Monitoring the rock-mechanical safety of underground limestone quarries using fibre optic sensing technology

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ABSTRACT: A fibre optic monitoring system has been installed in two limestone quarries in Valkenburg aan de Geul, The Netherlands, to monitor pillar stability and to give early warning of locations at risk of collapse. The system is highly sensitive and can detect creep deformation of the pillars as small as 1 micrometer. Measurements are displayed via a web-based data portal and alerts are triggered if the creep velocity exceeds pre-determined thresholds or if creep accelerates.

We present the design of the monitoring system and results from the first three years of operation. We show examples of the natural behaviour of the pillars and we present a number of deviating patterns that sparked particular interest. We also share some lessons learnt that can be used when designing and installing similar systems in other quarries, caves or mines.

Keywords: Monitoring, safety, limestone mining, fibre optics.

1 INTRODUCTION

In the Dutch and Belgian provinces of Limburg the Maastrichtian bedrock contains some layers of calcarenite which are virtually free of flint. These layers have been mined by room and pillar methods since the Middle Ages for the production of building stone. The quarries are situated at depths of 50 m at most and range in size from a few galleries to labyrinths of 85 ha. The now abandoned quarries are of great historical and cultural value, often containing paintings, drawings and sculptures. Their touristic exploitation (at least 500 000 visitors per year) is economically important for the region.

In many of the quarries, pillars have become fractured and unstable, finally resulting in several large-scale pillar collapses extending over up to 8 hectares (e.g. Bekendam 1998, Bekendam 2020). Pillar shortening due to creep deformation plays an important role and is still going on. The hazards of falling rock and air blasts inside the quarries are particularly serious for the mines with touristic exploitation. In addition, several quarries are located below buildings, roads and other surface structures, which would potentially be catastrophically damaged by surface subsidence.

To monitor the safety of the Gemeentegroeve (40 ha) and the Sibbergroeve (85 ha), near Valkenburg aan de Geul, a fibre optic monitoring system was installed in the autumn of 2019 in areas of deteriorated pillars. The Gemeentegroeve in particular is a popular tourist attraction, with guided tours throughout the year and an annual Christmas market attracting more than 100,000 visitors. Both quarries are also frequented by bat environmentalists or (mining) historians. The purpose of the monitoring system is to provide continuous, real-time measurements of shortening of the deteriorated pillars. The system provides automatic early warning of pillars at risk of collapse, so that for example reinforcements can be provided in time.

In this paper, we present the design of the monitoring system (section 2). We present some results from the first three years or monitoring (section 3), including both typical behaviour and a number of anomalous events. We also discuss some lessons learnt from the design, installation and operation of the system (section 4). The conclusions are presented in section 5.

2 DESIGN OF THE MONITORING SYSTEM

The monitoring system is based on fibre optic technology. Fibre optic sensors have been increasingly adopted for a wide range of structural monitoring applications, leveraging their advantages in continuous and simultaneous sensing of large numbers of points distributed over long distances efficiently. Fibre optic sensors offer superior performance in terms of long-term stability and the ability to have passive sensing points that do not require electrical power at the node (Karabacak et al. 2016). The system used here provides continuous, high-frequency and real-time measurements of the vertical distance between the ceiling and points near the bottom of the pillars. Our sensors are fully resistant against the high-humidity environment inside the quarries and are expected to last for at least 10 years. The more sensitive electronic read-out equipment is placed outside the quarries, where operating conditions are milder and where they can be accessed easier for maintenance.

All measurements are displayed in near real time via a web-based data portal. The system automatically checks whether the rate of creep deformation stays within safe limits – safety alerts are triggered if the creep velocity exceeds pre-determined thresholds and/or if creep accelerates.

2.1 Monitoring locations

In the Gemeentegroeve, 47 sensors were installed on pillars which showed signs of damage due to previous creep, such as cracking or spalling. In the Sibbergroeve, 34 sensors were installed. The height of the ceiling above the floor of the quarry varies between 1.5 and 4 meters.

