Natural thermal strains close to surface of rock slopes. Measurement and modeling of the "Rochers de Valabres" case

Véronique Merrien-Soukatchoff, Yann Gunzburger, Cécile Clement

Natural thermal strains close to surface of rock slopes

Measurement and modelling of the "Rochers de Valabres" case

Véronique Merrien-Soukatchoff* — Yann Gunzburger* — Cécile Clément†**

** LAEGO, Nancy-Université, Parc de Saurupt, CS 14234, F-54042 Nancy, France*

*** Institut National de l'Environnement Industriel et des Risques (INERIS), Ecole des Mines de Nancy, Nancy, France. †Present address: ANTEA, 1 rue du parc de Brabois, F-54500 Vandœuvre, France*

Corresponding author: V. Merrien-Soukatchoff - Phone: (+33) (0)3.83.58.42.92 - Fax: (+33) (0)3.83.53.38.49 - E-mail: Veronique.Merrien@mines.inpl-nancy.fr

RÉSUMÉ. *Les variations naturelles de température sont souvent mentionnées pour leur rôle sur les instabilités de pente. Pendant plusieurs années, des mesures thermomécaniques in situ ont été réalisées sur le site des Rochers de Valabres" (Alpes-Maritimes) afin d'étudier les phénomènes thermomécaniques de surface. Le site expérimental est d'abord présenté. 8 cellules CSIRO regroupées en 3 stations ont été installées à des profondeurs variant de 0 à 50 cm. Pour comprendre les déformations des jauges des cellules CSIRO soumises aux variations de température, une solution analytique et des modélisations du problème d'un forage, dans un milieu élastique semi-infini, soumis à des variations de température sont présentés. Les données in situ sont ensuite analysées au regard de ces calculs. L'ordre de grandeur des déformations mesurées est comparable à celles calculées, confirmant les phénomènes pris en compte dans les calculs. L'analyse précise des données est, par contre, plus problématique en raison de l'influence de la température sur la cellule CSIRO elle-même, de problème de dérive et de variation dans le temps du comportement des jauges de mesures. L'influence de la déformabilité de la cellule CSIRO sur la mesure a été modélisée et confirmée par des tests de laboratoire et des modélisations.*

ABSTRACT. *Natural temperature variations are often are thought to play a role in slope instabilities. For several years, in situ thermo-mechanical measurements have monitored the "Rochers de Valabres" (Alpes-Maritimes, France) site to examine thermomechanical surface phenomena based on in situ measurements. First, a description of the experimental site is presented in this paper. Eight CSIRO cells grouped in three stations were installed at different depths varying from 0 to 50 cm. To understand CSIRO cell strains under temperature variations, analytical solutions and modelling of the problem of a borehole* *subjected to temperature variations, in a semi-infinite elastic media, are presented. The in situ data were analysed based on these computations. If the order of magnitude of the strain measurements is quite similar to those computed, confirming the computed phenomena, an accurate analysis of the data is difficult due to several instrumental problems: drift, the influence of the temperature on the CSIRO cell itself, and the variation in the time of the gauge behaviour. The influence of the CSIRO cell deformability on the measurements was modelled and confirmed through laboratory tests and modelling.*

MOTS-CLÉS : *Roche, versant, thermo-élasticité, modélisation, solution analytique, forage, cellule CSIRO.*

KEYWORDS: *Rock, slope, thermo-elasticity, modelling, analytical solution, borehole, CSIRO cell.*

1. Introduction

The expected climate changes in the future raise questions on the impact of climatic factors on the stability of rock slopes, especially those alongside important thoroughfares or threatening nearby populations. The role of climate and paleoclimate changes is presumed to be significant in slope evolution and instability activation (see, for example, Soldati *et al.*, 2004 and Borgatti *et al.*, 2010.). Thus, the accurate effect of the temperature variation is often invoked in a qualitative way, but its impact is currently difficult to quantify.

The work undertaken in recent years on the "Rochers de Valabres" (French Alps) experimental site have aimed to improve the understanding of thermomechanical phenomena and the surface characterisation of their potential impact as a preparatory factor of rock slope instability.

The thermo-mechanical behaviour of rock masses has mainly been studied at high stress levels with controlled temperature variation. Subsurface rock-masses of rock slopes submitted to natural temperature variation are in a different context:

- rock-masses are at low stress level, and, consequently, stress variations due to temperature fluctuations may be of the same order of magnitude as the in situ stress;
- fractures at the surface of rock slopes may be widely open;
- the temperature at surface is not controlled; it varies continuously with different periods (day, season, year, and multiyear) and never reaches a steady state; and
- mechanical and thermal boundary conditions are linked to a given topography and are thus 3D and complex.

Surface temperature oscillations are known to contribute to rock falls through:

- the accumulation of thermally-induced micro-cracks (Berest *et al.*, 1988);

- the non-reversible movements of rock blocks along pre-existing fractures when submitted to thermal loading (Matsuoka, 2001 and 2008; Gunzburger *et al.*, 2005; Watson *et al.*, 2004; Vlcko *et al.*, 2005); and

- freezing and thawing process (Coutard *et al.*, 1989; Matsuoka, 2001, 2008; Anderson, 1998; Bost, 2008, Frayssines *et al.*, 2006).

The objective of this paper is to investigate the mechanical effects of natural variations of the temperature field on a rock slope. Only the effect of positive temperatures was studied, and freezing and thawing processes were excluded.

The analysis is based on analytical solutions and numerical modelling and is compared to thermal and mechanical time series data from the "Rochers de Valabres" field site. The understanding of rock temperature and especially the role of insulation will be presented by Gunzburger *et al.* (in prep.) based on a the same temperature time series.

Due to the monitoring devices on which the investigations are based, the inquiry is limited to almost continuous rock faces. The first paragraph describes the site and monitoring method. Analytical and modelling computations are presented in the next two paragraphs as a reference for the monitored strains presented subsequently.

2. The "Rochers de Valabres": a field laboratory for surface thermomechanical phenomena investigations

The "Rochers de Valabres" (Figure 1) is a gneissic rock slope located in the Mercantour Massif (southern French Alps). Since 2002, this site has been monitored by various instrumentations (e.g., geophysical devices, geotechnical apparatus, and a meteorology weather station, see Figure 2) to better understand rock slope behaviour (Clement, 2008; Clement *et al.*, 2008; Clement *et al.* 2006, Dünner *et al.* 2006; Dünner *et al.* 2009; Gunzburger 2004; Merrien-Soukatchoff *et al.* 2006, Merrien-Soukatchoff *et al.* 2007, Senfaute, G. *et al.*, 2007), especially the role of climatic factors in this behaviour. A stress measurement campaign had been also undertaken.

The site experienced two rock falls in May 2000 and October 2004 with volumes of 1000 m^3 and 40 m^3, respectively. Among the potential causes for these failures, temperature variations have been cited as one possible preparatory factor (Gunzburger *et al.*, 2004, 2005; Clement *et al.* 2009).

