THE MONITORING OF TECTONIC MOVEMENTS IN NATURAL CAVES.

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ABSTRACT

A study case, carried out in the Ramioul cave in Belgium, has demonstrated the potential of monitoring ground deformation in a cave in order to predict rock collapse in a nearby quarry. A second study was conducted in the Rochefort Laboratory of Geodynamics to monitor water flow rates. Several sensors, developed at the Royal Observatory of Belgium (ROB) under the name of EDAS (European Data Acquisition for Scientists), were installed. They included drip meters, temperature sensors, extensometers, light meters and air pressure meters.

Using the high precision reached by these techniques and data collected over several years, it has been demonstrated that a new system can be envisaged which could be used to complement other methods for predicting catastrophic events induced by tectonic processes.

INTRODUCTION

The earth’s crust can be considered to be in a continuous state of motion; some of the movements will be slight, caused by relatively small injections of energy, sources of which would include gravitational tides, pressure, rain, aquifers and oceanic loading. Sources of large injections of energy would include tectonic activities, volcanic events and fault ruptures. Only the latter types are capable of causing catastrophic events. Understanding the nature of the effects of small injections of energy is important because the two are closely related, as the transfer function for both of them depends on the medium through which the energy travels, that is the crust itself.

Any method that can be proven to detect the small ground deformations caused by known small injections of energy, for example earth tides, would therefore be useful in detecting the small changes which are present before rupture. We consider this period before rupture to be the forecasting interval, see Fig. 1.

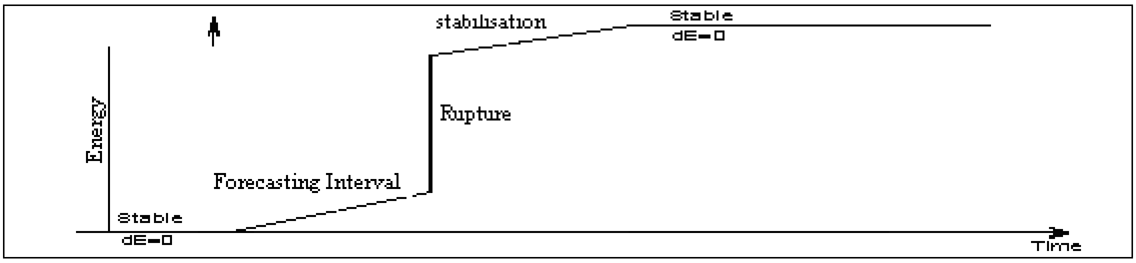


Fig 1: Sketch map of a geophysical hazard process.

In order to forecast the rupture it is necessary to detect a significant change in the medium from a stable situation to a developing one, which corresponds to the preparation of the rupture process. This forecasting interval could have various durations dependent on the local patterns. The complexity of the interactions involved in the process dictates a multi-parameter approach, selecting the factors that affect the energy transfer process. An opportunity to test this hypothesis arose in a cave in Ramioul in Belgium, where visitors had observed some ground movements over a period of several years.

GROUND DEFORMATION MONITORING IN THE RAMIOUL CAVE

In order to further the understanding of the motion it was decided to carry out observations of strain in the cave, alongside light intensity, air pressure and air temperature. Two extensometers, developed at the Royal Observatory of Belgium [Cai Wei Xin et al.,1989], were placed across two newly generated cracks which demark bedding planes. Figure 2 shows photographs of the two strain meters (P21 and P22).

Figure 2 Photographs of extensometers P21 and P22

Different electronic interfaces connected to the self-made instruments generate frequency modulated output signals, which are in turn recorded by counting within the EDAS system [van Ruymbeke 2001]. These files were analysed at a later date, using the software package µDAS Grapher, which has been specifically created for EDAS files.

The cave of Ramioul is situated near a quarry where explosions occur almost every day at 14:00 local time (13:00 UT). Figure 3 shows a single step on the extensometer records, this coincides with an explosion and represents a slight enlargement of the two cracks. The height of one step is about 7µm, this gives an indication of the high precision achieved with the two extensometers. There is a good correlation between the two graphs; the difference in the short period modulation is due to the presence of water in the rock adjacent where the sensor P21 is anchored.