2.2 Design of sensor assembly and mounting on the pillar walls/ceilings.

The system is based on Fibre Bragg Gratings (FBG), which are embedded in standard glass fibre cables. To mount the sensors on the pillars, two anchors were bolted into the limestone at each location: one vertical in the ceiling, and one horizontal in the pillar wall, near the floor (see Figure 1). The anchors were manufactured out of high-grade stainless steel (DIN EN 1.4404), to avoid corrosion over time in the near 100% humidity environment in the quarries. Anchors were installed by drilling holes in the wall and ceiling, injecting a chemical anchor (epoxy-based) and then screwing the anchor bolts in. Laser levels were used to align the two anchors, such that the glass fibre can be strung straight.

The fibre with embedded FBG sensor is spot welded on the anchor plates, using small secondary plates connected to the fibre beforehand in the factory. Before spot welding, a pre-defined tension is added to the sensor by suspending a weight on it – this prevents the fibre from becoming slack over time due to factors such as temperature variation and pillar compression. A separate FBG temperature sensor is installed next to each strain sensor and is used to compensate for thermal expansion of the fibre under temperature fluctuations. Finally, the full sensor assembly is covered by a plastic cap to prevent it from being physically damaged and as protection against ambient influences.

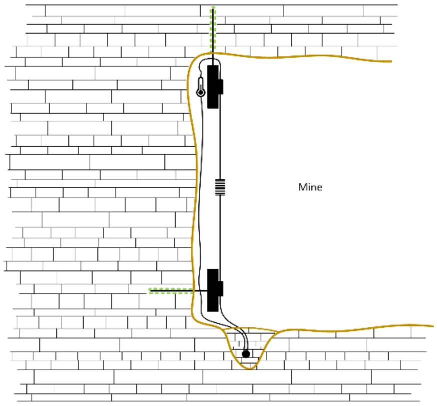

Figure 1. Sensor mounting on the limestone pillar wall and ceiling.

2.3 Cable network

A single multi-channel fibre optic interrogator (model FAZ I4G; Ibrahim et al. 2016) was placed near the entrance of both quarries, where the environmental conditions (mainly humidity) are more benign than inside the quarries, and where power and internet connections are readily available.

More than 10 km of fibre optic cables were installed in the two quarries, to connect the sensors to the interrogators. The cable networks were tailored to the labyrinthine layout of both quarries and consist of a combination of multi-fibre backbone cables, junction boxes and single-fibre cables – special care was taken to minimize signal attenuation at fibre splitters or extension connectors. In some places, custom 'branch-out' points were used to branch off an individual channel from a multi-fibre backbone cable, without needing additional connectors in the other channels (see Figure 2).

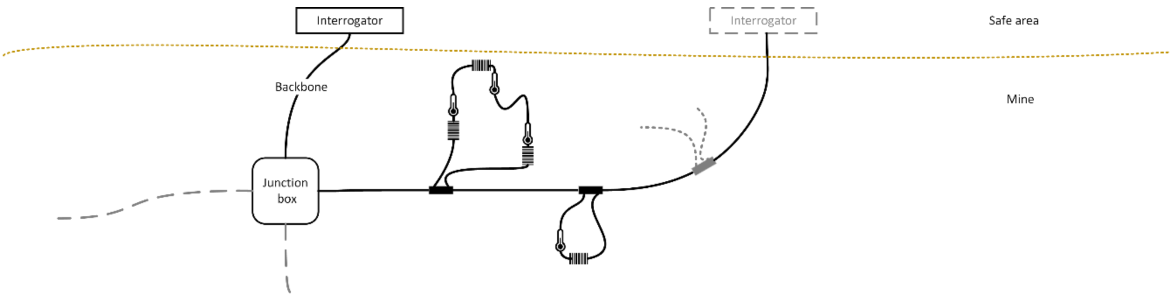

Figure 2. Schematic representation of the cable network in the mines.

The cable networks were designed with full redundancy such that the sensors can also be interrogated from secondary entry points to the quarry – in a scenario where part of the quarry would collapse, the surviving sensors behind the collapsed area can be interrogated via one of those secondary entry points. All cables were laid in underfloor trenches, to preserve the historical character of the quarries.