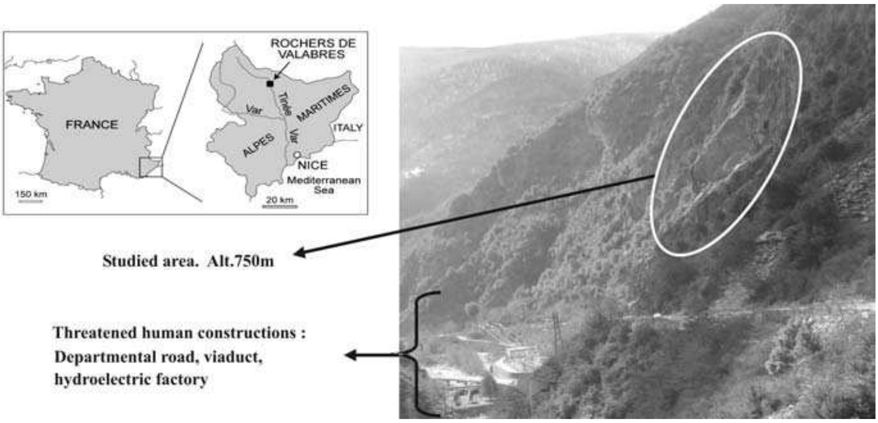

Figure 1. *Location of the "Rochers de Valabres" experimental site in the Southern French Alps (From Clement et al., 2009)*

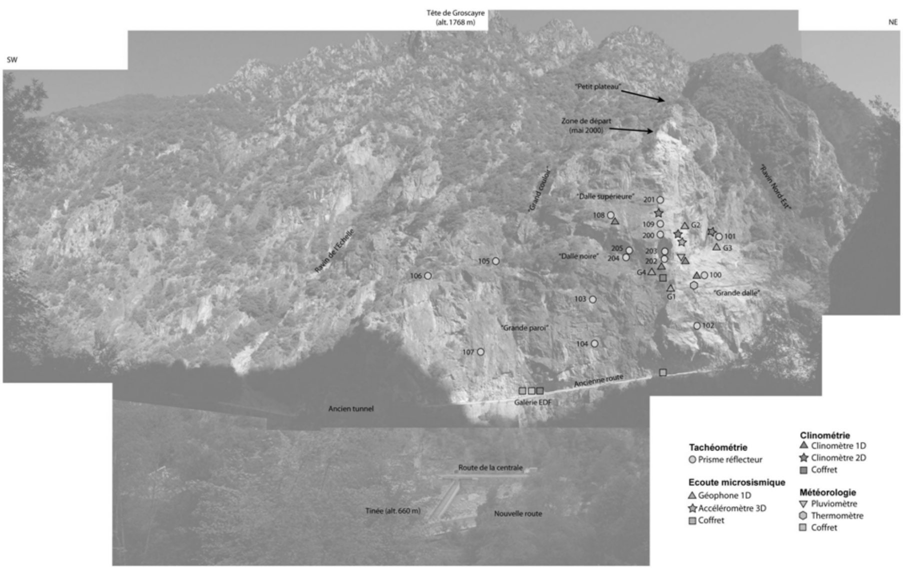

Figure 2. *Location of the different monitoring devices at the "Rochers de Valabres" experimental site*

In 2005, CENARIS (The French National Geohazard Monitoring Centre of INERIS) carried out the installation of thermometric and thermomechanical measurement devices. The installation consisted of both a thermometric multipoint sensor, which enables the measurement of rock temperatures at various depths (up to 0.5 metres), and three groups of CSIRO (Australia's Commonwealth Scientific and Industrial Research Organisation) strain cells installed at depths of 0.2, 0.3 and 0.5 metres in boreholes (Dünner *et al.*, 2007). The measurement devices are organised in 3 stations (Figure 3), with each station in a different topographic configuration and consisting of cells at different depths between 30 and 50 cm.

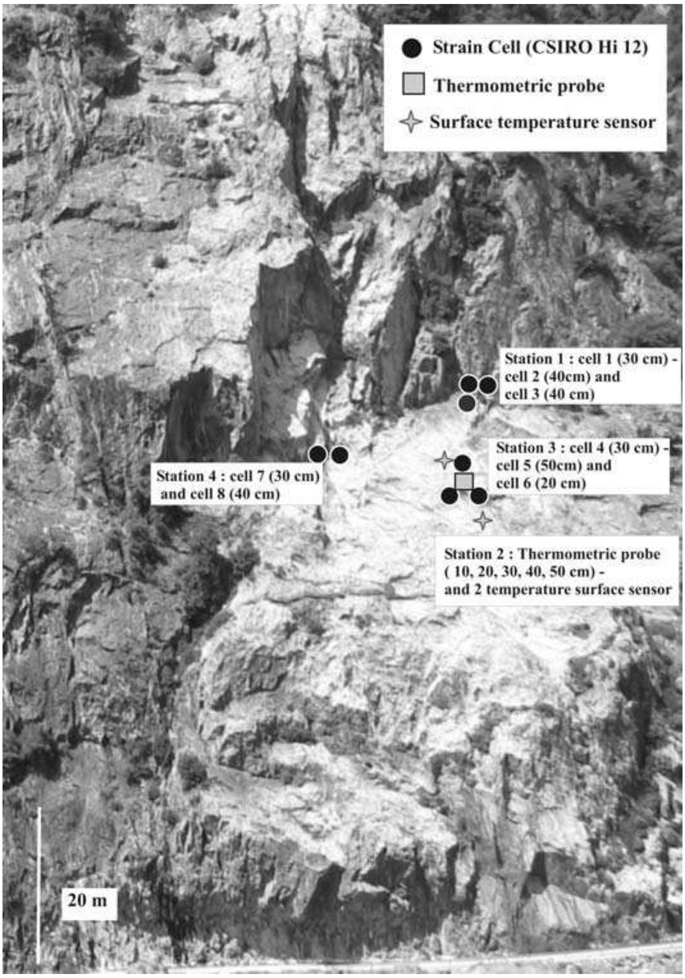

Figure 3. *Location of CSIRO strain stations*

Each cell (CSIRO Hi 12, hollow cylinders), comprising 12 strain gauges (Figure 4), was glued with epoxy cement into a 38-mm diameter borehole. Two of the gauges (gauge n°1 and 7) lie parallel to the cylinder axis and measure axial strain (ε_{zz}), five are orthoradial (gauge n°2, 6, 8, 11 and 12) or annular ($\varepsilon_{\theta\theta}$), and the other five are diagonal (ε_{45} and ε_{135}). The strain gauge resolution is ±2 10^{-6}. Each cell is also equipped with a thermal gauge.

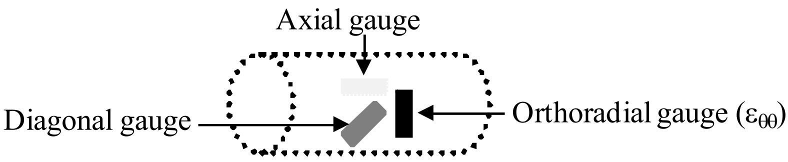

Figure 4. *Orientation of the strain gauges within a CSIRO cell.*

Hourly thermomechanical measurements were recorded between April 2006 and May 2008. Due to acquisition breakdowns, the network was operational for 58% of the total experiment duration, and the longest period of continuous auscultation was 182 days. Some gauges were out of service since the beginning of the acquisition. Over time, the number of gauges in use declined, and the operating rate of each cell varied from 25 and 100%.

3. Analytical computation of thermal surface strains with and without a borehole

3.2. *Thermal surface stresses and strains*

Let us consider the case of a semi-infinite medium whose straight free surface is submitted to temperature variations (Figure 5a). Temperature variations decrease in amplitude with depth (Gunzburger *et al.*, 2005). Assuming thermoelastic behaviour, when the surface temperature changes, the free surface moves: for a temperature increase, the free surface moves outward and vice-versa. Due to boundary conditions (and not taking into account any weight), the stress in the z direction (perpendicular to the surface) is zero. If x and y are the directions perpendicular to z, then there is no strain in theses directions.