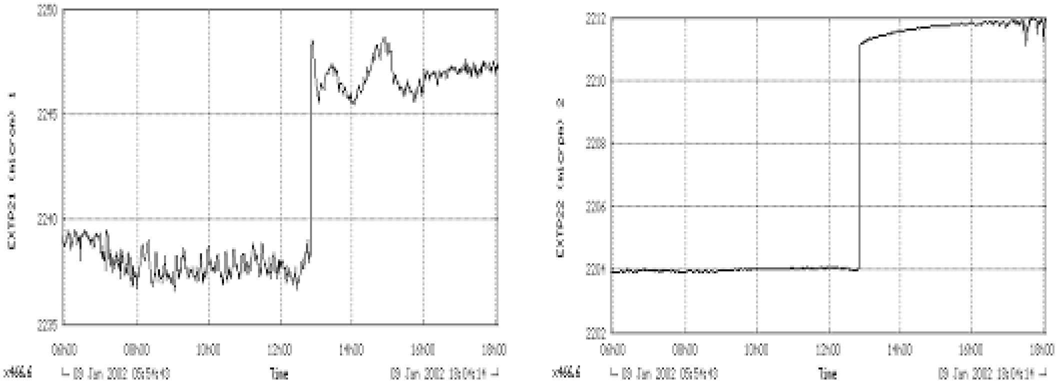


Figure 3 A jump occurring on 9th Jan 2002 in the two signals from P21 and P22

Figure 4 shows how the drift of the signal starts to accelerate in August. The drift ends abruptly on 6th February, when a 40,000 tonne block falls from the quarry face.

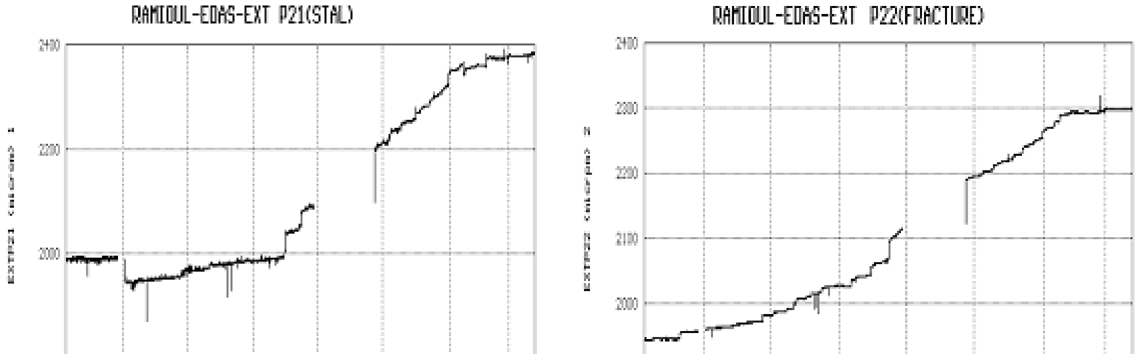


Figure 4 Signals from P21 and P22 taken over a six month period

If we compare figure 4 with Figure 1, we find that both graphs begin and end with a horizontal (stable) section and both have positive slopes (forecasting periods) between these two sections; suggesting that there is indeed a build up of strain energy in the rock.

To confirm a relationship between the above recordings in the cave and the observations in the quarry, BEFE software (Boundary Element and Finite Element) was used. The cave follows a fault line, which is parallel to the bedding layers in the rock. Strain analysis was carried out perpendicular to the fault plane (Tshibangu, J-P et al 2004). The light green mesh on figure 5 shows the deformed shape of the rock mass in its final stages before collapse. The overall displacements obtained are oriented towards the excavation with horizontal surfaces being curved downward. These displacements induce tensile stresses that are responsible for the opening of the cracks. It should be pointed out that this situation was not in evidence prior to excavation, but that it was induced by excavation of quarry material.