2.4 Data processing

The interrogator acquires raw wavelength measurements from all sensors every 7 and every 30 seconds for the Gemeentegroeve and Sibbergroeve respectively. Wavelengths are converted into strain using predetermined calibration parameters, and the temperature sensor is used to correct for thermal effects. Using the length of the sensor (anchor to anchor), the variations in strain are converted into pillar creep. For presentation purposes, the creep measurements are down-sampled to 15 minute and daily averages.

The creep velocity and acceleration are calculated daily by fitting a 1st and 2nd order polynomial to the creep measurements, using a local computer connected to the interrogator. Separate fits are made over periods of one day (creep velocity), one month and a whole year (creep velocity and creep acceleration).

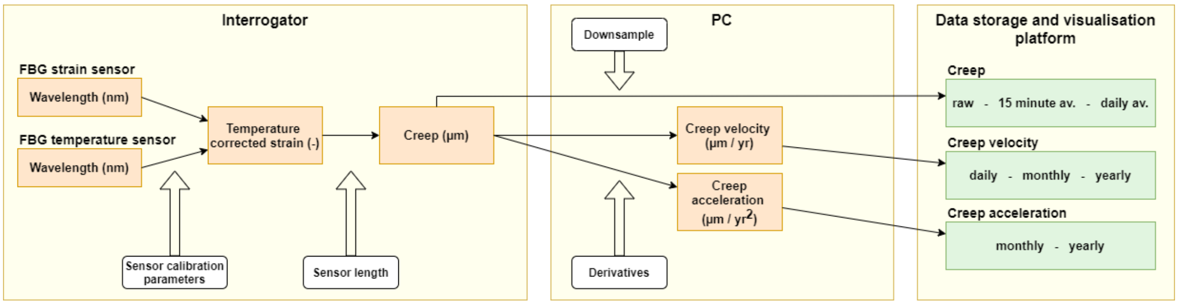

Figure 3. data processing pipeline.

All down-sampled measurements (creep at 15 minute and daily intervals, creep velocity and creep acceleration at all intervals) are stored in a central database and presented in near real-time in an online data visualization platform. The system issues automatic warnings via email if preconfigured thresholds for creep velocity or acceleration are exceeded – when this happens, in-situ inspections can be carried out to assess whether there is reason for concern and whether measures must be taken to avoid further instability of the pillar.

3 MONITORING RESULTS

3.1 Accuracy / noise levels of measurements

The extreme sensitivity of FBG sensor technology results in a highly sensitive system. The typical 1σ standard deviation of the full frequency temperature-corrected creep measurements is well under 1µm. For the down-sampled data, this is even less. In practice, the precision of the creep measurements is probably limited by systemic biases, such as imperfect thermal corrections. In particular, sensors near the entrance of the quarries or close to air vents are influenced by daily and seasonal temperature variations: whilst we correct for thermal response of the glass fibres themselves, we do not correct for expansion of the anchors bolted in the limestone. Furthermore, the limestone pillars themselves will also respond to the temperature fluctuations of the ambient air, so some of the observed creep variations will probably be real.

Because the creep velocity and creep acceleration are determined by simple least-squares fits to the creep measurements, they are sensitive to noise in the data. The longer the baseline of the fits, the smaller the influence of the noise. The typical 1σ standard deviation of the creep velocity measurements is between 50 and 150 µm/yr for the daily fits, and between 25 and 50 µm/yr for the monthly fits. The standard deviation of the monthly creep acceleration values varies between 250 and 1000 $\mu m/yr^2$.

It is difficult to quantify the absolute accuracy of our measurements, given that there is no reference measurement system available which can measure the creep deformation with a comparable precision. However, because we are mostly interested in *changes over time* of the creep velocity and acceleration, the absolute values are actually not critical. For our purposes, the precision and the repeatability of our measurements are the most important factors.

3.2 Natural creep behaviour of the pillars

Clear seasonal variations are present in the creep observations, with an increase in the winter and early spring, and a decrease over the summer and early autumn (Figure 4). Typical creep velocities are a few tens of µm/yr in the winter. In the summer, creep is either absent completely, or even marginally negative (<25 µm/yr expansion of the pillars). A possible explanation for the higher creep in the winter months would be the excess ground water content in that period, which causes extra load on the pillars – however, further investigations would be needed to confirm this.

