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TECHNOLOGICAL CLASSIFICATION OF UNDERGROUND EXCAVATION WORKS IN GEOTECHNICAL MONITORING SYSTEMS

Djaksimuratov Karamatdin Mustapaevich
Candidate of Natural Sciences, Nukus Mining Institute

Joldasbayeva Aysulu Baxitbay qizi
Student of Nukus Mining Institute:

Bayramova Minevvar Axmet qizi
Student of Nukus Mining Institute:

Tolibayev Erlan Amangeldi o'g'li
Student of Nukus Mining Institute:

Maulenov Nurlibek Axmet o'g'li
Student of Nukus Mining Institute:

A B S T R A C T	*K E Y W O R D S*
Geotechnical stability is a major concern for the long-term safety and integrity of underground infrastructures such as tunnels, railway stations, mine shafts and hydraulic power chambers. An effective geotechnical monitoring system is able to provide adequate warning to underground personnel prior to any unexpected major geotechnical failure. This paper reviews the conventional geotechnical monitoring sensors and the emerging Fibre Optic Sensing (FOS) techniques, pointing out their unique features and major differences. Recent advances in various FOS based monitoring systems, including Brillouin time domain distributed optical sensors and fibre Bragg grating (FBG) sensors, are investigated through a critical review of the laboratory studies and field applications used for underground geotechnical monitoring. Particular emphasis is given to fibre packaging, temperature compensation, installation methods and instrumentation performance in the underground environment. A detailed discussion of the advantages and limitations of each FOS monitoring system is also presented in this paper.	*Underground geotechnical monitoring ,Conventional geotechnical instruments ,Distributed optical fibre sensors, Fibre Bragg grating Brillouin optical analysis.*

Introduction

Underground infrastructures such as tunnels, mine roads, power stations and oil storage facilities play a critical role in the economy of any country. Due to the inherent uncertainty and complexity of the geological conditions in an underground environment, rock stability is one of the major concerns during the design and construction phase of any underground excavation. Without an effective geotechnical monitoring scheme, unexpected rock failure due to excessive rock deformation may lead to catastrophic injuries, fatalities and significant financial loss. Conventionally, rock mass monitoring is based on mechanical and electrical sensors, whereby the desired physical quantity being measured is translated and transmitted as electric signal. This is typically an advantageous method of sensing as these techniques are well established, have proven reliability records and known manufacturing costs. However, these sensors can only provide limited number of sensing points and the accuracy of the strain measurements may be subject to electromagnetic interferences from those mining machinery used underground. For the safety concerns, the use of electrical components are likely to trigger gas explosion in underground where combustible environment is present without proper explosion-proof measures. In addition, manually-read strain sensors such as extensometers and load cells lack the capability to provide frequent and real time measurements, and the necessity of manual reading unavoidably exposes mine personnel to hazardous environment. Over the past decade, fibre optic sensing (FOS) techniques have been investigated as a superior alternative to electrical sensing for a number of advantages: (a) immune to electromagnetic interference and radio frequency interference; (b) intrinsically safe due to the use of non-electrical sensor components; (c) light weight and compact; (d) suitable for real time automated data acquisition and (e) large number of sensing points. FOS has proved to be successful in structural monitoring for a wide range of civil engineering applications such as bridges, dams, underground tunnels and mines. Innovative structural monitoring FOS systems allow distributed measurement of strain at high spatial sampling rate over a large monitoring area. Furthermore, these sensors provide the ability to simultaneously measure a range of parameters on the same network such as strain, temperature and deformation. This paper aims to provide a comprehensive review of the instrumentation of FOS techniques for underground excavations. The conventional geotechnical monitoring instruments are discussed in Section 2. This is followed by an overview of the FOS technologies and their applications for underground geotechnical monitoring in Sections 3 and 4, respectively. Some practical aspects of FOS systems field implementation such as fibre encapsulation methods, temperature compensation techniques and strain transfer loss are covered in Section 5. Finally, a recommendation on future research opportunities and gaps are provided.

Conventional geotechnical monitoring instruments

Generally, underground geotechnical monitoring involves measuring multiple parameters such as strain/deformation, displacement, stress and seismicity for rock mass stability. However, this paper will only focus on strain and displacement sensors as excessive rock mass movement is one of the major concerns in the stability of underground excavations. The choice and layout of geotechnical monitoring instruments depend on the functions of the roadway, the rock mass properties and the ground control methodology in use. Fig. 1 illustrates some of the most widely used rock mass monitoring instruments in underground coal mines.