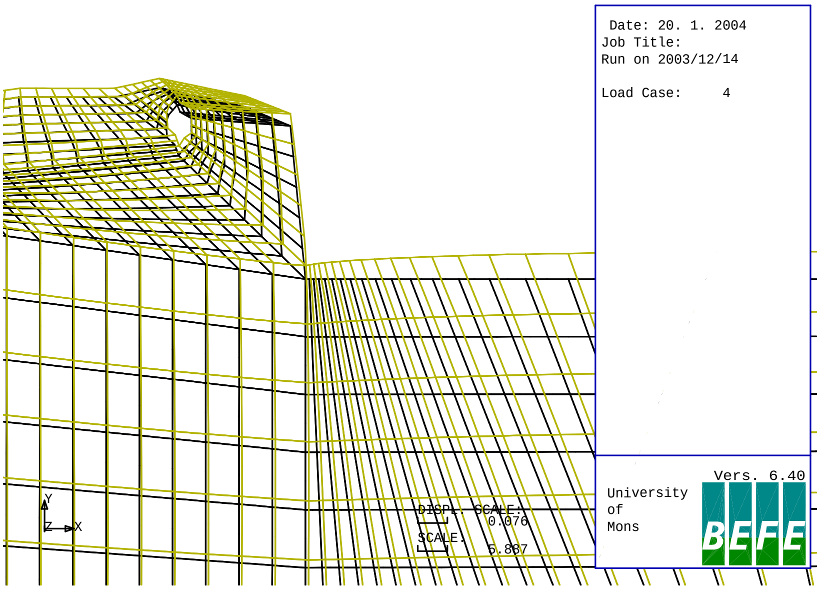


Figure 5: Deformed shape of the mesh (light green) in the current stage of excavation.

The BEFE results support the extensometer results in demonstrating that there is a build up of stress in the rock itself immediately prior to the collapse of the rock face. These findings suggest that a sudden trend change in records obtained in the protected environment of caves, could be a suitable indicator of a build-up to a catastrophic event.

SENSORS IN THE CAVE AT ROCHEFORT

During visits to the Rochefort caves, to check on installations, it was observed that the rate of water dripping into the cave varied from place to place and over time and it was felt that these changes might be influencing the climate in the cave. Which we related this to Kyoto University's observations in a tunnel of an unusual increase in the discharge rate of groundwater prior to an earthquake [Wakita, H 1995]. It was therefore decided that a series of drip meters for different flow rates should be installed, alongside the other sensors including thermometers.

In Belgium the current climate is temperate, with cold winters and warm mild summers, and rain is always a possibility. On the roof of caves we find many small cracks filled with calcium carbonate. The carbonate carried in the flowing water is deposited inside the cracks, causing it to decrease in size. Over time the diameter of a crack could decrease gradually until it reaches quasi-molecular dimensions. The gap may sometimes become completely closed. Three sensor types were designed to monitor the variability of the water flow rates observed in the caves.

Tipping Bucket

The first set of water flow monitoring equipment consists of two twin drip meters situated, one below the other, under a 60 cm diameter collector set-up, where a large quantity of water falls from the roof of the cave. The gauges here are commercially manufactured [Rain-o-Matic®]. Figure 6 is part of the record of one of the tipping buckets for the period January, 27th, 2003 to August, 26th, 2003.

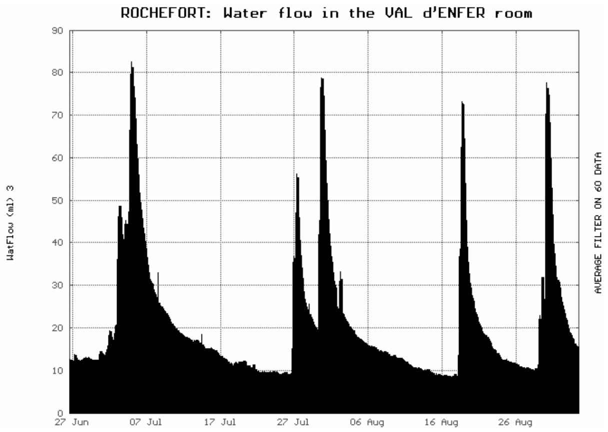


Figure 6 Water flow as measured by the tipping bucket drop meter

The peaks represent the increases in water flow (maximum 400cm³/min) caused by rainfall. The time from the top of a peak to its foot is typically about 10 days, i.e. the time to empty the water, which is stored in the rocks above the cave after the fall of rain. If a second rainfall arrives before the effect of the previous one has disappeared, the two rainfall modulations will add together; this effect is shown after the second peak. This meter is therefore useful for monitoring rainfall patterns and the porosity of upper rocks.

Syphon drip meter

The second type of water-flow monitoring equipment is a siphon drip meter, installed directly beneath a crack [van Ruymbeke, M. et al, 2001b]. As the water collects in the container, the water level is recorded by a capacitor in the centre of the container. When the height of the water reaches the syphon outlet pipe the container automatically empties and water collection starts again.