Considering elastic behaviour and applying the thermo-elastic relationships:

$$\Delta\sigma_{ij} = \frac{E}{(1+\nu)} \cdot \varepsilon_{ij} + \frac{\nu E}{(1-2\nu)(1+\nu)} (\mathrm{tr}\varepsilon) \cdot \delta_{ij} - \frac{E}{(1-2\nu)} \alpha \cdot \Delta T \cdot \delta_{ij} \quad [1]$$

$$\varepsilon_{ij} = \frac{(1+\nu)}{E} \cdot \Delta\sigma_{ij} - \frac{\nu}{E} . \mathrm{tr} \Delta\sigma_{ij} \cdot \delta_{ij} + \alpha \cdot \Delta T \delta_{ij} \quad [2]$$

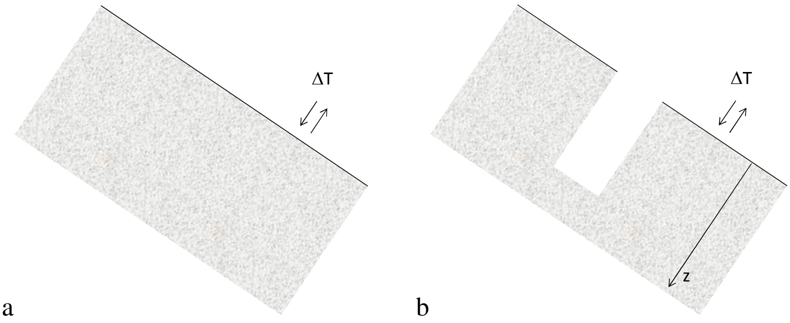

Figure 5. *a- Semi-infinite medium submitted to temperature variations. b- Semi-infinite medium with a borehole perpendicular to the surface submitted to temperature variations.*

The stress in x and y directions (or r and θ, using cylindrical coordinates) are

$$\Delta\sigma_{xx} = \Delta\sigma_{yy} = \frac{\nu E}{(1-2\nu)(1+\nu)}\varepsilon_{zz} - \frac{E}{(1-2\nu)}\alpha \cdot \Delta T = \Delta\sigma_{rr} = \Delta\sigma_{\theta\theta} \qquad [3]$$

The strain in the z direction can be deduced from the previous relationships:

$$\varepsilon_{zz1} = \frac{(1+\nu)}{(1\text{-}\nu)}.\alpha \cdot \Delta T \qquad [4]$$

The stresses in the x and y directions (or r and θ, using cylindrical coordinates, which will be useful below) are

$$\Delta\sigma_{xx} = \Delta\sigma_{yy} = \frac{\text{- E}}{(1-\nu)}\alpha \cdot \Delta T = \Delta\sigma_{rr1} = \Delta\sigma_{\theta\theta1} \qquad [5]$$

3.2. *Stresses and strains along a borehole in a semi-infinite medium*

3.2.1. *Influence of a borehole*

Let us now consider the case of a borehole, drilled in a semi-infinite medium submitted to temperature variations (Figure 5b) with the hypothesis that the borehole has only a mechanical influence and no influence on the temperature distribution in the medium.

In elasticity, due to the superposition principle, drilling a borehole before varying the temperature is equivalent to drilling after temperature variation.

The stress and strain variations caused by temperature variation (stage 1) are the same as those computed in the previous paragraph. The stress and strain variations caused by borehole drilling (Stage 2) after temperature variation can be considered according to the Kirsch solution, assuming a long hole. In cylindrical coordinate, during the drilling stage:

- $\sigma_{\theta\theta 2}$ varies from its initial value to twice its initial value according to the Kirsch solution ($\Delta\sigma_{\theta\theta 2} = 2\Delta\sigma_{\theta\theta 1} - \Delta\sigma_{\theta\theta 1} = \Delta\sigma_{\theta\theta 1}$),
- σ_{rr2} varies from its initial value to zero ($\Delta\sigma_{rr2} = 0 - \Delta\sigma_{rr1} = - \Delta\sigma_{rr1=} = -\Delta\sigma_{\theta\theta 1}$),
- ε_{zz2} and $\Delta\sigma_{zz2}$ are zero and thus:

$$\varepsilon_{\theta\theta 2} = \frac{(1+\nu)}{\mathrm{E}}.\Delta\sigma_{\theta\theta 2} - \frac{\nu}{\mathrm{E}}.\left(\Delta\sigma_{\theta\theta 2} + \Delta\sigma_{rr2} + \Delta\sigma_{zz2}\right) = \frac{(1+\nu)}{\mathrm{E}}.\Delta\sigma_{\theta\theta 1} - \frac{\nu}{\mathrm{E}}.\left(\Delta\sigma_{\theta\theta 1} - \Delta\sigma_{\theta\theta 1}\right) \quad [6]$$

$$\varepsilon_{rr2} = \frac{(1+\nu)}{\mathrm{E}}.\Delta\sigma_{rr2} - \frac{\nu}{\mathrm{E}}.\left(\Delta\sigma_{\theta\theta 2} + \Delta\sigma_{rr2} + \Delta\sigma_{zz2}\right) = -\frac{(1+\nu)}{\mathrm{E}}.\Delta\sigma_{\theta\theta 1} - \frac{\nu}{\mathrm{E}}.\left(\Delta\sigma_{\theta\theta 1} - \Delta\sigma_{\theta\theta 1}\right) \quad [7]$$

Therefore, the orthoradial and radial strains are

$$\varepsilon_{\theta\theta 2} = \frac{(1+\nu)}{\mathrm{E}}.\Delta\sigma_{\theta\theta 1} = \frac{(1+\nu)}{\mathrm{E}}.\frac{-\mathrm{E}}{(1-\nu)}\alpha\cdot\Delta T = -\frac{(1+\nu)}{(1-\nu)}.\alpha\cdot\Delta T \quad [8]$$

$$\varepsilon_{rr2} = -\frac{(1+\nu)}{\mathrm{E}}.\Delta\sigma_{\theta\theta 1} = -\frac{(1+\nu)}{\mathrm{E}}.\frac{-\mathrm{E}}{(1-\nu)}\alpha\cdot\Delta T = \frac{(1+\nu)}{(1-\nu)}.\alpha\cdot\Delta T \quad [9]$$

The total strain (ε_{zz}, ε_{rr}, $\varepsilon_{\theta\theta}$) due to temperature variation in a borehole is the sum of the strain due to the temperature variation without the borehole (ε_{zz1}, ε_{rr1}, $\varepsilon_{\theta\theta 1}$) and the strain due to borehole excavation without the temperature variation but with initial stress due to the temperature field (ε_{zz2}, ε_{rr2}, $\varepsilon_{\theta\theta 2}$).

$$\varepsilon_{zz} = \varepsilon_{zz1} + \varepsilon_{zz2} = \varepsilon_{zz1} = \frac{(1+\nu)}{(1-\nu)}.\alpha\cdot\Delta T \quad [10]$$

$$\varepsilon_{\theta\theta} = \varepsilon_{\theta\theta 1} + \varepsilon_{\theta\theta 2} = 0 + \varepsilon_{\theta\theta 2} = -\frac{(1+\nu)}{(1-\nu)}.\alpha\cdot\Delta T \quad [11]$$

$$\varepsilon_{rr} = \varepsilon_{rr1} + \varepsilon_{rr2} = 0 + \varepsilon_{rr2} = \frac{(1+\nu)}{(1-\nu)}.\alpha\cdot\Delta T \quad [12]$$

3.2.2. *Remarks on the analytical solution*

Several objections could be raised against the translational invariance hypothesis:

- The borehole is not infinite; and
- The temperature varies along the borehole, and thus, a cross section at a depth z will differ when z is varied.

This analytical solution shows the following:

- the axial and orthoradial strains along a borehole, due to temperature variations at the surface, are, at a point, of the same amplitude but of opposite sign (shortened for one, elongated for the other); and

- considering a sinusoidal temperature variation (Carslaw *et al.*, 1959, Gunzburger *et al.*, 2005) with an average value T0, a period τ of 24 hours and a temperature amplitude A (See Table 1):

$$T(z,t) = T_0 + Ae^{-z/\delta} \cdot \cos\left(\omega \cdot t - \frac{z}{\delta}\right) \qquad [13]$$

and

$$\varepsilon_{zz} = -\varepsilon_{\theta\theta} = \frac{(1+\nu)}{(1\text{-}\nu)}.\alpha \cdot Ae^{-z/\delta} \cdot \cos\left(\omega \cdot t - \frac{z}{\delta}\right) \qquad [14]$$

Figures 6 and 7 show the curve computed for a temperature variation between 0°C and T(z,t) according Equation [13], with T_0=0°C.

