Towards Long-Term Monitoring of the Structural Health of Deep Rock Tunnels with Remote Sensing Techniques

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ABSTRACT. Due to the substantial need to continuously ensure safe excavations and sustainable operation of deep engineering structures, structural health monitoring based on remote sensing techniques has become a prominent research topic in this field. Indeed, throughout their lifetime, deep tunnels are usually exposed to many complex situations which inevitably affect their structural health. Therefore, appropriate and effective monitoring systems are required to provide real-time information that can be used as a true basis for efficient and timely decision-making. Since sensors are at the heart of any monitoring system, their selection and conception for deep rock tunnels necessitates special attention. This work identifies and describes relevant structural health problems of deep rock tunnels and the applicability of sensors employed in monitoring systems, based on in-depth searches performed on pertinent research. The outcomes and challenges of monitoring are discussed as well. Results show that over time, deep rock tunnels suffer several typical structural diseases namely degradation of the excavation damaged areas, corrosion of rock bolts and cable bolts, cracks, fractures and strains in secondary lining, groundwater leaks in secondary lining, convergence deformation and damage provoked by the triggering of fires. Various types of remote sensors are deployed to monitor such diseases. For deep rock tunnels, it is suggested to adopt comprehensive monitoring systems with adaptive and robust sensors for their reliable and long-lasting performance.

KEYWORDS. Deep Rock Tunnels, Structural Health Monitoring, Remote Sensors, Long-Term Monitoring, Long-Term Structural Integrity of Tunnels.

INTRODUCTION

Nowadays, deep tunnels are increasingly necessary in any developed society as they can perform multiple key functions such as water supply, irrigation, sanitary drainage, mining, transportation, nuclear waste disposal, and so on. However, as gigantic engineering structures, their erection is usually costly and always accompanied by considerable risks. Such risks habitually lead to major problems that affect the structural health of the tunnels. In fact, during their excavation and throughout their lifetime, deep tunnels are generally confronted with several health problems namely, damage, cracks, fractures, rockbursts, groundwater leaks, convergence deformation, etc. When they are not detected and treated within a reasonable timeframe, these health issues evolve and become significant over time, seriously impairing the structural integrity and stability of the tunnels. While these are typically expected to operate for over a hundred years, it is therefore essential to properly monitor their structural health so that they are safely operational as intended. One of the aims of structural health monitoring is to control any deterioration detected by any change in structural response [1]. More specifically, monitoring the condition of structures refers to the implementation of appropriate strategies aiming at supervising the relevant parameters which are most often mechanical, physico-chemical or environmental. Indeed, to deal with frequent unforeseen events in underground tunnels, monitoring has been applied since Peck [2] and Terzaghi [3] have implemented observation methods. For ensuring safety during tunnelling, these methods are always strongly required [4]. As stated by Powderham [5], it is possible to adapt design during construction and help manage risks through the application of such methods. For deep tunnels which mostly experience variations in geotechnical sections and groundwater conditions as well as unpredictable geology [6], also heavily stressed supports and large convergences [7], the observations that are linked to monitoring techniques, are the only way to guarantee the safety and stability of these structures over a given period. In deep rock engineering, continuous monitoring is mandatory to effectively ensure safe functioning at all times [8]. In general, ongoing monitoring is essential for the efficient long-term management and exploitation of any underground tunnel. Its indispensability is all the more pronounced as the burial depth of tunnels is increasingly important. Changes in high in-situ stresses, high temperatures, high groundwater pressures and flows are generally common throughout the life of deep rock tunnels. Consequently, ensuring their continuous safety and stability remains a major challenge and cannot be done without adequate and efficient monitoring systems. The latter must be able to provide the real state of health of the tunnels, in order to adopt effective and real-time relevant decisions. As conventional methods are not always suitable for these purposes [9, 10, 11], more adequate and accurate techniques are therefore deeply imposed. One cannot ignore the relevance played by reliable techniques in the monitoring of tunnels [12, 13], since these structures are generally located in difficult environments with presence of dangerous substances, wetness, absence of natural light, etc. It is essential to choose or design the most appropriate monitoring systems with respect to rock characteristics and excavation conditions to obtain accurate monitoring data in order to make adequate decisions in a timely manner. This is because that integrity and serviceability of deep tunnels are relevant and should always be assessed by long-term structural health monitoring.