It can be seen from Figure 7 that the frequency decreases when the capacitance increases with the rise in water level until the syphon comes into effect; at which point the frequency returns to the high value, corresponding to low capacitance. One cycle lasts approximately one hour and corresponds to a relatively large amount of water (100cc).

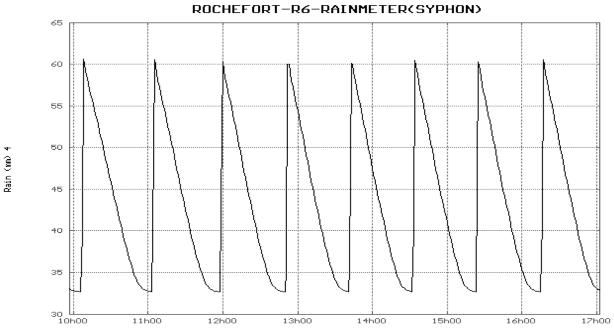


Figure 7: 100 cc per hour water flow measured by the syphon drip meter.

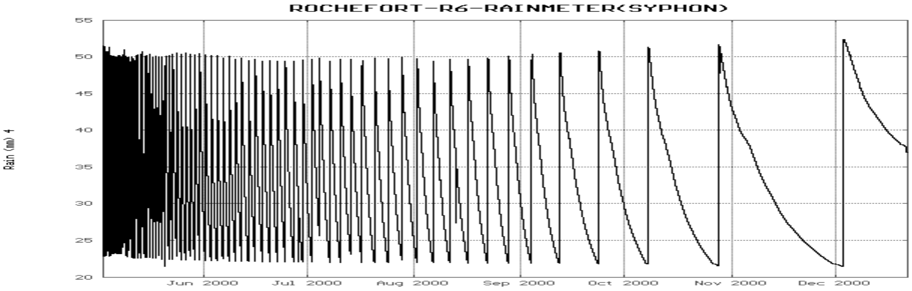


Figure 8: Fast (100cc per hour) to slow (100 cc per month) water flow recorded by the syphon drip meter

From Figure 8 it can be seen that the water flow speed changes considerably from May to December. During the period of low water flow we can see that the time taken for the siphon rain-meter to fill up is greater than a month. The rainfall modulation records align with the seasonal climatic conditions.

Drip Meter

The third rain-meter recording site is located where the water flow is much less, only a few drops a day. Consequently the sensors differed greatly from the others; electronic monitoring of the diameter of the drop was used to enable us to follow, in real time, the growth of the drops. Drip rates as low as two drops a day can be detected with a precision of 1µm. These sensors are equipped with a hollow tube, which is placed directly below where the water drop appears at the end of the stalactite [Sondag, F. et al., 2003]. Three drip meters have been set up, see fig 9. The flow at the location of the second drip meter soon dried up and no records are presented for that meter.

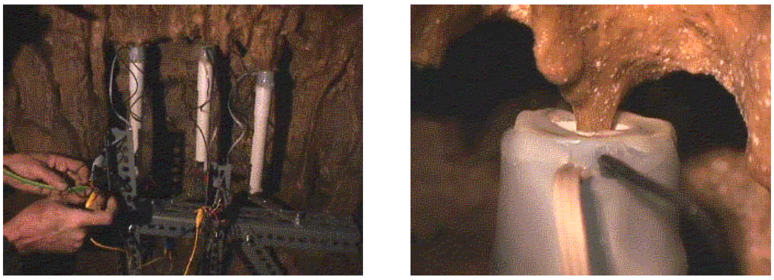


Figure 9 Photographs of the location three drop meters and the detail of one sensor.

Figure 10 shows parts of the records of the two drip-meters $R7_2$ and $R7_1$. The time interval between two drops of water falling through the sensor $R7_2$ is less an hour..