3.3 Anomalous events

Since the installation of the system, in the autumn of 2019, two anomalous events were recorded by the monitoring system.

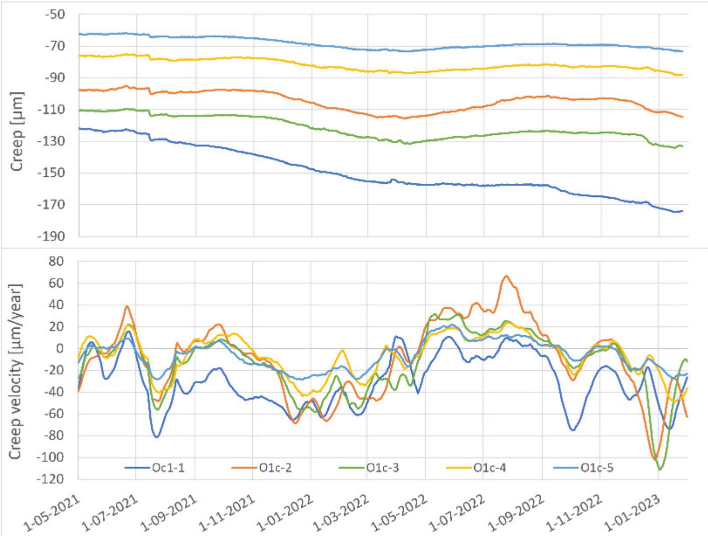

Figure 4. Top: daily creep observations in area Oc1 in the Sibbergroeve from 1-5-2021 till 25-1-2023. Bottom: creep velocity measurements (monthly fits). Negative velocity corresponds to pillar compression.

3.3.1 July 2021: heavy rainfall and flooding of the river Geul

On July 13th and 14th 2021, a stationary low-pressure system delivered heavy rainfall in parts of Germany, Belgium, Luxemburg and the Netherlands, causing amongst other places flooding of the river Geul in the Valkenburg area. The event has also had a noticeable effect inside the quarries: at almost all of the monitoring locations, a sudden increase in creep of several µm was recorded (Figure 5, left-hand side; also visible in Figure 4). The most likely explanation of the excess creep is the sudden deposit of up to 50 mm of water per hour in the afternoon of July 13th (Garcia-Marti et al. 2021), and the extra weight that this put onto the pillars.

Note that the daily creep velocities measured over these days exceeded the thresholds at many locations and many alarm notifications were issued by our system. Thus, this event provided a useful test of the system. Note also that at all locations, the creep velocity returned to its pre-event level within one or two days. There are no indications of lasting damage as a result of this event.

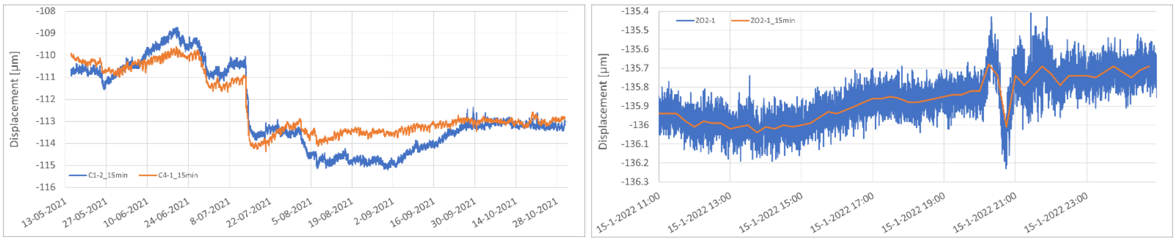

Figure 5. Left: increase of creep in the Gemeentegroeve, caused by heavy rainfall in the period 13 - 15 July 2021. Right: atmospheric shockwave from the eruption of the Hunga Tonga-Hunga Ha'apai volcano on 15 January 2022, as recorded in the Gemeentegroeve.

