Potential of embedded Fiber Bragg Grating networks for seismic characterization of an Excavated Damaged Zone

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Abstract. Seismic methods offer a non-destructive and repeatable solution adapted to the long-term monitoring of the zone affected by the excavation of galleries in deep geological repositories. This study provides preliminary observations and feedback from an in-situ experiment conducted in the Bure Underground Research Laboratory (Meuse, France). A network of Fiber Bragg Grating (FBG) sensors was embedded in boreholes drilled perpendicularly to the wall of a gallery through the first meters affected by the excavation, to assess our ability to measure P-wave propagation velocities and their temporal variations. A newly developed interrogation system was tested in real conditions. Reference accelerometers were embedded for comparison. Two high-frequency active seismic campaigns (1 - 5 kHz) were conducted for this purpose. Preliminary velocity models are presented. The benefits of this approach and the challenges to overcome in terms of signal-to-noise ratio are summarized in this contribution.

1 Introduction

Deep geological repository of high-level and, long-lived intermediate-level radioactive waste is a solution being actively developed in several countries, including Finland, Sweden and France.

In France, the Bure Underground Research Laboratory (BURL), whose construction started in the early 2000s, is dedicated to observe and study directly the argillaceous layers (Callovo-Oxfordian claystone formation), at about 490 m depth and to test and prepare industrial solutions that could be used for future deep repository known as Cigéo.

In this context, the knowledge and ability to monitor the area affected by the drilling of the galleries, and located near the disposal, in the so-called Excavated Damaged Zone (EDZ, Armand et al. 2013, 2014), have been an active subject of research over the last years.

A large variety of methods has been implemented to improve the knowledge of the hydro-mechanical properties of this area, and its evolution in time. In particular, seismic methods have been employed to study the healing of this zone under mechanical loading in the BURL

(De la Vaissière et al., 2014) or to monitor this zone over several years in the Horonobe Underground Research Center (Osaki, 2023).

The recent development of optical fiber technologies dedicated to the measurement of the propagation of mechanical waves, especially Distributed Acoustic Sensing (DAS), offers new opportunities thanks to their limited cost (excluding the interrogation), their low intrusivity and their resistance to harsh environments. Nevertheless, the use of such systems at short wavelengths (< 1 m) for frequencies above 1 kHz remains limited to date.

In contrast, Fiber Bragg Gratings can be used to measure seismic waves at frequencies more adapted to short-scale seismic applications in civil engineering. However, the potential of these innovative sensors for high frequency seismic imaging/monitoring is still being explored.

The FO-US project (ANR-21-CE04-0007) has focused on the possibility of deploying and interrogating these sensors in field seismic monitoring campaigns, with the challenge of increasing the number of channels that can be interrogated simultaneously in the same optical fiber, while having a large signal to noise ratio.

For this purpose, an experiment has been conducted in one of the galleries of the BURL (GRM3). Optical fibers with several FBGs were embedded in two parallel boreholes, together with reference accelerometers in a Vertical Seismic Profile (VSP) configuration. Active seismic sources (hammer and vibrating actuator) were employed at the surface of the wall of the gallery. After an initial measurement campaign, water was injected in two other boreholes placed within the setup to evaluate the effect of rock hydration on the seismic velocities.

This contribution reports on the experimental setup, the quality of the data acquired and the main difficulties encountered. Preliminary P-wave travel time tomographic models obtained before and after hydration of the rock are presented.

2 Experimental setup

The FBG network was deployed in two measurement boreholes, drilled horizontally over 6 m across the EDZ of gallery GRM3 in the BURL. Four optical fibers (F1 to F4, Fig. 1), containing 7 FBGs each (FXB1 to FXB7, Fig. 1), were embedded in a cement grout. Four additional reference accelerometers of type B&K 4381 (A309XX in Fig. 1), were also buried at 1.6 and 4.4 m depth for comparison.

The opto-electronic system used to interrogate the FBGs, was developed and operated by the CEA. It is based on the edge-filtering method (Melle et al, 1992), which consists of emitting a narrow band light source, here a laser, within the fiber core at a wavelength on the edge of the reflectivity peak of an FBG. Variations in intensity of the reflected light are monitored. These intensity changes result from the shift of the reflectivity peak, as seismic waves dynamically strain the FBG. This system includes 7 tunable laser sources and a wavelength multiplexer to interrogate up to 7 distinct FBGs simultaneously. The analog signals from the FBG interrogator and the accelerometers were digitized at 1.25 MHz using a single acquisition rack, named TOMAG, developed by UGE.