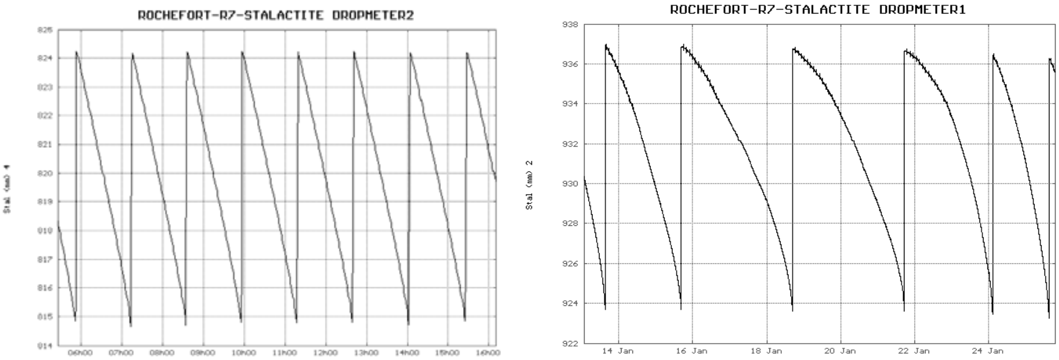
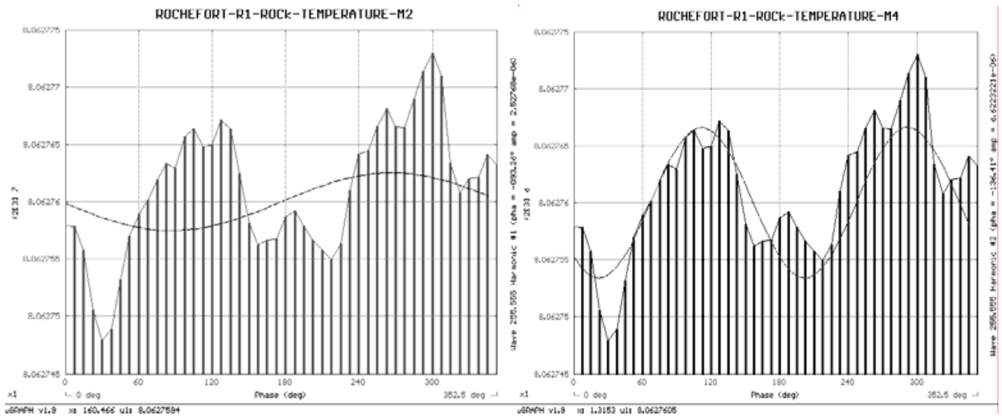


Figure 10 The water flow at $R7_2$ The water flow at $R7_1$

The flow for the sensor, $R7_1$ shows that the time between two drops of water varies from drop to drop, and can be more than three days. These changes of flow rates can be very sudden and cannot therefore be attributed to the seasonal modulation recorded by the syphon drip meter. At these low levels of water flow it is likely that we are recording events that are due to the changing geometry of the cracks, which our earlier work suggests may be influenced by the build up of stress within the rock itself.

Temperature Sensors

Results from other sensors in the cave also provided evidence that the strain in the rock can be detected using these high precision techniques. If we can detect any influence of tidal stress independent from atmospheric conditions, it would prove the high level of precision accessible by water flow monitoring. We selected the main lunar M2 strain component [Melchior 1983] and its harmonic M4 for our graphical analysis named HiCum, which is a stacking method developed at the ROB. It is capable of extracting, for well-defined periods, information about very small modulations [van Ruymbeke, M. & al., 2003].



M2 Rock T° Amplitude 2.53µ°C M4RockT°Amplitude 6.62µ°C

Fig11: The HiCum on the main lunar wave M2 and its harmonic M4 for the rock thermometers.

Figure 11 presents the HiCum analysis for rock temperature recorded by a micro Kelvin EDAS temperature sensor. For the rock temperature, the M2 amplitude (2.53µ°C) shows a non-linearity compared to the higher amplitude of M4 (6.62µ°C). The M2 effect present in the rock temperature would suggest that tidal stresses could be influencing water flow in a complex manner.

CONCLUSION

The use of EDAS, which is under development at the ROB, has provided the means for the continuous monitoring of many varied parameters. The sensors have proved to be capable of detecting modulations with a high degree of precision.

The work in Ramioul indicates that strain can be detected in rocks prior to a catastrophic event. The water flow monitoring, as carried out in Rochefort, demonstrated different methods of monitoring water flow to cover a variety of events that affect water flow rates. In addition the harmonic signals found in the temperature records lead us to believe that the temperature is linked to water flow modulation, which in turn is affected by strain modulation in the rock.

If a link between plate movement and water flow can be established then, using these high precision techniques, caves can be used as ‘sensors’ of stresses and could become a useful tool in the prediction of catastrophic events.

The above study cases are in caves in areas of low tectonic activity, further studies should now be carried out using these sensors at sites of greater tectonic activity in order to understand the different types of transfer functions.

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