Convergence stations

Convergence stations are designed to measure the relative displacement between any two reference points around an excavation. Some of typical types of convergence indicators are shown in Fig. 2. Ghose and Ghosh investigated the daily roof-floor closure rate using telescopic convergence rods in a freshly excavated roadway for one month until the roof convergence rate decelerated significantly. Through back analysis of convergence measurements, a mathematical expression was derived to predict the critical roof convergence based on the rock mass rating, roadway span and roof density. Convergence stations have the advantage of easy installation. However, only surface displacement around tunnel can be measured, which ignores the strain changes within the rock mass. Also, installation of these devices often block access way for excavation activities.

Extensometers

Rock mass embedded monitoring devices such as rod, wire, magnet extensometers can monitor relative displacement between anchored points at various depths in large volume rock mass. Fig. 3 shows two types of extensometer widely used in underground coal mines. In a field study at an underground coal mine in New South Wales, Australia, the mechanical behavior of laminated coal mine

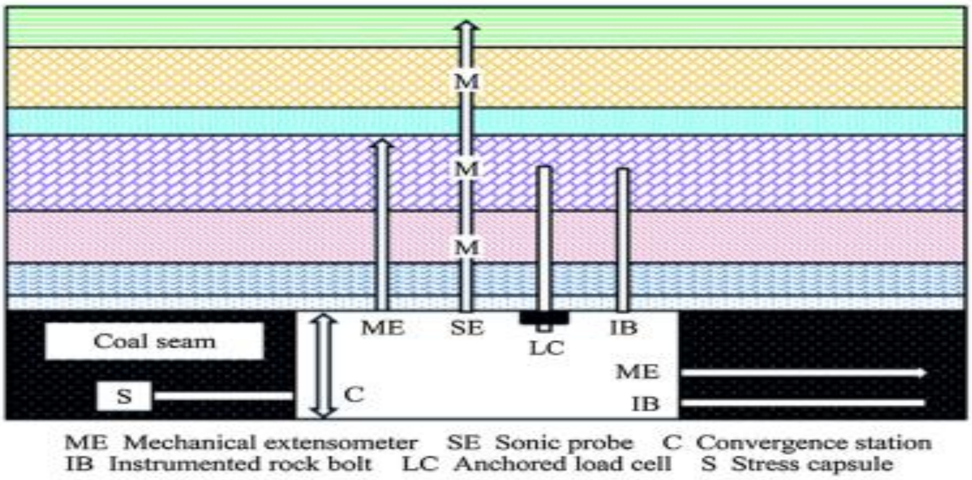

Fig. 1. Typical instrumentation for strata monitoring for underground coal mines.

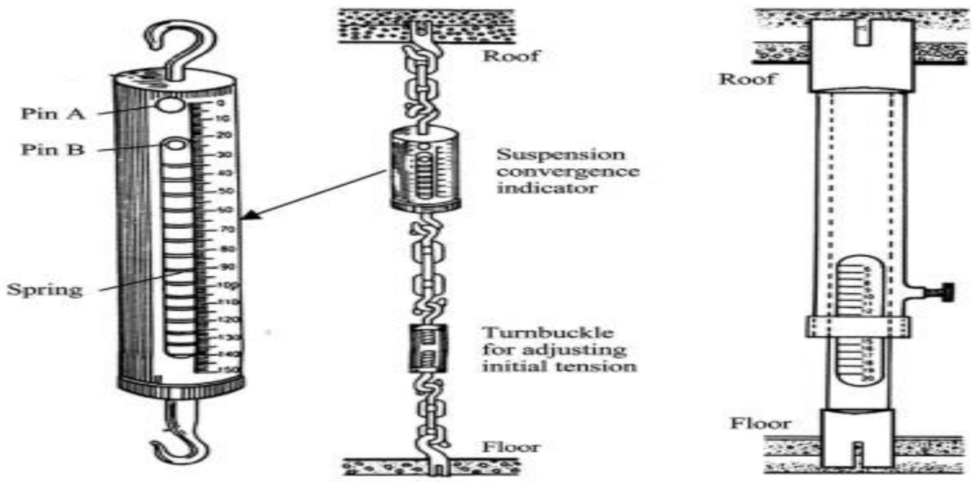

Fig. 2. Convergence indicators-suspension spring type (left); telescopic rod type (right).