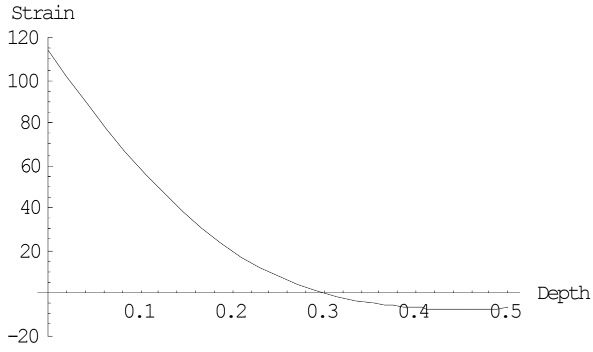

Figure 6. *Computed axial strain (*10^6) versus depth for a variation of temperature from O°C to T(z,0) at t= 0, given by (9)*

Parameter	Symbol	Value and Unit or (Unit)
Temperature	T(x,t)	(K)
Average temperature	T_0	(K)
Thermal amplitude at the surface	A	(K)
Period of temperature solicitation	τ	24 h (86400 s)
Pulsation of temperature solicitation	$\omega = 2\pi/\tau$	(s^{-1})
Thermal conductivity	λ	2.95 $W.m^{-1}.K^{-1}$
Penetration depth	$\delta = \sqrt{2a/\omega}$	(m)
Specific heat capacity	c_p	836 $J.kg^{-1}.K^{-1}$
Expansion coefficient	α	7.5 10^{-6} K^{-1}
Thermal diffusivity	$a = \lambda/(\rho.C_p)$	1.3 10^{-6} $m^2.s^{-1}$
Density	ρ	2.7 10^3 $kg.m^{-3}$
Young's Modulus	E	20.7 GPa
Poisson ratio	ν	0.24

Table 1. *Thermo-elastic parameters: Definitions and values for a gneissic rock, used in the analytical and numerical computations (modified from Gunzburger et al. 2005).*

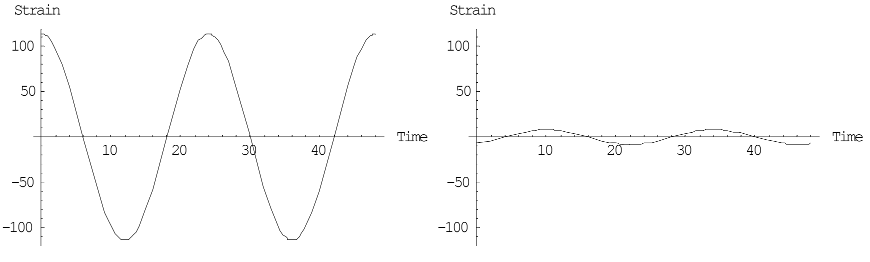

Figure 7. *Computed axial strain (*10^6) over 48 hours versus time (in hours) at z=0 and z=0.5 for a variation of temperature from 0°C to T(z,0), at t=0, as given by (9)*

4. Numerical modelling

The analytical solution was completed by a thermo-elastic computation performed with CESAR-LCPC-v4 to investigate the influence of the length of the borehole. A 50-cm-long borehole was modelled in an axisymmetric numerical model. The dimensions of the model are given in Figure 15. A variation of the temperature from zero to T(z,0) was applied. Figures 8 and 9 show the results, and the comparison between Figure 6 and Figure 8b shows the weak influence of the borehole length. The computed axial and orthoradial strains are equal in magnitude and of opposite sign as in the analytical solution, and their magnitudes are similar to that of the analytical solution.

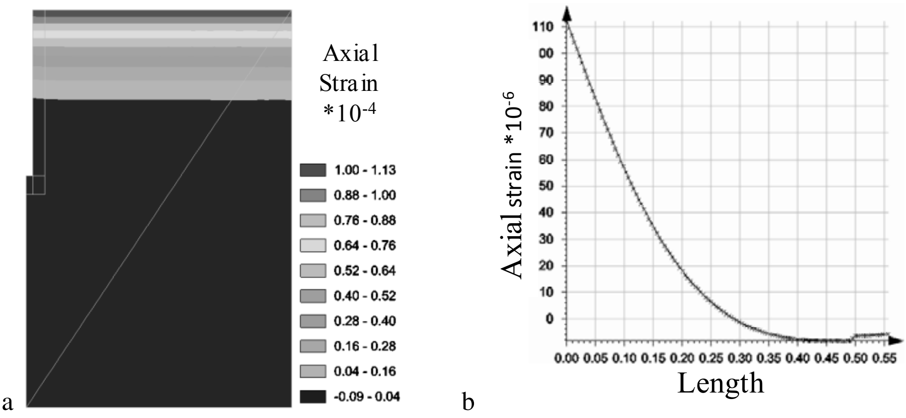

Figure 8. *Computed axial strain in an axisymmetric numerical model. a: Isovalues. b: cross section of the boundary of the borehole down from the top*

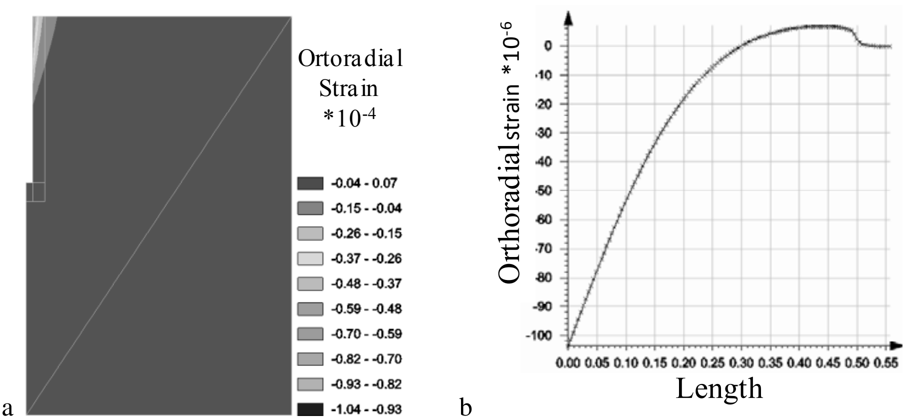

Figure 9. *Computed orthoradial strain in an axisymmetric numerical model. a: Isovalues. b: cross section of the boundary of the borehole down from the top*

The numerical modelling confirms the analytical solution and shows that the influence of the length of the hole is negligible.

5. In situ data

5.1. *Rough data*

The analysis of the in situ data showed different types of behaviour. Figure 10 presents the example of Cell 4 between 28/04/2006 and 08/05/2006. Globally, the axial strains increased with temperature, whereas the orthoradial strains decreased; however, the upper value of the axial strain seemed to reach a maximum and to remain at this maximum for several hours, which may be an indication of sensor saturation.

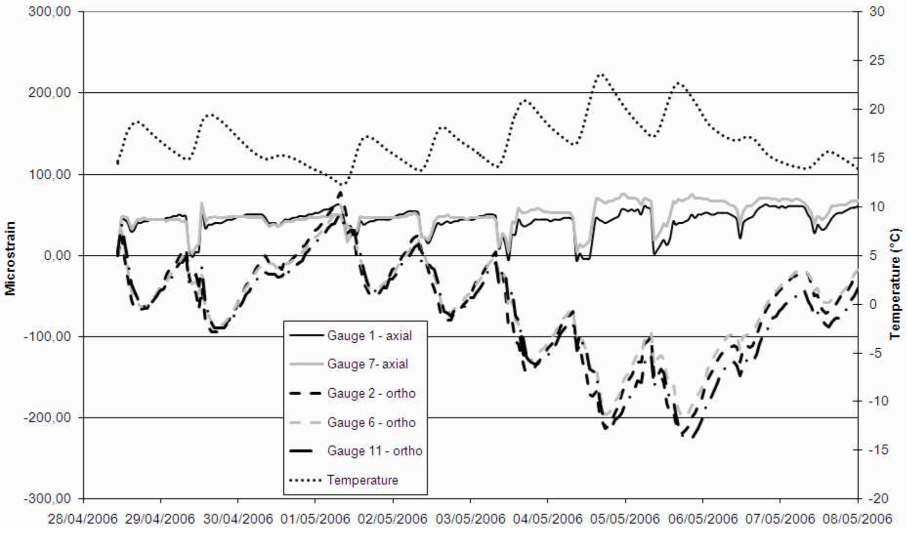

Figure 10. *Micro-strain variations of gauges of Cell 4 (30 cm depth) between 28/04/2006 and 08/05/2006*

Over a longer period, the gauge behaviour was more inconsistent. Figure 11 presents the case of the axial gauges of Cell 5. If, during a short period, the axial strains increased with temperature, then during a long period, the gauges can be subjected to drift: between 3/7/2006 and 7/12/2006, no measurements were performed, and Gauge 7 varied according to the temperature variation, whereas Gauge 1 increased. Such a drift phenomenon is visible in the behaviour of numerous gauges.