According to the literature, various sensors have been designed with the aim of obtaining more and more efficient results in monitoring the structural health of underground tunnels. For instance, in order to control the long-term stability of the Bai Ni-jin No. 3 tunnel of China, Li et al. [14] have developed a FBG enclosed in a metal groove that monitors the second lining. Thanks to the data obtained from the monitoring system, they argued that the stability of the mentioned tunnel was maintained. Based on a laboratory simulation, Xu et al. [15] showed that distributed fiber optic sensors can well illustrate the dynamic deformation and distribution of surrounding rocks of deep mine tunnels. By conducting experimental survey and full-scale test in moderately seismic areas, Bursi et al. [16] revealed that considerable nonlinear strains on tunnel lining can be depicted by FBG sensors. However, to exhibit high performance, such sensors monitoring nonlinear deformation should be unbonded [16]. By performing a security monitoring on structural loads into highway tunnels in Žilina, Slovakia, Fajkus et al. [17] explained that thanks to the installed temperature sensors into the primary lining, the detected changes in the Brillouin frequency are assumed to originate from the combined effects of the concrete lining shrinkage and the temperature change of the tunnel systems. Madjdabadi et al. [18] experimentally demonstrated that large strains in tunnels can be potentially and continuously monitored using distributed Brillouin detection systems combined with fiber optic sensors. In order to predict rock bolt failure in a deep roadway located at the Zhangji Coal Mine, Anhui Province, China, Tang et al. [19] used four instrumented rock bolts (equipped with FBG sensors) capable of monitoring the stress distribution along the rock bolts. In a deep tunnel of the Jinchuan No. 2 mine, Gansu province, China, 3D laser scanning was utilized to monitor large convergence deformations where the results were served to design adequate support systems capable of limiting the convergence rate to an admissible value [20]. For their part, Li et al. [21] combined strain gauges and FBG sensors to monitor the stability of surrounding rocks in a bifurcated tunnel in Enshi City, Hubei Province, China, and found that accurate measurements were made. To improve the monitoring of transverse strain in shielded tunnels, an optical-

electric co-sensing tape (OECST) has been proposed by Jiao and Zhou [22] as a hybrid sensor. According to them, such a sensor incorporates distributed fiber optic sensors (DFOS) equipped with coaxial cable Fabry-Perot interferometric sensors (CCFPI) in a polyurethane tape having high elasticity. However, DFOS can accurately measure small strains, and CCFPI large strains with low accuracy [22]. To adequately monitor the water inrush in the Yuelongmen tunnel, Wang et al. [23] proposed vibrating wire sensors which are mainly composed of seepage pressure gauges, single-point displacement gauges and rock stress gauges. Taking the Kaiyuan tunnel in Jinan, Shandong Province, China, as engineering object, Lin et al. [24] demonstrated that ground penetrating radar (GPR) can be widely employed in detecting deficiency of tunnel lining structures. However, GPR imaging are more interesting to be interpreted and analyzed if the tunnel linings are free of rebars [25]. In this sense, with the aim to better identify voids in tunnel lining from imaging provided by GPR, Wang et al. [25] have recently developed a generative adversarial network based on elimination of clutters from rebars. These examples can illustrate that remote sensing techniques are widely developed in tunnel engineering and are essential to provide real-time monitoring in this field. At the same time, it is observed that underground structures are placed deeper and deeper where the geological conditions are increasingly complex. Therefore, continuous consideration of the monitoring techniques is of tremendous importance to improve their performance in deep rocky environments.

The intention of this article is to comprehensively describe typical structural health issues of deep rock tunnels and to present an overview of the monitoring carried out by remote sensing techniques. Moreover, the great importance of the use of these techniques in this field is shown. Importantly, the article may contribute to a better understanding of deep tunnel structural diseases and the great need to adopt robust monitoring systems to ensure reasonable structural integrity at all times. Furthermore, the article highlights the appropriate use of remote sensing techniques in deep rock engineering as well as the development of new monitoring strategies aiming at improving monitoring efficiency. Owing to the complex conditions that generally face deep rock engineering, it is important to mention that deep tunnels behave differently than shallow tunnels. To this end, a comprehensive presentation of the remote sensing techniques employed in deep tunnels can provide sources of motivation to design or develop newest strategies that can improve the monitoring conditions of these structures. In fact, to our knowledge, there has not been a study that focuses on a comprehensive overview related to monitoring the structural health of deep rock tunnels. Therefore, this study is of tremendous consideration.