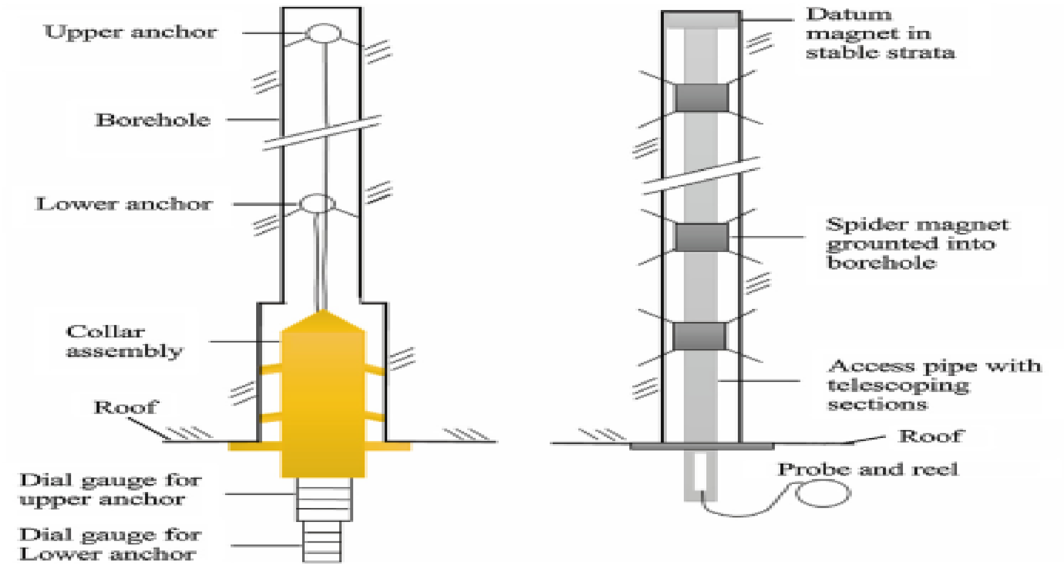

Fig. 3. Multi-point extensometers - wire (left); magnet (right).

Roof strata and its implications for roof support design was investigated using a combination of wire and sonic extensometers. These instruments were installed across the roof span to provide roof deformation at different horizons as well as the height to which roof softening occurred during different mining stages . Wire extensometers are also routinely used to monitor roof strata movement for underground coal mines in Australia. In UK and Canada, two-anchor wire extensometers (tell-tales) are installed at every 20 m in roadways and in all intersections . Sonic probe extensometers with up to 20 anchors are installed immediately after the roof bolting as part of the roof monitoring program in South Africa. For multi-anchor rod extensometers, the increased number of anchors will normally require a larger sized borehole. This reduces the measurement accuracy of rock movements caused by the perturbed stress field between the rock mass and the extensometer. Wire extensometers usually require smaller boreholes. However, the steel wires will have difficulty in maintaining tension levels due to the kinking effect, resulting in lower accuracy for wire extensometers over the long term. Roof displacement with mechanical multi-point extensometers requires periodic manual recording, resulting in difficulty in reading the values for high mine roadway.

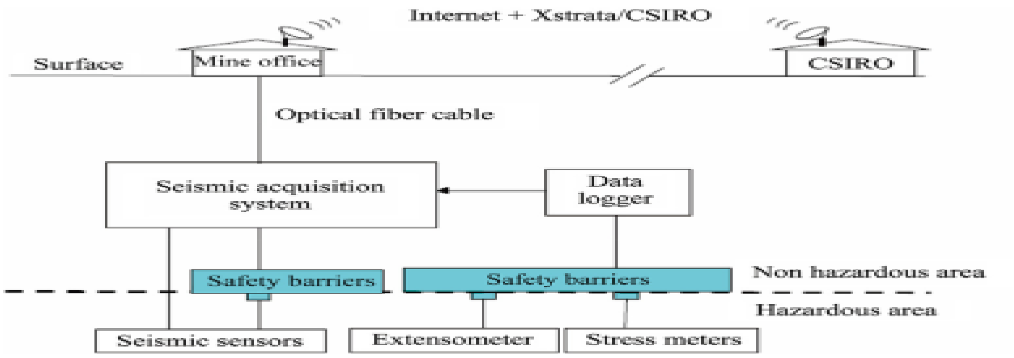

Fig. 5. Integrated real time roof monitoring for underground coal mines
was determined by taking into account the engineering characteristics and geological conditions of the cavern.

