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# Estimating tunnel wall displacements using a simple sensor based on a Brillouin optical time domain reflectometer apparatus

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ABSTRACT

A strain monitoring system based on a PVC tube instrumented with optical fiber connected to a Brillouin Optical Time Domain Reflectometer (BOTDR) apparatus is proposed to monitor rock mass movement in an underground mine. The optical fiber is glued along four lines of the tube surface which are rotated 90° one from each other to capture in-plane and out-of-plane tube bending displacements. A laboratory experimental program is undertaken to validate the proposed sensor as a monitoring tool. In the laboratory, PVC tubes are subjected to controlled displacements on 4 points that represent the attachment locations of the sensor to the rock mass to simulate possible response in the rock mass during mining activities. The longitudinal strain recorded by the optical fiber compare well with the ones provided by the traditional electrical resistance strain gauges. Considering the sensor tube as a one-dimensional linear beam-type element, a back-analysis algorithm is implemented to estimate displacements on the surface of the rock mass using the recorded longitudinal strains. The proposed sensor is installed in a tunnel mine and preliminary strain measurements of this field trial are reported. The conclusions of this study suggest that the proposed sensor can be regarded as a promising and safe tool for tunnel monitoring.



## 1. Introduction

Monitoring strain in structures such as bridges, tunnels, pipelines, and buildings are important for disaster prevention, detecting the deterioration of structures, and reducing the repair and maintenance cost of structural members [1–3]. In particular, tunnel excavation in rocks induces changes in the local stress field and subsequent deformation; thus the purpose of the instrumentation of the tunnel walls is to monitor displacement in order to maintain safe operational practices, evaluate the stability, and measure rock mass properties. In addition to the complexity of the analysis of possible failure mechanisms, rock, as a natural material, is heterogeneous and difficult to characterize completely. In order to avoid large displacement and failure inside underground mines, geotechnical engineers consider stress, seismicity, and displacement measurements. In situ field monitoring is therefore essential to decrease the probability of failure and perform mining activities safely.

Deformation in underground structures are usually monitored by recording the displacements of a limited number of carefully selected points allowing the key warning signs of instability to be appropriately monitored. Borehole extensometers and inclinometers are commonly used in underground measurements [4–6]. Their use, however, frequently requires a data acquisition system close to the zone that is being monitored increasing the risk of the workers who are taking the measurements. In the last years, geodesy has offered an alternative technology suitable for such applications in which a large number of control points are considered. Electronic theodolites have been used to monitor induced deformation during tunnel excavation in which the data collected can describe 3-D changes of the tunnel walls and compare them with the expected values to check the safety of the tunnel excavation [7,8]. Geodesic instruments, however, require regular cleaning regime to ensure that they are working properly due to their exposure to demanding working environment (dust and humidity) usually encountered during excavation works and mining activities.

Strain measurements with a distributed Brillouin scattering based sensor system appear to be a promising alternative for the health monitoring of civil structures as explained in [9]. The BOTDR-based fiber optic technique can provide a distributed measurement of physical parameters of structures over a long distance. For Brillouin-based optical sensing, the entire length of fiber optic cables is used for both data transmission and strain

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sensing. As such, using the BOTDR technique makes it possible to measure the strain continuously (every 5 cm) along the fiber optic cable rather than at discrete points, with a spatial resolution that can be varied. Fiber optic sensors based on Brillouin scattering make use of a nonlinear interaction between the light and the silica material of which the fiber is made. If light pulses are transmitted down a fiber, part of the pulse is scattered back at every point along the fiber. The scattered light experiences a frequency shift that depends on the fiber temperature and strain (i.e., local properties of the fiber). A system based on this type of sensing is a useful tool for structural and health monitoring of underground structures [10–13].

Optical fiber sensors have many advantages over other measurement systems such as immunity to electromagnetic interference, being lightweight and small size, and low power. A large number of sensors can be monitored at the same time from one acquisition data equipment, as well as the fact that equipment and personnel can be at a long distance from the monitored area thus improving safety as mentioned in [14–16]. In this context, optical fiber sensors appear to be a promising alternative to monitor rock mass displacements during mining activities.

In this study a strain sensor based on the BOTDR technique is proposed to estimate rock mass displacements from longitudinal strain measurements. The proposed instrument consists of a polyvinyl chloride (PVC) tube instrumented with Brillouin fiber optic sensor along its external surface. This sensor is validated in the laboratory by comparing the recorded longitudinal strain measures with the strain measured by electrical resistance strain gauges. The installation of the sensor in a underground mine, preliminary sensor readings, and a back-analysis procedure implemented to utilize the longitudinal strains measured by the sensor to estimate rock mass displacements at the interior of a tunnel due to operational mining activities are presented and discussed in this paper.