METHODS AND MATERIALS

An extensive search was performed on trusted web platforms (publishers and search engines) based on the guidelines offered by Okoli and Schabram [26] and Machi and McEvoy [27]. Thus, a relevant analysis of articles published in various scientific journals was carried out. The entire methodology adopted for this study is illustrated in Fig. 1.
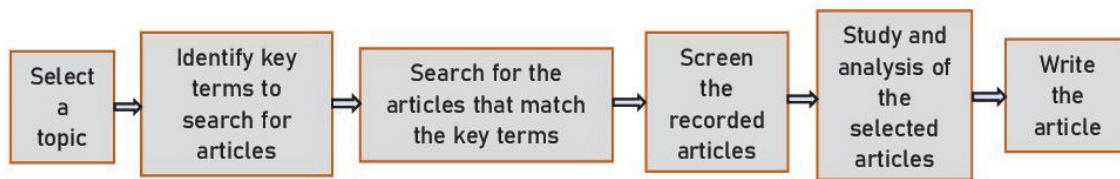

Figure 1: Workflow of the research

During the search, a list of several keywords (deep rock tunnel structural diseases, deep rock tunnel structural health monitoring, deep tunnel remote sensor applications, deep tunnel monitoring support systems, long-term structural integrity of deep tunnels) was used. After identifying many works, these are recorded. A categorization of the articles was made in accordance with their fields. Thereby, the retained articles are those which match the fields of this study. Subsequently, for each retained article, a scan was minutely effectuated taking into consideration the abstracts and the main topics. For guaranteeing an adequate selection by keeping in mind the concerned research topic, the articles have been scrupulously examined. The final selection contains only the works corresponding to the overall objective of this study. To elaborate this article, on the papers finally retained, thorough analyzes are conducted. It should be noted that it is very difficult to report on all the existing articles related to the field of this study. Nevertheless, the satisfaction with the results is reflected in the considerable number of articles that are retained in the final selection.

STRUCTURAL HEALTH MONITORING OF DEEP ROCK TUNNELS

Structural health monitoring (SHM) is a vital task that is required to effectively control the safety and stability of deep tunnels at all times. Through its ability to provide information on the actual conditions of structures, the SHM is crucial in decision-making concerning the continued operationalization of structures [28]. In fact, it is recognized that constructions in the underground spaces are the most perilous constructions [29], and the dangerousness is increasingly high as the burial depth of the structures increases. As reported by Li et al. [30], three systems constitute the main components of the common SHM namely, sensors, data processor and health evaluator. The SHM makes it possible to analyze and judge the state of health of the structures thanks to the signals obtained from sensors in real time [31]. While excavating, it is crucial to ensure the safety and stability of tunnel face. Then, as the digging progresses, the safety and stability of any section of tunnels is required in order to avoid any early failure and to protect human lives and economic expenses. Furthermore, tunnels are required to be operated safely throughout their lifetime. However, capacity loss and premature tunnel failures can be triggered due to crack growth resulting from several harmful effects of technical disruptions, environmental erosions and unexpected earthquakes [32]. Ageing is also a pertinent factor which can suddenly cause partial or total failure of the tunnels. In fact, the structure of tunnels inevitably deteriorates over time due to several health problems. Markedly, in their early stages, most of the health problems cannot be detected by simple visual inspections, especially for deep rock tunnels. Whereas, when left undetected in real time, such health issues can develop and seriously attack the structural integrity and stability of tunnels. In such situations, the vulnerability of tunnels to premature failures is a major concern. Consequently, there is still an urgent need to adequately monitor the structural health of tunnels to prevent early failure that may be caused by critical health issues. For instance, when cracks are in their severe states, they usually lead to the failure of structures [33]. Therefore, continuous and effective monitoring of the structural conditions is of primary importance to ensure the safety and stability of tunnels in real time, particularly at great depths where the surrounding rocks generally exhibit complex behavior. For example, due to the triggering of rockbursts which are frequent and very detrimental to the structure of deep hard rock tunnels, adequate sensors must be properly installed to monitor the associated microseismic events [34]. In addition, as unexpected groundwater inflows are common at great depths and greatly affect human life and rock properties [35], they should be carefully monitored [23]. Monitoring data processing helps to make appropriate decisions based on tunnel structure conditions. For real-time decisions, it is imperative to opt for real-time monitoring. As stated by Stajano et al. [9], real-time maintenance is needed to prevent the tunnels from collapsing, which is the worst case. Indeed, to maintain the long-term performance of tunnels, the assessment of their structural health is essential [38], which requires long-term monitoring throughout their lifetime [34, 37].

