the blast data for which the positions are known.

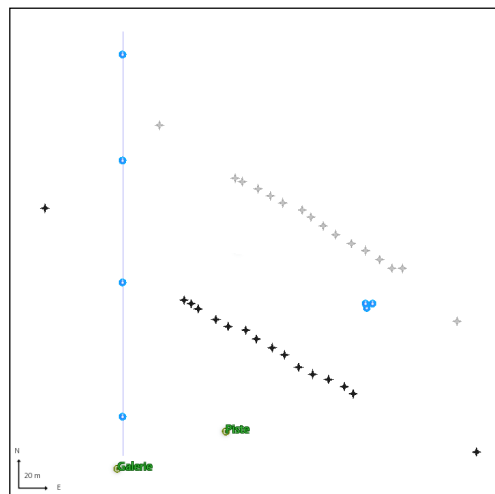


Figure 3. Positioning as seen from above of the seismic profiles carried out on the western edge of the slope of the Ruines de Séchilienne. The blasting points of the PS7 profile are shown in grey, those for the PS6 profile are shown in black.

32 blasts were analysed; the origin time measurement (T_0) is available for 25 of them. Most had a unit charge of approximately 100 g of explosives; a few offset blasts, at the end of the profile were of a greater charge. All were recorded by the PISTE station while the GALERIE station – the farthest away from the blast points – only detected ~70% of them (Table 3), with a signal-to-noise ratio that was degraded in relation to the PISTE station. This can be explained by the response from the SGa 3D accelerometric sensor installed at the gallery entrance, which intrinsically has background noise that is higher than the other probes equipped with geophones. However, the data set is of good enough quality to confirm the proper coupling of probes with the rock mass, as well as their capacity to detect low-energy events at more than 240 m.

	PISTE Station	GALERIE Station
Number of blasts recorded	32	22
Number of associated seismograms	224	154
% of seismograms having a S/N ratio > 10	82%	26%
Mean hypocentral distance (m)	102	145
Max. hypocentral distance (m)	241	306

Table 3. *Main characteristics of the calibration data studied.*

Analysing polarisation by wave rotation is used to calculate incident angles (azimuth and dip) of the ray path at the three-component probe from a 3D seismogram (Tastet *et al.*, 2007, Contrucci *et al.*, 2010). For the seismograms having a good signal-to-noise ratio, this analysis shows that the azimuth of the seismic rays is in general compliant with that expected under the hypothesis of straight rays: the mean deviation between the calculated and measured azimuths is 8° , with a standard deviation of 15° . This means that measuring the azimuth should make it possible to constrain efficiently the location of microseismic sources. The deviations between dips calculated according to the straight ray hypothesis and measured dips reveal velocity contrasts between the superficial layers. As such, at sensors S40 and S80, the weak dips measured most probably indicate the presence of a low-velocity layer on the surface. An analogous observation is made using dips measured by the sensor positioned at the bottom of the gallery.

As a preliminary approach, it is therefore suggested here to develop a velocity model with two layers inclined 40° to the south (in order to comply with the topography of the site) and for which the velocities V_p are obtained by a simple calculation of hodochrones (between 0 and 40 m deep: $V_p = 2450 \text{ m.s}^{-1}$ and beyond 40 m deep: $V_p = 4500 \text{ m.s}^{-1}$); and the velocities V_s are calculated according to the theoretical ratio V_p/V_s (the seismograms do not have any S waves). With this simplified model, the blasts are relocated with an average tolerable horizontal error of 20 m, which can be explained, in accordance with what was shown in the network simulation study, by the contribution of the polarisation angles in the location algorithm. On the other hand, the location error in depth is greater; the average magnitude is 50 m and the calculated depths are systematically lower than the real depths. This can be explained by the fact that the velocity model proposed results in substantial residue on the dips.

3.4. Presentation of microseismic data: the main signatures

In parallel to the work aimed at calibrating the tool for locating microseismic focuses, the microseismic data acquired over time has been examined in order to compile a catalogue of the main event signatures. Since it was put into service in November 2009, the microseismicity network has detected more than 70 seismograms. It records very short events (of a duration of 10^{-1} s), as well as longer events (of a duration from one to several seconds), and also a few regional quakes. The signals identified as being linked to the slope's microseismic activity show substantial variability in terms of waveforms, frequency content, amplitude and duration. As such, 4 groups can be distinguished:

- seismograms likely linked to small rockslides and/or small falling blocks at the bottom of the gallery (Figure 4). These signals are recorded exclusively by the GALERIE station. These are high-frequency signals (higher than 100 Hz) of short duration (less than 0.2 s), with a higher amplitude on the 3D sensor provided at the bottom of the gallery. This first group currently comprises a set of about fifteen events. Their occurrence appears to be random. It is not possible at this stage to establish the origin of these events, between the natural ageing of the gallery walls, or that of a major deformation mechanism of the surrounding rock in this gallery. Nevertheless, the inclinometers integrated into the microseismic 3D sensors indicate a rotation movement from the bottom of the gallery towards the core of the slope (north-south axis), although no particular developments have been measured along the east-west axis, as confirmed by the CETE data,