Fibre optic strain sensing technologies

Fibre optic sensors can generally be categorized into extrinsic and intrinsic sensors, based on whether the sensing region is where the optical signal leaves the cable and is modulated in another medium; or into distributed, quasi-distributed and point sensors, based on the continuity of the sensing points. Table 1 lists the FOS sensors used in underground geotechnical monitoring.

Integrated real time remote monitoring

In most cases, underground geotechnical monitoring involves monitoring large geological structures such as faults. Therefore, the present monitoring systems incorporate the information and networking technologies that enable continuous and remotely controlled automatic monitoring of the structure to improve operation safety and data accuracy. Automatic data recording extensometers were firstly introduced to underground coal mines using electric transducers. To understand the roof behavior and failure process in coal mines, Shen et al. conducted a field experiment using an integrated real time monitoring system with extensometers, stress-meters, and a seismic sensor to measure rock mass deformation, stress change, and seismicity in roadway roofs during mining-induced failure [19], as shown in Fig. 5. Surface rock movement such as convergence and crown settlement was monitored by electronic total station and extensometers. Vibration-string displacement meter and rock bolts, which were installed through the surrounding access tunnels, were used to measure the internal rock displacement and stress induced in the bolts. The layout of the monitoring points

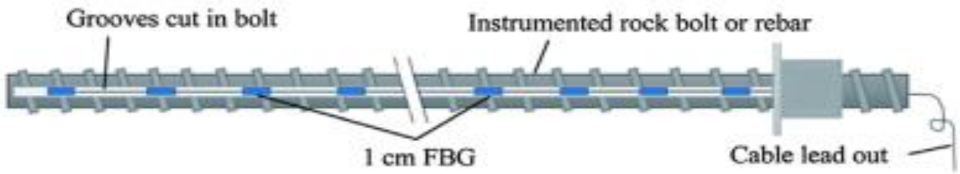

Fig. 4. Illustration of an instrumented rock bolt.

Applications of FOS in underground mine geotechnical monitoring

Distributed fibre optic sensors

The focus of this section is to present the published geotechnical applications using distributed scattering sensors in underground rock mass monitoring. In 2006, a six-month geotechnical monitoring trial was conducted in a Chile mine by a BOTDRbased strain sensing system to monitor the mining induced changes in the state of underground roadway. Two groups of optical fibre sensors are fixed to the rock bolts from the ceiling and tunnel wall respectively with 3 m interval. The undercut mining zone is located 60 m above the tunnel, as shown in Fig. 8. Elongation strain up to 2500 me was measured in the optical fibre during the undercutting and ore extraction activities. The main limitation of this system is that it could only qualitatively detect the rock deformation. To obtain quantitative horizontal and vertical rock movement, a proper geometrical algorithm needs to be developed. An innovative BOTDR-based distributed strain sensing network was evaluated qualitatively by Wang and Luan for the monitoring and detection of mine roof collapse. The sensing fibre is fully attached to the structure with epoxy resin and the entire roof sensing area is partitioned into various 1 m grids by an orthogonal fibre layout, as shown in Fig. 9. This design can fully separate the four strain gage signals which are reflected by optical fibre sensor

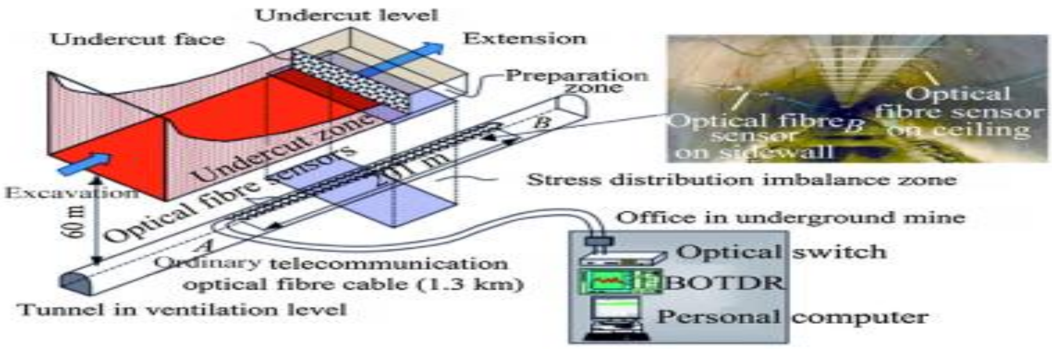

Fig. 8. Sketch of BOTDR distributed underground mine tunnel convergence monitoring system