3.3.2 January 2022: eruption of the Hunga Tonga-Hunga Ha'apai volcano

The eruption of the Hunga Tonga-Hunga Ha'apai volcano on January 15th 2022 produced an atmospheric shockwave travelling around the entire world. The wave also reached The Netherlands, travelling from the north over the country after 20.00 local time, and was recorded by barometers throughout the country (Assink et al. 2022). The wave was also measured by our sensors, showing a dip of ~0.3 micrometers by most of the sensors in both quarries (see Figure 5, right-hand side).

4 LESSONS LEARNT

Installing a monitoring system in these quarries was not a routine job, even for specialist geo-monitoring engineers. Throughout the design and installation of the system, as well as during the subsequent operations, a number of challenges were encountered. One was particularly unexpected and is worth mentioning here.

During the first months after installation, we measured unexpectedly high creep (up to several 100s of µm/year) at all measuring locations. Over a period of up to 12 months, this initial high creep velocity slowed down everywhere, after which a more steady creep was observed, at rates more in line with the expectations. Our hypothesis is that the installation of the sensors caused local tension in the limestone rock around the anchors. Because the rock is so soft (UCS generally of 1.5–3 MPa), it is assumed that the added tension causes slight gradual deformation in the area directly around the anchor, which ultimately causes a slight shortening of the distance between the two anchors.

For future installations, the initial settling period must be taken into account. The reliability of the measurements during the initial settling period is limited. In our case, only large, rapid deformations exceeding the settling speed could have been detected in this period.

5 SUMMARY AND CONCLUSIONS

We have installed a fibre optic sensing system to monitor the rock-mechanical safety of two limestone quarries. Fibre optic sensing offers a number of key advantages which make it very suitable for these kind of monitoring challenges. The sensors inside the quarries are passive and fully resistant to the constant, near 100% relative humidity inside the quarries. They are expected to last for at least 10 years, without maintenance. A single interrogator placed near the entrance of the quarry is able to continuously and simultaneously measure large numbers of points distributed over long distances.

Our system measures creep deformation of pillars in the quarries with extremely high precision and generates automatic alerts when the velocity and acceleration of the creep deformations exceed pre-configured thresholds which could indicate a risk of pillar instability.

The measurement data give unique insights in the geomechanics of these limestone quarries, well beyond the prime goal of the system as a safety monitoring system. Our system provides an unprecedented view on the natural behaviour of the quarries, as well as their response to external events. In particular, the extremely high frequency and accuracy of our measurements (several times per minute, with µm precision, compared to the conventional manual measurements of at most a few times per year) will allow future studies of the influence of e.g. weather or human activities on the surface on the rock mechanics of the limestone quarries and the ground layers above.

REFERENCES

Assink, J., Bosveld, F., Meirink, J.F., Selten, F. and Mol, W. 2022. Drukgolven in Nederland na de eruptie in Tonga op 15 januari 2022. Journal: Meteorologica, Volume: 31, 2022, pp.20-22.

Bekendam, R. F.: Pillar stability and large-scale collapse of abandoned limestone room and pillar mines in South-Limburg, the Netherlands, PhD thesis, TU Delft, Delft, the Netherlands, 361 pp., 1998.

Bekendam, R. F.: A reanalysis of the collapse of the Heidegroeve: subsidence over an abandoned room and pillar mine due to previously unknown mine workings underneath, Proc. IAHS, 382, 269–275, https://doi.org/10.5194/piahs-382-269-2020, 2020.

Garcia-Marti, I., Whan, K., Noteboom, J.W., and Siegmund. P., 2021. Insights about extreme precipitation in Limburg from crowdsourced data (https://www.knmi.nl/research/weather-climate-models/updates/insights-about-extreme-precipitation-in-limburg-from-crowdsourced-data).

Ibrahim, K., Farnan, M., Karabacak, D.M., Singer, J.M., 2016. Enabling Technologies for Fiber Optic Sensing. Proc. SPIE 9899, Optical Sensing and Detection IV. https://doi.org/10.1117/12.2234975

Karabacak, D., Farnan, M., Ibrahim, S., Todd, M., and Singer, J. (2016). Fiber Optic Sensors for Multiparameter Monitoring Of Large Scale Assets. 8th European Workshop on Structural Health Monitoring (EWSHM 2016). *e-Journal of Nondestructive Testing*. 21(8). https://www.ndt.net/?id=20127