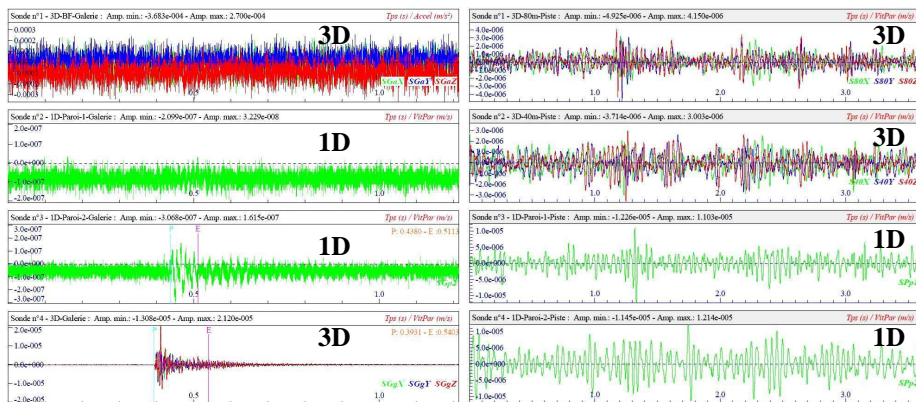


Figure 4. Left: seismogram recorded on 15/08/10 at the GALERIE station and linked to falling blocks at the bottom of the exploration gallery (amplitude in m/s versus time in s). Right: seismogram recorded on 31/12/09 at the PISTE station and linked to a tremor (amplitude in m/s versus time in s).

– seismograms supposedly linked to basic activity of the mountain, more commonly referred to as "tremors". These signals are detected by one or the other station, or by both simultaneously. Their frequency content varies between ten and a hundred Hertz: they last between 0.5 and 1.5 s. This second group includes about fifty seismograms of which more than half have been recorded at the PISTE station (Figure 4),

– seismograms potentially linked to rockslides in the active zone of movement. These signals are recorded at the PISTE station only, by far the closest to the active zone. They have a higher amplitude on the 1D wall sensors (SPp1 and SPp2) than on the 3D sensors provided in drill-holes (S80 and S40); the arrival times of the P waves are such that $T_{1D} < T_{3D}$. Their duration is relatively short (less than 0.2 s) and their frequency is between 50 and 100 Hz. Finally, an analysis of the angles of incidence of the seismic rays with 3D sensors reveals a quasi-vertical dip. This third group includes about ten seismograms (Figure 5),

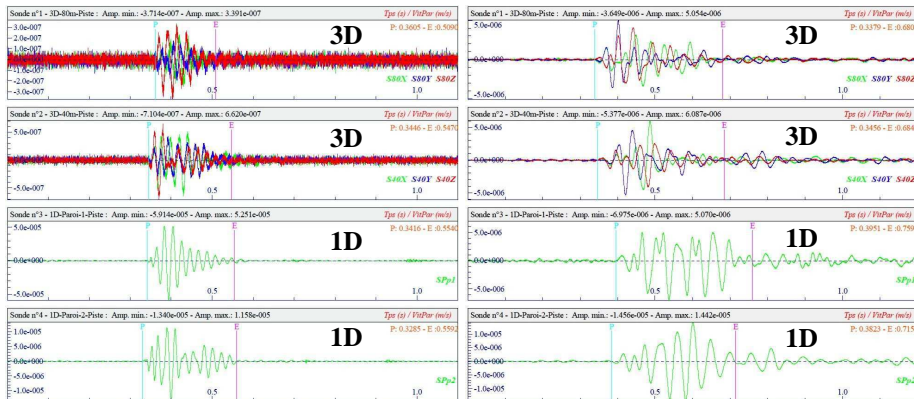


Figure 5. Seismograms detected by the PISTE station sensors (amplitude in m/s versus time in s). Left: seismogram recorded on 14 June 2010 and linked to a rockslide. Right: seismogram recorded on 8 April 2010 and linked to a microseismic event.

– microseismic events properly speaking. For the moment, these signals are detected only by the PISTE station sensors (installed on the western edge of the active zone). Their frequency is relatively low (less than 50 Hz); the arrival times of the P waves are such that $T_{S80} < T_{S40} < T_{1D}$ although the amplitudes are slightly higher on the 1D sensors (SPp1 and SPp2) than on the 3D sensors (S80 and S40). Overall, the analysis of the angles of incidence, especially of the azimuth, shows that these microseismic events are generated to the east of the microseismicity system: this direction

coincides with the active zone of the slope. This fourth group consists of about ten seismograms (Figure 5).