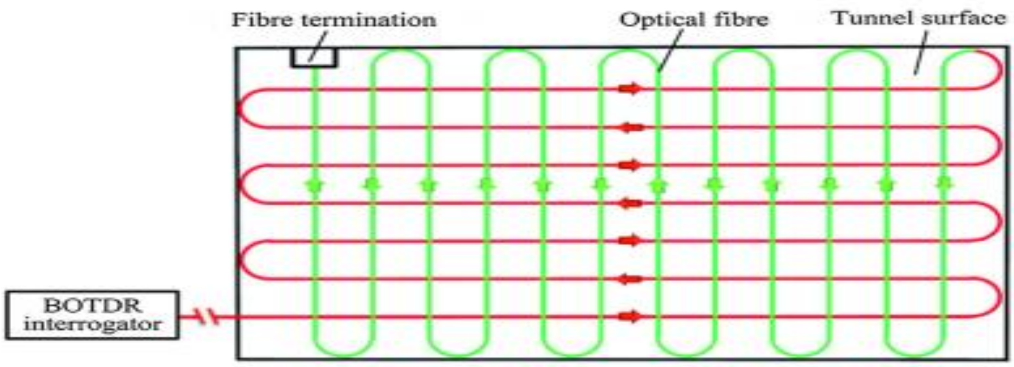

Fig. 9. Instrumentation layout of BOTDR based mine roof monitoring grid in different time so as to improve the measurement accuracy.

However, positioning of each fibre segment means it is challenging to map the strain distribution across the entire monitoring surface. The BOTDA scattering technique has been applied extensively in a wide range of civil structure heath monitoring (SHM) projects including tunnels, piles, pipelines and bridges [34–36]. In the mining industry, a very limited number of case studies on underground rock mass monitoring have been identified so far. In 2012, a field investigation was conducted in an underground metalliferous mine where temperature compensated strain sensing fibres were installed in monitoring breakthrough holes drilled through 25 m thick, 1000 m deep sill pillars. A BOTDA system with looped fibre configuration monitored the mining-induced strain in five sill pillars with optical fibre grouted in each borehole, as seen in Fig. 10. The field strain response measured by the FOS system is qualitatively consistent with the deformation readings obtained from the benchmark extensometers, although details and absolute magnitude differ. The authors suggested such quantitative discrepancy was partly due to strain transfer factor among the fibre-groutrock mass system as well as the large signal noise (up to 400 me) that conceals the true rock deformation with the similar magnitude. Madjdabadi et al. simulated the borehole-grout-fibre interaction to investigate the strain transfer between the rock mass and the optical fibre . A number of factors that affect the strain transfer are examined including borehole diameter, grout stiffness, rock mass plasticity and the existence of joints. The authors further evaluated the BOTDA for measuring extension and shear deformation in rock. For the extensional test with up to 5000 me, the results showed a clear linear correlation between applied strain and frequency shift for all strained lengths above half the spatial resolution of the system. However, the sensing cable is less sensitive to lateral movement. A parabolic relationship between applied strain and frequency shift resulted in small shear displacements not being able to be detected by the instrument. The applications of high spatial resolution PPP-BOTDA in strain sensing have been primarily limited to laboratory settings so far. investigated the performance of PPP-BOTDA for rock deformation under deep mining conditions . A physical simulation model of 400 cm in length, 40 cm in width, and 144.5 cm in height was created with a 12 m long optical fibre loop inclined at 25————————————— laid in the rock strata. With this experimental set-up, a dynamic roof deformation of up to 15,500 me as well as development height of the caving and fissure zones in the roof can be characterized during the advancement of the working face. Recently, a PPP-BOTDA system was utilized in monitoring the internal movement of roof and floor strata under simulated mining activities for a two-seam coal mining physical model . A tight buffed sensing fibre with polyurethane jacket was installed in the vertical grooves in the model using gypsum concrete. The similarity test results showed that the strain distribution measurements from the sensing fibre was in good agreement with those obtained using photogrammetry method. The formation and development of characteristic tensile zone can be identified during different mining stages. Alternative ways to improve spatial resolution of strain sensing include using optical frequency domain techniques (OFDR). OFDRbased strain sensors are able to provide a spatial resolution in the order of centimeters. However, their sensing distance is generally less than 100 m . Very limited applications of geotechnical monitoring using OFDR have been reported. Lanticq et al. evaluated OFDR and BOTDR systems in detecting embedded cavity in railway tunnels. The results from the 1:1 scale laboratory experiment demonstrated better strain sensing performance of the OFDR system in determining the size of the embedded cavities. With a high spatial resolution of the system, 5 mm embedded cavities were detected.