Conventionally, the monitoring of tunnels can be made by using different equipment such as extensometers, instrumented rock bolts, convergence stations, etc. However, remote sensing techniques allow real-time monitoring [36], and they are more suitable for harsh and often perilous environments [39]. Remote sensors can be categorized into wired and wireless sensors. Regardless of their category, sensors have to provide appropriate capability in accordance with the roles of the structures and also provide clear information [40]. Fiber optic sensors are among the widely employed sensors in tunnel engineering. From the point of view of their detection mode, they can be distributed, quasi-distributed or extrinsic and intrinsic. When the sensing points are continuous, they are distributed, quasi-distributed sensors, and otherwise there are extrinsic and intrinsic. Fiber Bragg Grating (FBG), Fabry-Perot, Rayleigh Optical Time Domain Reflectrometer (ROTDR), Rayleigh Optical Frequency Domain Reflectrometer (ROFDR), Brillouin Optical Time Domain Analysis (BOTDA), and Raman are the most fiber optic sensors used in underground engineering. They usually monitor strain and temperature. An exception is made for the Raman-based sensor which can mostly monitor temperature [41, 42]. Additionally, acoustic waves and mechanical vibration can be detected by Fabry-Perot sensors; and parameters such as pressures and humidity can be monitored by Distributed Brillouin Optical sensors [42]. Note that FBG is largely utilized, among the fiber optic sensors that monitor strain and temperature, in structural health monitoring for civil engineering structures, as reported by Bhaskar et al. [43]. Tab. 1 shows pertinent information on fiber optic sensors mainly utilized on underground engineering.

In fact, referring to Gong et al. [38], the parameters showed in Table 1 can be programmed to assess other parameters such as displacement, pressure, vibration, acceleration and acoustic; Range refers to sensing distance; By increasing the sensing distance, the accuracy degrades. It is extremely important to prevent any degradation in the accuracy of the detection capability of the sensors. The more accurate the sensing capability, the more accurately data can be collected and the more robust structural health monitoring can be. Note that the overall vigor of any structural health monitoring largely depends on the data collected from the installed sensors [44]. Accordingly, the arrangement of sensors is required to be optimized for effective monitoring [45]. The optimal arrangement of sensors is paramount to obtain more accurate monitoring data,

which is necessary for better processing and better decision making. Adequate SHMs are essential in decision making related to tunnel situations or treatments. Fig. 2 shows specific objectives of SHM applied to tunnel engineering.

Sensors	Sensing method	Main parameters or Measurement	Resolution (Accuracy)	Range	Modulation method
Fabry-Perot	Point	Strain / Temperature	0.01% gauge length	$10,000\ \mu\varepsilon$	Phase
FBG	Quasi-distributed	Strain / Temperature	$1-2\ \mu\varepsilon$ / $0.1℃$	$5000\ \mu\varepsilon$	Wavelength
Rayleigh (OTDR)	Distributed	Strain / Temperature	$1m$ / $1℃$	$2000\ m$	Intensity
Rayleigh (OFDR)	Distributed	Strain / Temperature	$1cm$ / $0.1℃$	$100\ m$	Frequency
Brillouin (BOTDA)	Distributed	Strain / Temperature	$0.1\ m$ / $0.3℃$	$1000\ m$	Frequency
Raman	Distributed	Temperature	$1℃$	$8000\ m$	Intensity