As an example, Figure 12 also shows the variation of Gauge 7 versus Gauge 1 of Cell 5 during two different periods. The gauges varied in the same direction during both periods, but the ratio between the strain of Gauge 1 and the strain of Gauge 7 was globally very different between 28/04/2006 and 3/7/2006 as well as between 7/12/06 and 22/07/2007. Over shorter periods, for example, a period of eight consecutive days (see Figure 13); the ratio became more consistent around 0.65.

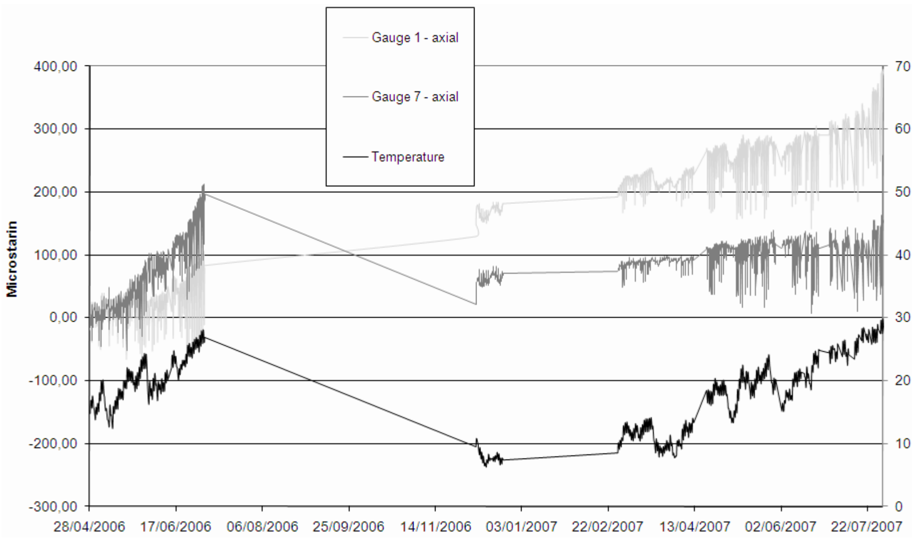

Figure 11. *Micro-srain variations of Cell 5 between 28/04/2006 and 22/07/2007*

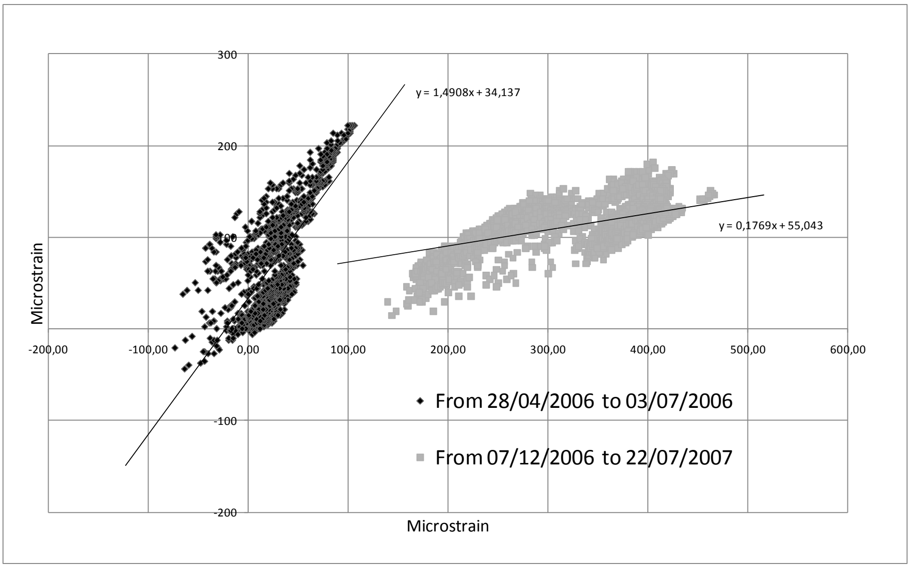

Figure 12. *Micro-strain variations of Gauge 7 versus Gauge 1 of cell 5 between 28/04/2006 and 3/7/2006 as well as between 7/12/06 and 22/07/2007*

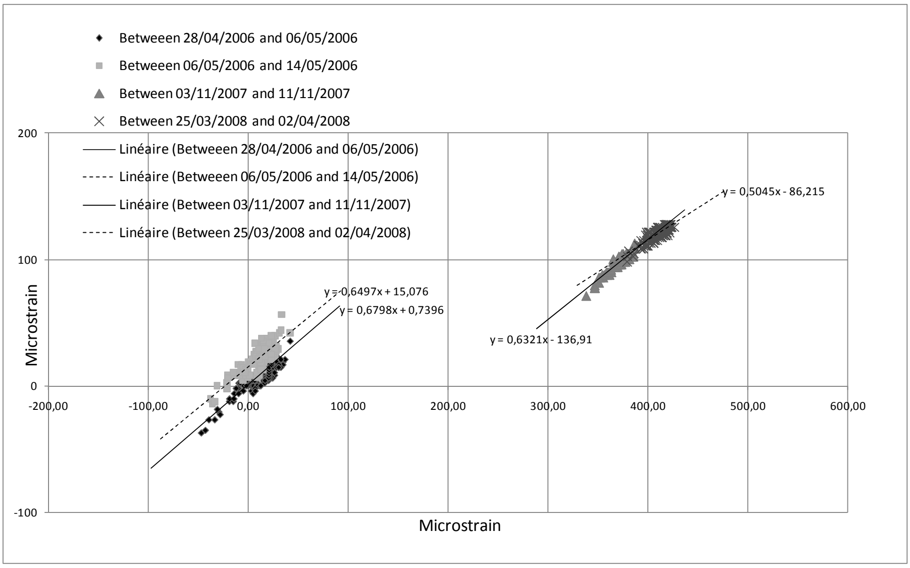

Figure 13. *Micro-strain variation of Gauge 7 versus Gauge 1 of cell 5 for different periods of 8 consecutive days*

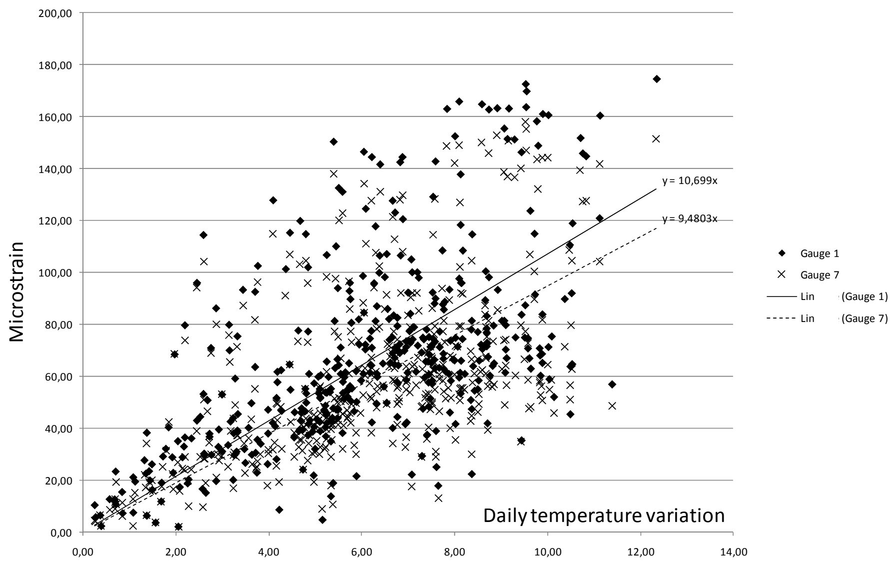

Figure 14. *Axial daily micro-strains amplitude versus temperature variations of Cell 6 between 28/04/2006 and 14/05/08*

For the daily strain amplitude versus temperature variations, the axial strains almost behave according to the analytical computation. Despite the large scatter, Figure 14 shows a linear relationship between the axial strains and temperature variations for Cell 6, and according to Equation [10], the ratio between the axial strain and temperature is approximately 10, which corresponds to a Poisson ratio of about 0.18. However, the orthoradial strains (Figure 15) had a significantly higher ratio than the axial strains, and a ratio greater than 21 leads to a computed Poisson ratio, according to Equation [11], of greater than 0.5. This trend was found for almost all cells.