As such, these first few months of measurement confirm that the configuration of the microseismicity system with sensors installed deep in the mountain side makes it possible to substantially overcome surface artefacts and noise. It promotes the detection of low-amplitude events (amplitude of $1.5 \cdot 10^{-6} \text{ m.s}^{-1}$). These events have almost solely P phases but as they are well polarised, the azimuths measured should make it possible to locate them with relative accuracy.

3.5. Presentation and assessment of the preliminary measurement data

3.5.1. Geodetic measurements

The principle of the GPS-RTK measurement implemented is to provide all the quantitative data required to analyse the surface displacement field with the finest possible degree of accuracy. As such, in order to retain as far as possible the "real time" aspect, the measurement corrections are sent in real time by the reference station at *Mont Falcon* to the measurement station on the slope (Figure 1): the measurements do not require any post-processing. In addition, the following parameters are associated with each measurement: number of satellites, number of measurements, DOP and number of corrections. These make it possible to identify any lower quality measurements which are then discarded at the analysis phase.

Figure 6 shows that the data is stable over the period. A few occasional acquisition failures have been observed; these are probably linked to the site's configuration. Indeed, the horizon is reduced at the level of the measurement station installed on the slope flank; it is occasionally visible by a number of satellites that is too low.

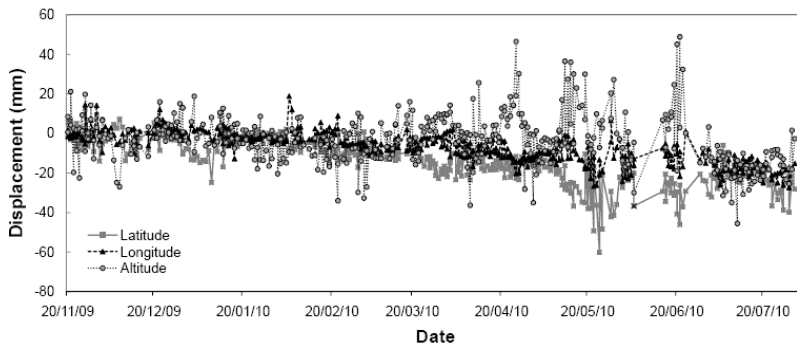


Figure 6. Variation in the geographical position of the GPS measurement station (*Mont Sec*) between 20/11/09 and 31/07/10.

Over the last six months, significant variations have been measured in latitude and longitude (Figure 6):

- the variations measured in latitude: -28.1 mm on 31/07/10, reveal a southward displacement,
- the variations measured in longitude: -15.1 mm on 31/07/10, reveal an eastward displacement.

With regards to variations in altitude, these were quasi-static as at 31/07/10: - 2.7 mm. These altitude measurements are furthermore considerably more unsettled than the latitude and longitude measurements. Intrinsically, the error is 1.5 to 2 times greater in Z than in X and Y. Finally, the absolute 3D displacement of the GPS measurement station was 32.1 mm as at 31/07/10.

This preliminary analysis shows that geodetic measurements are consistent with the displacements observed by the CETE (Pothérat *et al.*, 2009): the amplitudes measured are in line with expected values and the displacement vector also coincides with the direction of movement observed by the CETE.

3.5.2. Hydrogeological measurements

The piezometric measurements are carried out in the SP drill-hole for which the head is at NGF (General Levelling of France) 735 m. The pressure sensor, initially installed at a depth of 141 m, was raised by 2 metres (NGF 596 m) subsequent to intervention at the end of May 2010. The pressure measurements recorded (Figure 7) correspond to the water depth above the sensor (1 bar = 10 m).

From the end of November 2009 to the beginning of April 2010, the piezometric change shows a general tendency to recharge the groundwater that occurs during successive episodes of rainfall. The first 4 major recharge episodes caused a cumulative increase in the level of groundwater of more than 12 m. The recharge episodes are characterised by a rapid increase in the piezometric level, followed by a slower decrease which can be assimilated to a fall, with the aquifer not returning to its initial level after each recharge (Table 4).

The response of the aquifer to these recharges is typical of a fractured dual-permeability aquifer; the peaks induced by the episodes of rainfall are not symmetric. This shows the time lag in the participation of the various groups of discontinuity in the draining of groundwater. The most permeable fractures contribute to the rapid increase in the piezometric level. The permeable networks of discontinuities play a deferred role by slowing down the drop in the piezometric level during the period when the water table is low.

The response time of the aquifer regarding hydro-climatic events seems to change over the course of time. The time lag between the rainy episodes and the increase in the piezometric level appear to decrease. This behaviour would be consistent with a recharging of the aquifer, making the water table more reactive to the infiltration

episodes. However, this response time cannot be estimated with any real accuracy due to insufficient data feedback. As the site is located in a mountainous area, the snow mantle may well play a significant role between periods of precipitation and infiltration.