Series of hammer impacts were shot against the claystone, in 13 windows drilled through the shotcrete, over an aperture of 12 m centered around the head of the boreholes (Fig. 1). The center frequency of the hammer shots was about 3-4 kHz. Additionally, a vibrating source (Tira) was used to generate swept excitations between 1 and 2 kHz, for 3.5 s.

A first measurement campaign was conducted end of 2024 (initial state). To evaluate our ability to detect localized perturbations of the P-wave velocity, a hydration of the rock was operated end of 2024 between the two measurement boreholes, in two dedicated boreholes

(RGA 3021 and 3022, Fig 1), and a second measurement campaign was conducted in march 2025 (perturbed state).

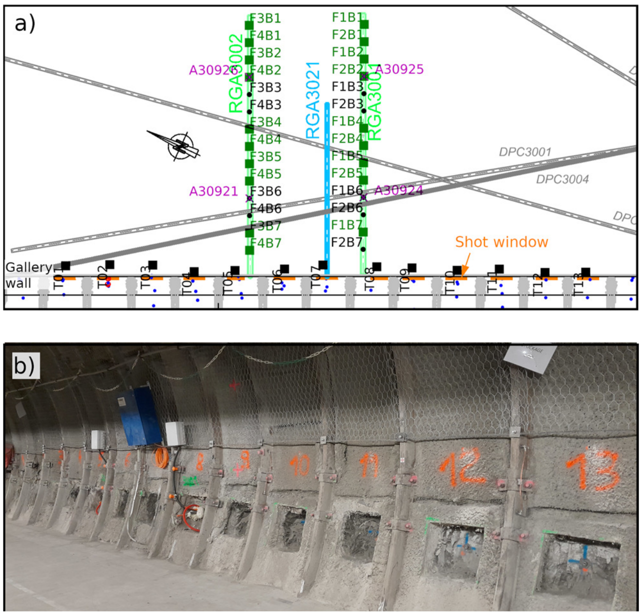

Figure 1: Experimental setup, (a) view from above. Orange marks indicate the windows drilled in the shotcrete to position the seismic sources in contact with the claystone. The 6 m deep instrumented boreholes RGA3001 and RGA3002 are shown in green. The hydration boreholes RGA3021 and RGA3022 are shown in blue. Green squares indicate operational FBGs, purple crosses indicate the 4 reference accelerometers. (b) photograph of the wall.

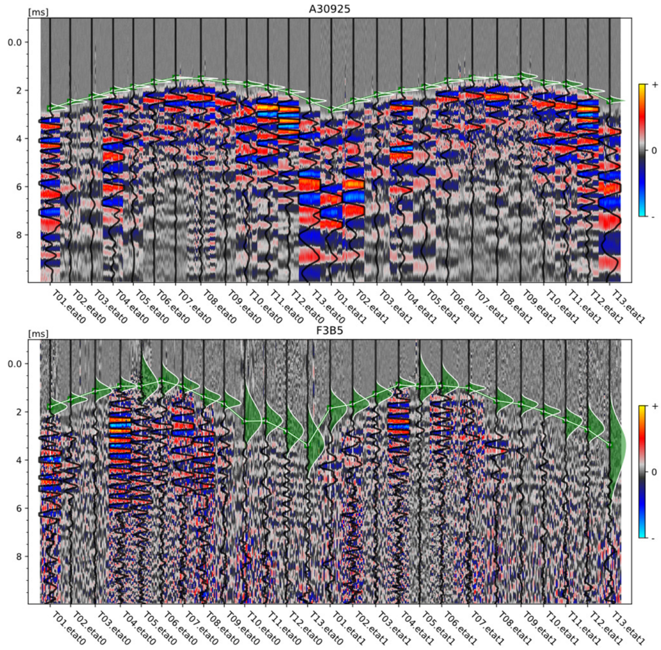

Figure 2 : Receiver gathers obtained for the reference accelerometer A30925 (top) and FBG F3B5 (bottom). The colored waveforms correspond to the ~20 repeated signals for each shot position. The black traces (saturated to increase readability of the first arrivals) correspond to the average waveforms. Green histograms indicate the travel time uncertainties. TXX indicate the number of the shooting window, etat0 (resp etat1) designate the initial (resp. hydrated) state.

3 Main findings

The acquired FBG measurements exhibit lower signal to noise ratios than the reference accelerometers. This suggests that these records must be stacked over more source repetitions or longer time periods. This difficulty can be overcome by longer acquisition campaigns. Nevertheless, in addition to the weaker SNR, spurious arrivals were observed on some FBGs especially for the hammer source when placed along the axis of the optical fibers. These spurious arrivals correspond to non-physical seismic wave velocity and are likely due to Fabry-Perot cavity resonance between several FBGs of the same fiber. These arrivals strongly reduced our ability to measure reliable P-wave travel times for some source-receiver paths.