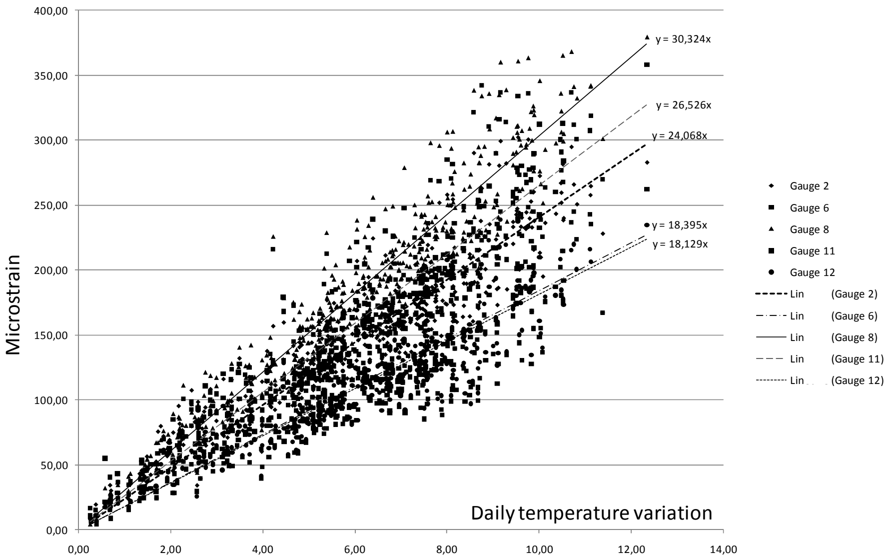

Figure 15. *Orthoradial daily micro-strains amplitude versus temperature variations of Cell 06 between 28/04/2006 and 14/05/08*

5.2. *Instrumental artefacts*

5.2.1. *Laboratory test*

To investigate the role of instrumental artefacts, some laboratory tests were performed on hollow cylinders containing a CSIRO cell and equipped with external strain gauges (Figure 16). Internal and external gauges should measure the same deformation.

The cores were those previously drilled during overcoring experiments (Clement *et al.*, 2009).

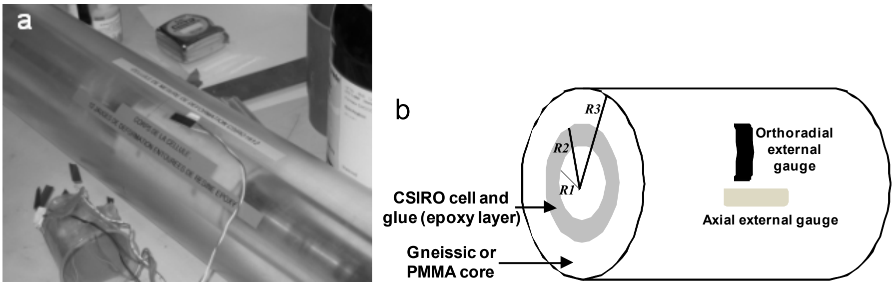

Figure 16. *Photography (a) and diagram (b) of an instrumented hollow cylinder core with a CSIRO cell inside and external strain gauges. R1 is the internal radius (R1 = 17.5 mm), R2 is the drill hole radius (R2 = 19 mm) and R3 is the external radius of the core (R3 = 73 mm)*

Hollow core cylinders of gneiss and PMMA (polymethylmethacrylate or "plexiglas") were submitted to controlled thermal variations in a climate store. PMMA was chosen as a reference because it is a homogeneous material, and its mechanical and thermal properties are close to that of the epoxy.

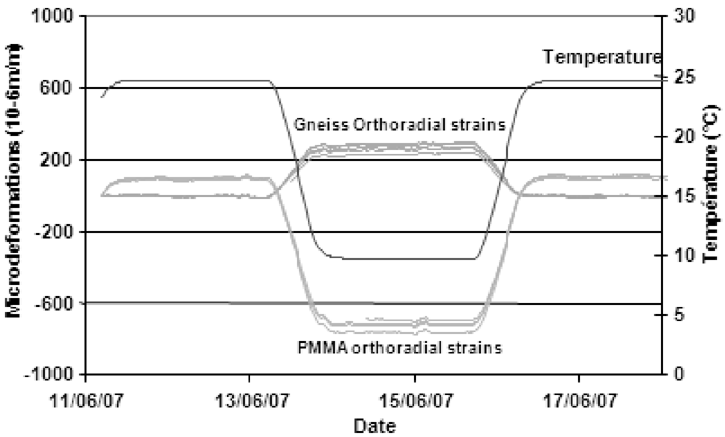

Figure 17. *Measured micro-strains due to imposed thermal variations*

Figure 17 shows the axial and orthoradial strains induced by the temperature variations. If the contrast between the coefficients of thermal expansion of the two materials is important, then their differential expansion can produce the opposite behaviour than expected. The core of gneiss, unlike the PMMA, exhibited elongation during cooling and vice versa when shortening was expected.

The measured CSIRO deformations were the result of the thermal expansion of the rock and epoxy. The axial strains were weakly affected by the epoxy layer, whereas the orthoradial strains were greatly affected.

5.2.1. *Numerical tests*

The role of the CSIRO cell in a drill-hole was investigated through numerical modelling. The CSIRO cell was represented as a 4-mm-thick cylinder of epoxy (Figure 18). The properties of the rock and the epoxy are shown respectively in Table 1 and Table 2. The modelled thickness is greater than the real one (1 mm epoxy + 1 mm of glue), but, due to mesh problems, it was difficult to reduce the thickness of the cylinder. However, the purpose of the modelling was conceptual: the intention was to investigate the type of perturbation induced in the strains by a CSIRO cell.

Expansion coefficient	α	$70\ 10^{-6}\ K^{-1}$
Density	ρ	$1.3\ 10^{3}\ kg.m^{-3}$
Young's Modulus	E	2.6. GPa
Poisson ratio	ν	0.4

Table 2. *Thermo-elastic properties of epoxy*

The influence of the CSIRO cell is shown by comparing the strain along the drill hole without (Figure 19) and with (Figure 20) a 4-mm-thick cylinder of material with the thermo-elastic properties of epoxy. The comparison was performed for a variation of temperature from zero to T(z,t1) with t1 = 6 hours. The axial strain is influenced by the epoxy cylinder, but, in the middle of the 10-mm cylinder, the value changed only slightly due to the epoxy cylinder. For the orthoradial strain the influence of epoxy cylinder completely modified the strain in the middle of the 10-mm cylinder. The disturbance is more significant when the temperature variation is large than when it is small.