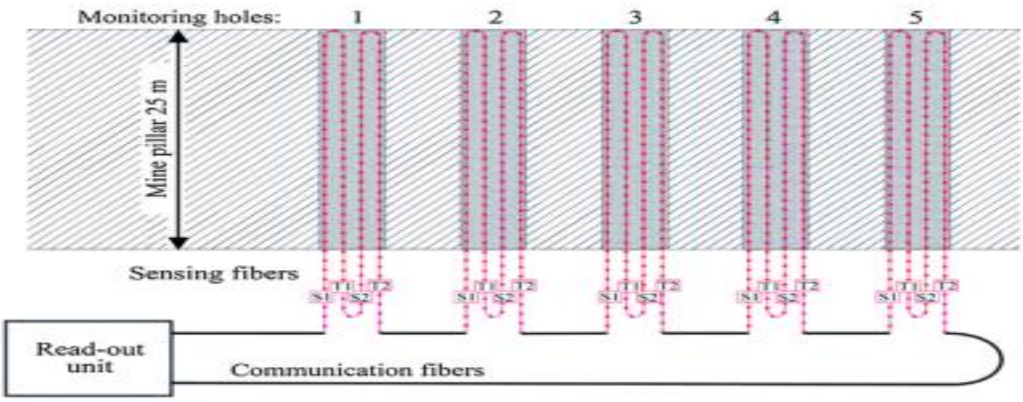

Fig. 10. BOTDA underground mine pillar monitoring system.

Forbes and Spearing reported a laboratory strain monitoring study along fully grouted rock bolts using a Rayleigh scattering
technique that provides spatial resolution of approximately 5mm . The standard telecom fibres are installed in diametrically opposed grooves in the rebar samples, replacing the conventional foil resistance strain gauges. Laboratory test results demonstrate that the measured strain profile along the grouted bolts agreed well with theoretical values under bending and axial pull loading, with less than 5% deviation. However, for a simple three-block shear test, the strain profiles were merely qualitatively similar to those predicted by theory and numerical modelling. By integrating the telecom-grade optical fibre to the geotechnical structure, a large number of highly sensitive and spatially resolved strain measurements can be obtained. Automated data acquisition and remote control can be realized, minimizing the underground personal exposure for data collection. However, several open questions still remain. First of all, the strain limit of fused-silica fibre used for long distance sensing is

approximately 3–5% [45], limiting its applications in macrostrain environment. Secondly, with a spatial resolution of 1 m, only the average strain along any 1 m segment along the fibre can be measured using conventional Brillouin sensors. This makes it unsuitable to characterize the strain distribution over small scale structure such as crack detection on concrete pile or underground coal mine roof separation monitoring where a local strain concentration is expected. PPP-BOTDA and Rayleigh scattering sensors are able to achieve a sub-cm spatial resolution, however, the maximum sensing range limits their applications in large scale structures.

Technical issues in the FOS instrumentation

Encapsulation techniques for optical sensing fibres

Although there are a number of strain sensing applications in which the bare FBG fibre is attached directly to the structure and covered by epoxy resin, extra care should be taken during installation because the bare fibres are fragile under excessive external loading and bending. In most cases, suitable encapsulation is required for the bare FBG fibre to survive the harsh installation and operating environment in the field. Fig. 15 includes some innovative FBG encapsulation techniques have been used to protect the bare fibres. demonstrated a metal slice based encapsulation FBG strain sensor, in which the bare FBG is glued to the mental base. Such sensors can be easily attached to the surface of metal or concrete bodies. Another common FBG encapsulation method is to enclose bare FBG fibre with a metal tube supported by anchorage holders. By mounting the encapsulated sensor on the structure surface, the FBGs effectively measure the average strain between adjacent anchorage holders. developed a long gauge FBG sensor designed for surface applications with large strain value. The FBGs are encapsulated in a steel tube with two fixing points that define the effective gauge length and can be used to monitor average strain between two mounting points on the structure surface. These encapsulated sensors need to be calibrated before use since the sensitivity of the bare FBG may be changed by the encapsulation materials. Improvement has been made by using fibre reinforced polymer as encapsulation material. Experimental results showed this method can lead to the same strain sensibility factor being achieved between FRP-FBG bar and the bare FBG, with the measurement precision of 1–2 me. In addition to the surface mounting methods, sensing fibres can also be integrated within a structure such as load bearing cables during the manufacturing process to monitor the material aging and stress