## 2. BOTDR optical fiber sensor description

PVC tubes of 5.0 m length, 25 mm and 40 mm external diameter, and 2 mm and 3 mm of thickness, respectively, were used to create the strain sensors. Standard properties of the PVC are: rupture tensile stress equal to 500 kg/cm$^2$, elasticity modulus of 30,000 kg/cm$^2$, and axial failure strain equal to 15% [17]. Strains along the PVC tube are measured using the BOTDR equipment where the optical fiber is located on the PVC tubes surfaces as shown in Fig. 1. The sensing fiber is nylon coated standard single-mode optical fiber with a diameter of 0.9 mm. It is glued to the PVC tubes by the use of epoxy glue applying an initial tensile force that approximately corresponds to a strain of about 0.1%. There are four lines of sensor fiber; upper ($z=0$, $y=d/2$), bottom ($z=0$, $y=-d/2$), left ($z=d/2$, $y=0$), and right ($z=-d/2$, $y=0$) and 3 loops between them (Fig. 2(a)). These loops are approximately 0.5 m length to avoid large signal losses. No compensation of temperature was applied as it was verified that changes in temperature during testing were lower than the error (i.e., 0.01%) given by the fabricant of the BOTDR equipment and verified in a experimental program [18] (however this compensation should be considered in the mine for long term measurements). These PVC tubes are also instrumented with 30 mm long electrical resistance strain gauges for validation purposes. Strain gauges give local measurements of longitudinal strain on the upper, lower and a lateral face of the PVC tubes, providing a strain resolution of 0.01% (PFL-20-11, TML). Strain gauges were installed slightly rotated relative to the optical fiber as depicted in Fig. 2a and their distributions along the length

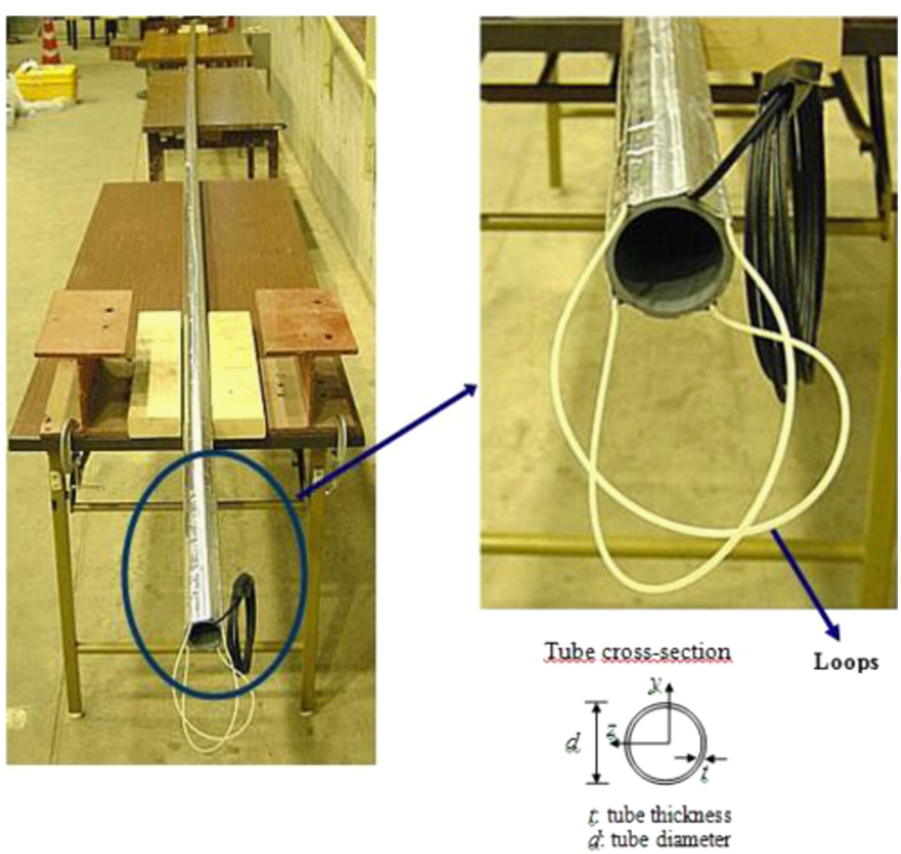


**Fig. 1.** PVC tube instrumented with optical fiber.