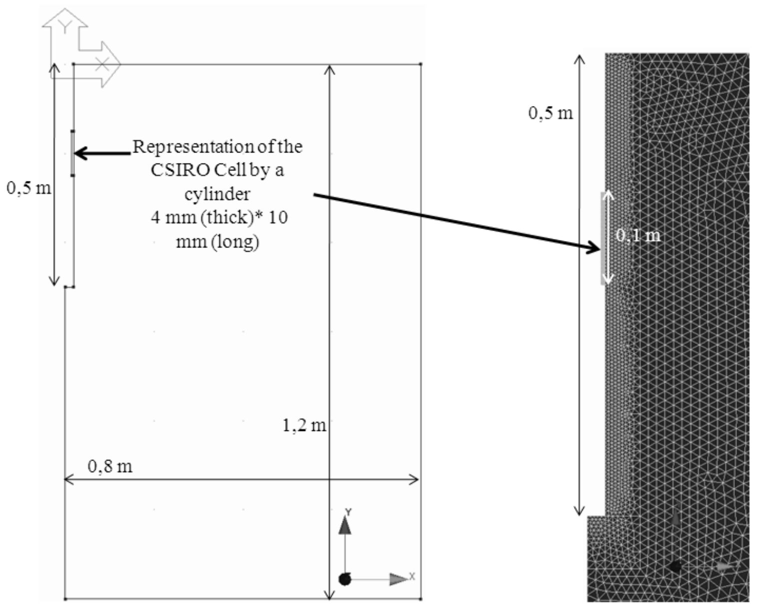

Figure 18. *Axisymmetric numerical modelling of a borehole and an epoxy cylinder within a semi-infinite medium. Size of the modelled zone (left) and enhancement of the borehole zone (right) showing the mesh refinement*

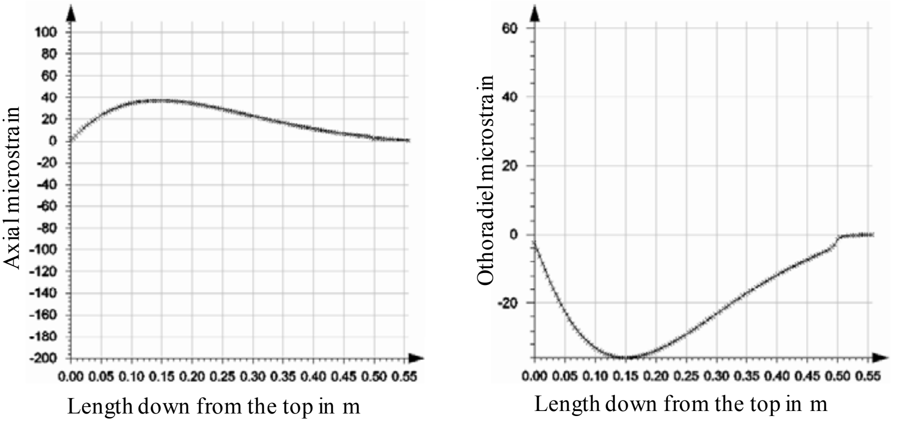

Figure 19. *Computed axial and orthoradial strains along the drill hole (down from the top)without an epoxy cylinder for a variation of temperature from zero to T(z,t1) t1 = 6 hours*

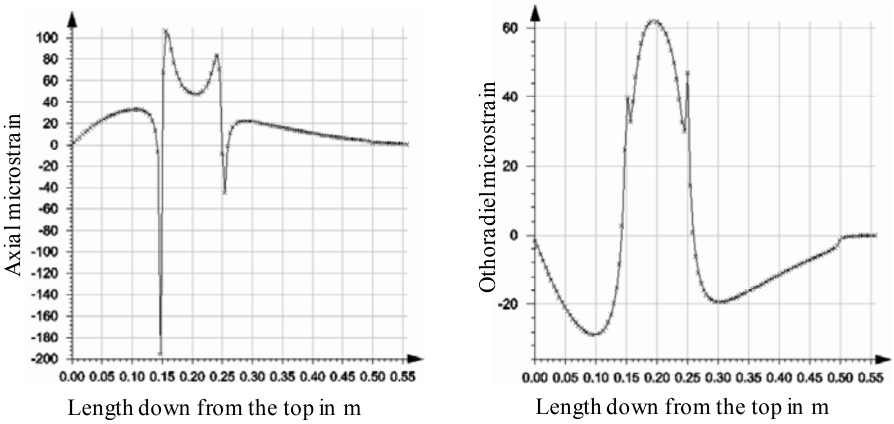

Figure 20. *Computed axial and orthoradial strain along the drill hole (down from the top)with an epoxy cylinder of 4 mm in thickness and 10 mm in length for a variation of temperature from zero to T(z,t1) t1 = 6 hours*

To take into account the influence of the cylinder thickness, other computations varying the Young modulus and dilatation coefficient of the epoxy were performed. They clearly showed that the CSIRO cells and epoxy glue used to seal the cell have an influence on the measured deformations. This influence is linked to temperature (for weak temperature variation, the influence is low) and cannot be simply corrected.

5.3. ***Thermal strain interpretation***

The existence of instrumental artefacts leads to doubt in interpreting the measurements. The axial thermomechanical strains seem to be weakly influenced by the CSIRO cells. They are in quite good agreement with the analytical and modelled solutions. The computed Poisson ratio (0.18) deduced from axial daily strain variation (Figure 12) was consistent with the expected value.

The orthoradial thermomechanical strains were affected by artefacts as a function of temperature.

Moreover, all of the measurements could be affected by drift and were not consistent over time (Figures 11 and 12).

The order of magnitude of the strains was, however, in good agreement with the computed solution; the influence of the thermal boundary conditions and the decrease of strains with depth were very clear (Figure 21). The daily strain at the surface amounted to roughly 2 10^{-4}, which is an important value that is equivalent to the effect of loading and unloading approximately 150 m of rock, considering the parameters listed in Table 1.

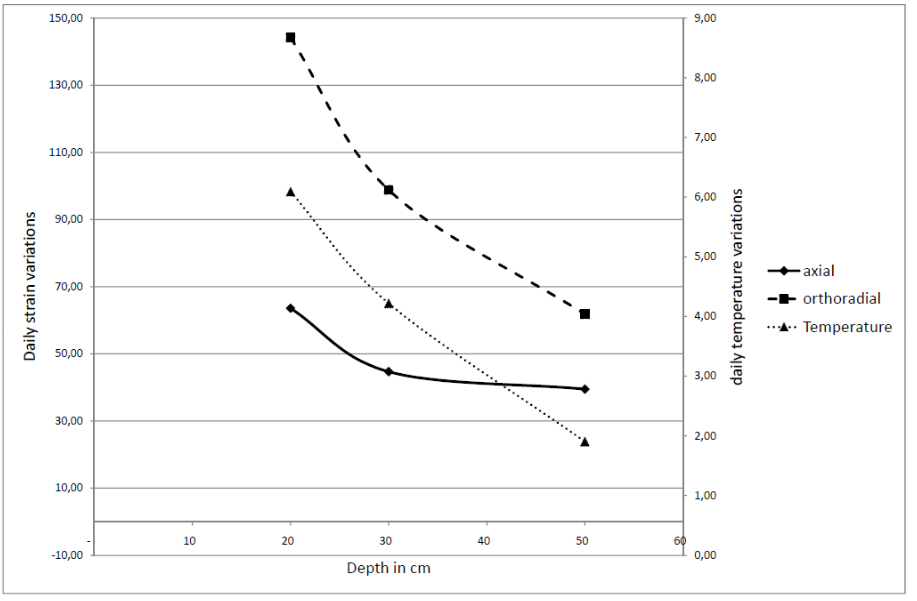

Figure 21. *Mean daily strain versus depth for Station n° 3 (Cells 6, 4 and 5 at, respectively, 20, 30 and 50 cm of depth)*

Up to now, based on measurements, it was not possible to deduce the influence of the geometry due to the differences between the 3 stations, as initially predicted.

In the absence of a borehole, thermal stresses (Equation [5]) are liable to inducing fatigue rupture as shown by Clément (2008), which may explain some observed instabilities.

6. Conclusions

The role of climate variations on slope evolutions and instabilities is difficult to grasp. Investigations undertaken at the "Rochers de Valabres" experimental site were designed to contribute to the understanding of thermo-mechanical phenomena. Yet given problems of measurement our attention focused on the expected strains and consistency of thermal strain measurements through CSIRO cells.

Analytical solutions and modelling developed herein are in good agreement and showed the importance of strain variations at the surface. The order of magnitude of the strains was confirmed by measurements, and they are well correlated with the thermal boundary conditions on the free surface of the slope.