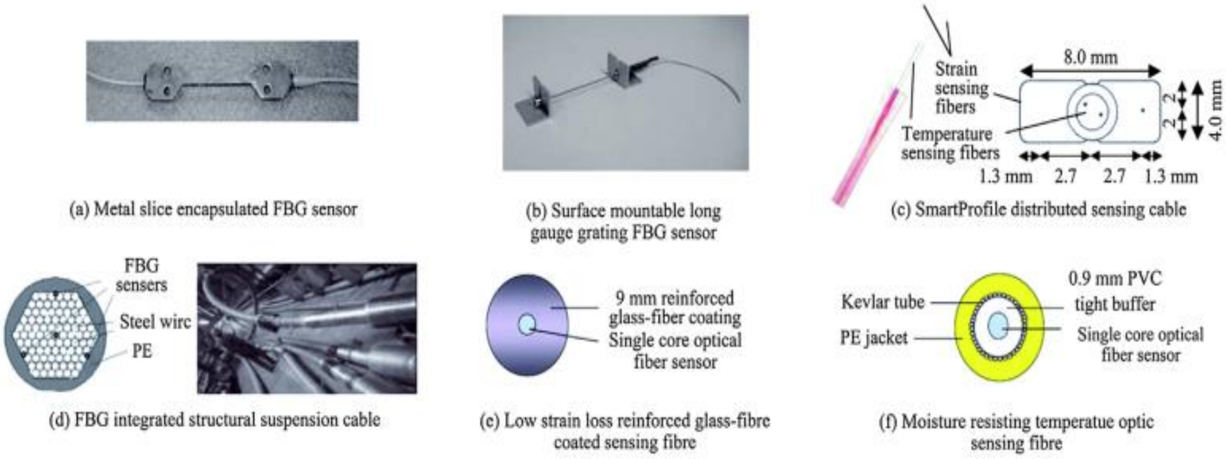

Fig. 15. Encapsulation techniques for optical strain sensing fibres: (a) Metal slice encapsulated FBG sensor; (b) Long gauge FBG sensor; (c) Smartprofile temperature compensated distributed strain

sensing fibre ; (d) FBG integrated structural cable ; (e, f) Customised distributed strain sensing fibre. distribution incorporated the FBG coaxially in a cylindrical silicone rubber tube. Such packaging makes it useful for sensing transverse loading characterized by the wavelength peak. Sham evaluated the impact of coating material of distributed optical fibre on the strain transfer loss for underground tunnel rock deformation . The author tested five different tight buffed optical cables in the laboratory setting under incremental load and the results showed that the sensing cable with a combination of PA protective outer coat, stainless steel metal tube and high bonding inner coat can achieve the highest long-term durability and strain transfer rate.

Cross-sensitivity between temperature and strain

Since both frequency shift in Brillouin scattering and wavelength shift in FBG systems are subject to strain-temperature cross-sensitivity, a number of researchers have presented a number of temperature compensation techniques for cases when only the pure mechanical strain is desired. Temperature compensation can be achieved with different instrumentation methods. One of the solutions is to use two closely spaced FBG arrays in the same fibre. were attached to the inner wall of the glass tube with epoxy and thus the strain induced elongation of G1 is negligible, while FBG G2 responded to both temperature and strain. For this technique, as the two FBGs share the same optical spectrum, the nominated Fig. 17 presented a roadside slope monitoring system using structural soldier pile and two independent FBG arrays. The FBG strain array is glued directly to the beam while the FBG strain free temperature array is firstly packaged in steel tube and then glued paralleled to the strain array. Similar instrumentation methods were reported in measuring the far end bending deformation of a cantilever beam. Since this technique utilizes separate channels for temperature compensation, it is ideal for strain sensing system with more FBGs required in each fibre. Another innovative solution for temperature compensation is to
combine an FBG with an LPG. With a longer period gratings written on the fibre during the manufacturing process, LPG sensors are more sensitive to temperature compared to FBG. By using this feature, the pure strain measurement on the FBG can be derived using the large difference in temperature responses between LPG and FBG . In a BOTDA based rock monitoring system in an underground metalliferous mine, a multi-fibre optic cable was used to provide temperature compensated distributed strain within 25 m long mine pillars. The sensing cable consists of two bonded and two free single-mode optical fibres embedded in a polyethylene thermoplastic jacket. The bonded fibres were used for strain monitoring while the other two were isolated from external strain for temperature measurements.