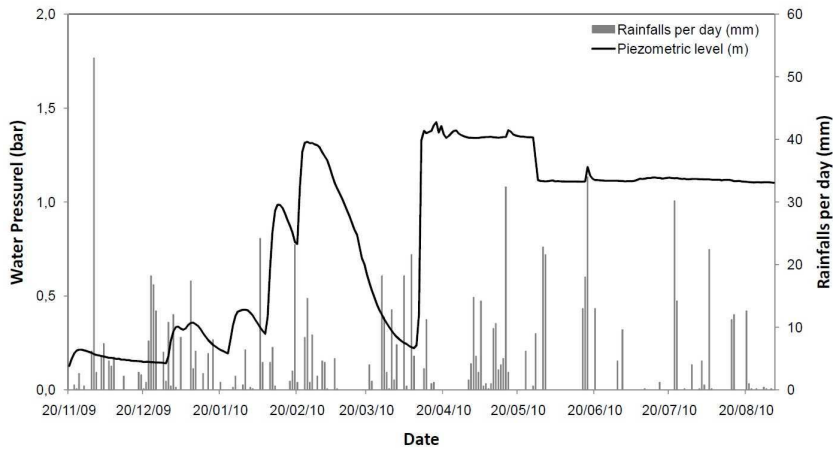


Figure 7. Piezometric and rainfall monitoring of the unstable slope of the Ruines de Séchilienne. In mid-April 2010, the piezometric measurements indicated that the drill-hole had become plugged. The jump in the measurement recorded at the end of May 2010 was caused by technical intervention: the pressure sensor was raised 2 m.

Initial level	Max. level 1 st recharge	Max. level 2 nd recharge	Max. level 3 rd recharge	Max. level 4 th recharge
20/11/2010	08/01/2010	29/01/2010	12/02/2010	24/02/2010
1.3 m	2.1 m	2.7 m	9.0 m	12.3 m

Table 4. Water level of the groundwater reached after recharges.

Starting in mid-April 2010, the piezometric measurements indicate that the borehole is plugged following the creation of a drill-hole² in the immediate vicinity of the SP borehole. The observations are as follows:

² On 9 April 2010, the CETE proceeded to create a carrot drilling (drilling with water) 5 m from the surface of the piezometric borehole. The work was completed mid-May 2010.

- the system is no longer reacting to hydro-climatic solicitations: the water level remains stable,
- there is no longer any fall phase that is typical of an open system: discontinuities seem to have been plugged,
- conductivity measurements indicate high mineralisation of the water and suggest the presence of sludge at the bottom of the borehole.

As things stand, the CETE is planning an air-lift type intervention in order to render the piezometric borehole newly operational.

4. Conclusion

The built-in multi-parameter measuring system, installed experimentally in 2009 on the western edge of the movement of the *Ruines de Séchilienne* in order to provide a deeper understanding of the hydrogeological behaviour of the slope and of its deformation mechanisms in depth, is operational. First of all, it provides relevant high-quality measurement data that is consistent with the measurements taken by the CETE on the site. The geodetic measurements – of low amplitude – reveal subsidence towards the valley, along with a displacement to the east. Likewise, the inclinometric data confirms a rotational movement at the bottom of the gallery towards the core of the mountain (along the north-south axis).

Subsequently, the microseismic and hydrogeological measurements given by the system provide us with some new insights:

- microseismicity clearly confirms that the slope of *Séchilienne* is a source of detectable and quantifiable microseismic activity: more than 70 microseismic signals have been recorded since the end of November 2009. These seismograms show a large degree of variability in terms of wave forms, frequency content, amplitude and duration, which suggests deep microseismic activity. Moreover, the calibration data acquired in 2010 confirms the system's high sensitivity and opens up interesting possibilities for processing and analysing activity detected on the slope,
- the piezometric change shows, during the first months, alternating groundwater charge / discharge cycles with rainy episodes, typical of a fractured aquifer. The measurements are unfortunately disturbed as from April 2010 with the creation of an additional drill-hole in the vicinity of the SP drill-hole. Since then, water renewal has stopped, indicating that the drill-hole is probably plugged.

The data collected through this experiment should therefore help to further the understanding of the behaviour of the slope in depth. However, work in processing and analysing the data needs to be extended. In particular, the processing of microseismic data will need to be fine-tuned in such a way as to allow for an analysis of the space-time distribution of the microseismic events. Emphasis will also be given to a cross-analysis of data in order to detect any seasonality effects and co-variations. It will also entail assessing the feasibility of a "routine" scientific exploitation of these

chronological series of multi-parameter data in order to clearly assess the contribution of so-called "integrated" devices in the management of the risks of land movement.

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