However, the gauges of CSIRO cells, used to investigate the phenomena, were subjected to drift and sudden unexplained changes. The influence of the cell itself on the measurements is important and was determined though laboratory tests and numerical modelling. Possible corrections can be applied; however, the measurements remain too heterogeneous to accurately study deformations due to temperature variations and especially the role of the geometry and fractures on site which was the intention of the monitoring devices. Some alternative devices should be considered to investigate these aspects. At the same site, optical fibber monitoring was also used in other boreholes to investigate the role of forced thermal conditions. The results of this instrumentation have not yet been analysed, and it is not possible to state whether this device will allow more than axial strain to be measured

Acknowledgements

This work program was performed in the framework of a research project (entitled STABROCK) thanks to the financial support provided by the French Ministry of Ecology, Energy, Sustainable Development and Sea (Ministère de l'Écologie, de l'Énergie, du Développement Durable et de la Mer : MEEDDM) through the RGU (Réseau Génie Civil et Urbain). This project seeks to assess the influence of climate change on rock slope stability (Senfaute *et al.*, 2007).

All authorisations and assistance from the Mercantour National Park and the national EDF electric utility are gratefully acknowledged.

7. References

Anderson R.S., « Near-surface thermal profiles in alpine bedrock: Implications for the frost weathering of rock », *Arctic and Alpine Research*, Vol. 30, n°4, 1998, p. 362-372.

Berest P., Weber P., *La thermomécanique des roches*, Orléans, France, Editions du BRGM, 1988.

Bost M., Altération par le gel des massifs rocheux : Etude expérimentale et modélisation des mécanismes de génération des contraintes dans les fissures. PhD Thesis ENPC, Paris, defended February 12, 2008, 281 p.

Carslaw H. S., Jaeger J. C., *Conduction of Heat in Solids. Second edition*. Oxford: Clarendon Press, 1959.

CESAR-LCPC v4. Finite Element Code CESAR-LCPC v4, User manual, ed.itech-LCPC. www.cesar-lcpc.com, 2003.

Clément C., Auscultation d'un versant rocheux soumis aux sollicitations thermiques naturelles. Cas des Rochers de Valabres (Alpes-Maritimes), PhD Thesis, INPL, Ecole des Mines de Nancy, Nancy, defended October 28, 2008, 220 p.

Clement C., Gunzburger Y., Merrien-Soukatchoff V., Dunner, C. « Monitoring of natural thermal strains using hollow cylinder strain cells: The case of a large rock slope prone to rockfalls ». *In: Z. Chen, J.M. Zhang, Z.K. Li, F.Q. Wu and K. Ho (Editors), 10th*

International Symposium on Landslides and Engineered Slopes, Xi'an, China, 2008, June 30 - July 4 2008, p. 1143-1149.

Clément C., Merrien-Soukatchoff V., Dünner C., Gunzburger, Y., « Stress measurement by overcoring at shallow depths in a rock slope: The scattering of input data and results », *Rock Mechanics and Rock Engineering*, Vol. 42, n°4, 2009, p. 585-609.

Clément C., Merrien-Soukatchoff V., Dünner C., Sausse, J., 2006, « Ecoute Microsismique appliquée aux versants rocheux instables. Exemple des Rochers de Valabres (06) », *Actes JNGG 2006*, Lyon 27-29 juin 2006, CD.

Coutard, J.P., Francou, B., « Rock temperature measurements in two alpine environments: implications for frost shattering », *Arctic and Alpine Research*, Vol. 21, n°4, 1989, p. 399-416.

Dünner C., Bigarre P., Clement C., Merrien-Soukatchoff V., Gunzburger, Y., 2007. « Field natural and thermal stress measurements at « Rochers de Valabres" Pilot Site Laboratory », *Proceedings of the 11th Congress of the International Society for Rock Mechanics (ISRM)*, Lisbon, Portugal, p. 69-72.

Dünner C., Merrien-Soukatchoff V., Bigarre P., 2006. « Mesures de contraintes naturelles dans un versant rocheux prédisposé aux instabilités », *Actes JNGG 2006*, Lyon 27-29 juin 2006, CD.

Frayssines, M., Hantz, D., « Failure mechanisms and triggering factors in calcareous cliffs of the Subalpine Ranges (French Alps) », *Engineering Geology*, Vol. 86, n°4, 2006, p. 256-270.

Gunzburger Y., Merrien-Soukatchoff V., Guglielmi, Y., « Influence of daily surface temperature fluctuations on rock slope stability: case study of the Rochers de Valabres slope (France) », *International Journal of Rock Mechanics and Mining Sciences*, Vol. 42, n°3, 2005, 331-349.

Gunzburger Y., Merrien-Soukatchoff V., Senfaut, G., Guglielmi Y., Piguet J.-P., 2004, « Field investigations, monitoring and modeling in the identification of rock fall causes, Landslides: Evaluation and stabilization », *Proceeding of the Ninth International Symposium on landslides*, June 28 to July 2, 2004, Rio de Janeiro, Taylor & Francis Group, London p. 557-563.

Gunzburger, Y. Rôle de la thermique dans la prédisposition, la préparation et le déclenchement des mouvements de versants complexes. Exemple des Rochers de Valabres (Alpes-Maritimes), Ph.D. thesis, LAEGO, Ecole des Mines, INPL, France, defended December 17, 2004, 174 p.

Matsuoka, N., « Direct observation of frost wedging in Alpine bedrock », *Earth Surf. Process. Landforms*, Vol. 26, 2001, p. 601-614.

Matsuoka N., « Frost weathering and rockfall erosion in the southeastern Swiss Alps: long-term (1994-2006) observations ». *Geomorpholy.*, Vol. 99, n°1-4, 2008, p. 353-368.

Merrien-Soukatchoff V., Clément C., Senfaute G., Gunzburger, Y., 2005. « Monitoring of a potential rockfall zone: The case of « Rochers de Valabres » site », *Proceedings of the International Conference on Landslide Risk Management*, 31 May-3 June, 2005, Vancouver, CD.

Merrien-Soukatchoff V., Sausse J., Dunner, C., 2006. « Influence of topographic roughness on the stress state in a sloped rock-mass », *In: A.V. Cotthem, R. Charlier, J.F. Thimus and J.P. Tshibangu (Editors), Eurock 2006 – Multiphysics Coupling and Long Term Behaviour in Rock Mechanics –International Symposium of the International-Society-for-Rock-Mechanics*, Liege, Belgium, 09-12 May 2006 p. 473-478.

Senfaute G, Merrien-Soukatchoff V, Clement C, Laouafa F., Dünner C, Pfeifle G, Guglielmi Y, Lancon H, Mudry J, Darve F, Donze F, Duriez J, Pouya A, Bemani P, Gasc M, Wassermarm J.,. « Impact of climate change on rock slope stability: Monitoring and modelling », *In: R. McInnes, J. Jakeways, H. Fairbank and E. Mathie (Editors), International Conference on Landslides and Climate Change. Proceedings and Monographs in Engineering, Water and Earth Sciences, Ventnor, England, 2007,* p. 237-245.

Soldati M., Corsini A. and Pasuto A., « Landslides and climate change in the Italian Dolomites since the Late glacial », *Catena*, Vol. 55, n°2, 20, January 2004, p. 141–161.

Borgatti L., Soldati, M., 2010. Landslides as a geomorphological proxy for climate change: A record from the Dolomites (northern Italy). Geomorphology, Vol. 120, n°1-2, 2010, p. 56-64.

Vlcko J., Jezny M., Pagacova Z. 2005. « Thermal expansion effect on slope deformation recordings at Spis Castle », *Proceeding. of 15th Conference on Engineering Geology (Tagung Ingenieurgeologie)*, 6-9 April 2005. Erlangen, Germany.

Vlcko J., Jezny M., Pagacova Z., 2005 « Influence of Thermal Expansion on Slope Displacements in Landslides », *In Landslides, Risk Analysis and Sustainable Disaster Management. Proceedings of the First General Assembly if the International Consortium on Landslides*, 2007, Springer Verlag, ISBN 978-3-540-28664-6, p. 71-74

Watson A.D., Moore D.P., Stewart, T.W., « Temperature influence on rock slope movements at Checkerboard Creek. In: Landslides: evaluation and stabilization », *Proceeding of the Ninth International Symposium on landslides*, June 28 to July 2, 2004, Rio de Janeiro, Taylor & Francis Group, London, p. 1293–1298.