To maximize the number of travel time observations, and to mitigate the impact of precursor arrivals due to missed hammer shots, weak signal to noise ratios, and Fabry-Perot spurious arrivals in some traces, the travel times were picked manually in each pre-stack signal. The obtained travel times range from 0.5 to 3.5 ms, depending on the source-receiver path. The travel time uncertainties inferred from the distribution of the picks on repeated shots, range from 20 microseconds on average for the reference accelerometers against 160 microseconds on average, and up to 420 microseconds for the FBGs. These uncertainties are used in the tomographic inversion to weight the observations (Tarantola, 2005). Consequently, the reference accelerometers have more weight in the preliminary tomographic images obtained (Figure 3).

The tomographic images are obtained using a standard 2 dimensional tomographic approach. Seismic rays are computed using the Fast Marching Method (FMM), and a 2 dimensional B-splines basis is used to parameterize to model. The minimization of the L2-norm cost function is done using a quasi-Newton iterative approach (Tarantola, 2005). The diagonal terms of the resolution operator are used to hide the zones of the model that are not resolved (the white transparent zone in Fig. 3 corresponds to a resolution lower than 10% of its maximum).

The obtained P-wave velocity values are slightly faster than previously observed in another gallery of the BURL, oriented similarly relative to the main regional horizontal stress (CDZ experiment De la Vaissière et al., 2014), used as an *apriori* velocity model in this study (see the velocity values under the white mask in fig. 3). A low velocity area (~2100 m/s) is observed over the first few tens of centimetres, while similar low velocities were observed over the first meter in the initial state of the CDZ experiment. The velocity changes between the initial and hydrated states seem to remain confined to the very shallow area. We believe that the resolution of the current images might not be sufficient to highlight the velocity variations associated with the hydration. A differential analysis of the first P-wave arrivals, might improve the localization and resolution of velocity changes in the future.

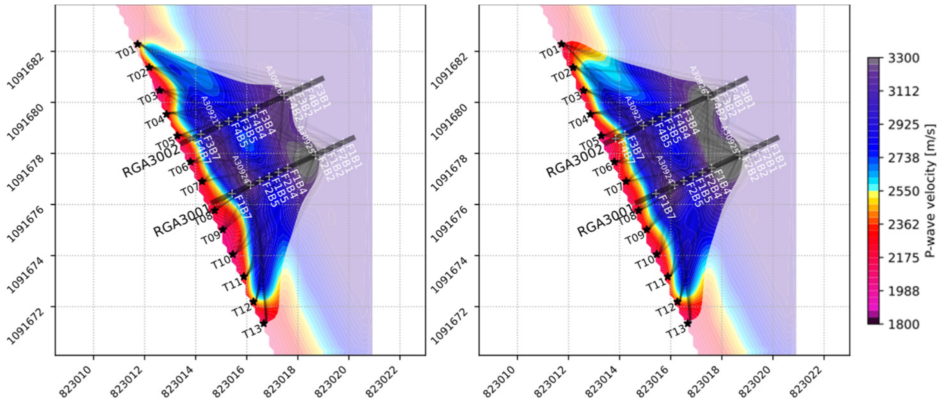

Figure 3 : Preliminary tomographic images obtained using the P-wave travel times measured on both accelerometers and FBGs, weighted by the corresponding uncertainties. The left (resp. right) image corresponds to the initial state (resp, hydrated state). A white transparent mask is applied to hide the zones of the image, where the resolution is low (<10%).

4 Conclusion and future work

This study demonstrated the feasibility of deploying a network of embedded FBGs to acquire seismic waves inside one wall of a gallery in a field experiment, excited from its surface in a VSP configuration. P-wave propagation times and associated uncertainties could be measured in the EDZ in the targeted frequency band (1 - 5 kHz). The main limitation identified with these data is related to the low signal to noise ratio, which could be partly overcome in future experiments by stacking more shots per source position.

We believe that the acquired data can be used to better understand the noise that affects the FBG measurements for in-situ experiments. Future work will focus on how to reduce or remove the observed spurious arrivals that we attribute to Fabry-Perot effects, either by modifying the design of the FBG network (e.g. by reducing the number of FBGs per fiber or by reducing the distance between them), or at the data processing stage. A potential approach is to use blind source decomposition techniques, whose potential has been demonstrated using similar data acquired at a reduced scale in the laboratory (Derrien et al, in prep).

5 Acknowledgment

This work was funded by the ANR-21-CE04-0007 FO-US project.

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