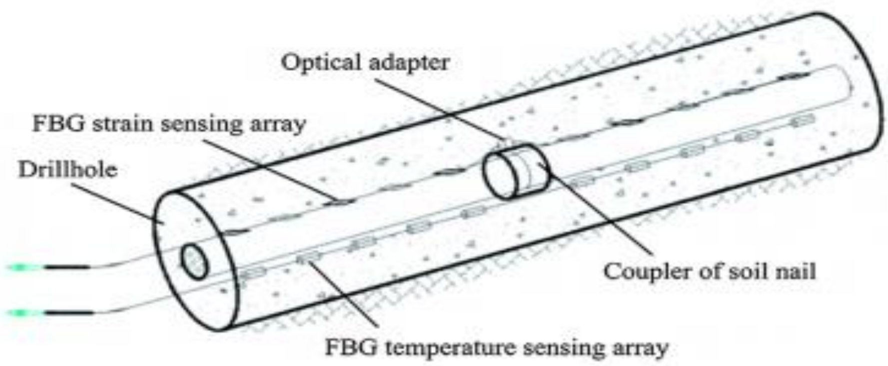

Fig. 17. Temperature compensated strain sensor using two FBG array.

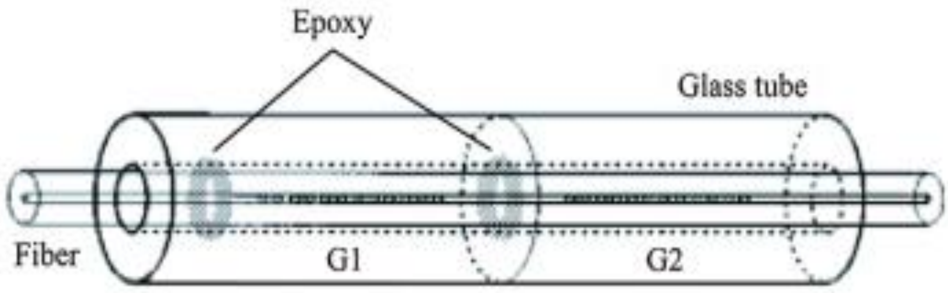

Fig. 16. Temperature compensated strain sensor using one FBG array

Conclusions

This paper presented the advances in underground geotechnical monitoring technologies, particularly fibre optic sensing (FOS) systems and their applications. Limitations of conventional mechanical and electrical sensors were discussed including the lack of real time data acquisition, measurement inaccuracy due to electromagnetic interference, and limited number of sensing points required for large-scale underground infrastructures. In order to address these issues, various laboratory and field studies using FOS techniques have been undertaken to investigate their suitability and reliability in monitoring underground rock mass deformations. An FOS system can be directly installed on the rock surface to monitor the surface convergence, embedded in the rock mass to obtain internal strain profile, or developed into a smart sensor head for large strain applications such as monitoring of roof separation in underground coal mines. Three dimensional rock movements can be interpolated from FOS strain measurements and geometric algorithms. FOS systems have demonstrated many advantages over the conventional sensors in providing reliable, real time and distributed measurements, however, there are still some major concerns in relation to their wider applications. These include: (a) the limited strain measurement range due to the low strain limit of the widely used silica fibres; (b) lack of standardized packaging techniques resulting in varied calibration factors for different sensors; (c) compromise between spatial resolution and sensing distance for distributed FOS systems and; (d) the strain transfer loss due to the interactions among the rock-grout-fibre system. Future studies should focus on the development of FOS smart sensor heads, which would be capable of providing distributed measurements in large strain environments, optimisation of fibre encapsulation and installation procedure to achieve better compliance among the rock-grout-fibre system and improving the interrogation technique for distributed sensing systems for higher spatial resolution. In addition, the development of FOS systems with wireless remote data retrieval technology should be pursued for large scale underground structures.

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