Table 1: Pertinent information on fiber optic sensors in underground engineering (after Gong et al. [38], with permission from Elsevier).
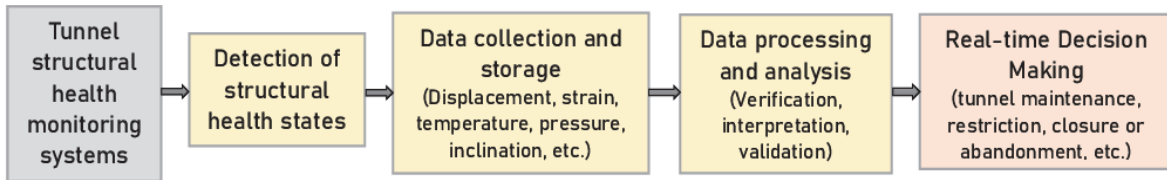

Figure 2: Relevance of tunnel structural health monitoring

Real-time decision making depends also on the reliability of the sensors used in SHM systems. Likewise, the type of decision is tributary of the severity extent of the health problems detected. In all situations, real-time decision making is essential for safety and economy. One the one hand, if decision outcome is favorable for maintenance, costs can be reduced by acting in real time. Besides, if tunnel traffic needs to be temporarily restricted, life and economy can be saved by avoiding unexpected accidents. On the other hand, if in the worst case, the tunnels have to be permanently closed, life and economy can also be saved by avoiding huge unforeseen accidents. In any case, real-time decisions are of paramount importance and can be made efficiently by adequate SHMs. For deep tunnels, comprehensive structural health monitoring leads to the monitoring of different parts of the tunnel structures with the aim of persistently monitoring their most critical health issues. Fig. 3 shows the critical components or aspects of tunnel structures where proper monitoring techniques are required (EDZ stands for Excavation Damaged Zones).
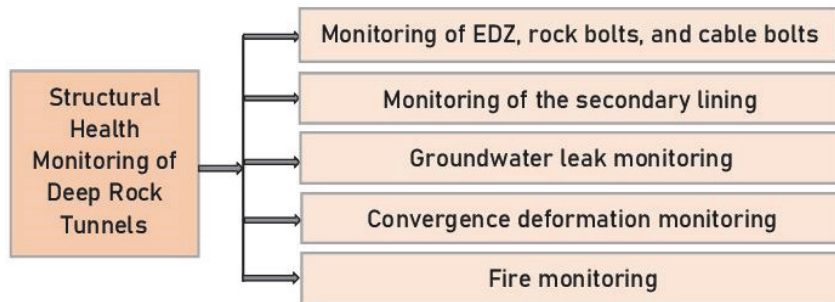

Figure 3: Structural health monitoring approach in deep rock tunnels

The monitoring data must be processed and interpreted adequately. Data interpretation play a key role in the establishment and adoption of maintenance plans. Therefore, the response from the sensors should be clearly detailed without any interference that could clog them. Representations of the structural disease detected in a given tunnel should be as accurate

as possible. Lighting variations and the presence of artifacts should be avoided in the images obtained from any monitored part of the tunnels [46].

Excavation Damaged Zones (EDZ), rock bolts and cable bolts: their need for monitoring

Once rocks are excavated around the tunnels, deformations start within minutes and can be significant over time. Such deformations are primarily the consequences of the inevitable formation of disturbed and damaged zones in the surrounding rock of tunnels. In particular in the excavation damaged zones (EDZ), pertinent rock properties are deeply and permanently degenerated [47, 48, 49]. Fig. 4 illustrates the typical position of the EDZ in a given tunnel. At great depth where strong in-situ stresses generally exist, EDZ evolves over time in any type of rocks. Especially in articulated rocks, the expansion of the EDZ can be composed of three stages (Fig. 5), namely acceleration, stabilization and acceleration stages [50]. In fact, as stated by Song et al. [48], the stability of underground structures is threaten by the evolution of EDZ which jeopardizes the support systems. In deep underground openings, the design of support systems can be optimized by accurate predictions of the extent of the EDZ [47]. However, it remains urgent to properly monitor the EDZ in order to control its development and make real-time decisions to protect the integrity of the support systems and the stability of the tunnels. To ensure stable conditions of the tunnel support systems, the extent of the EDZ must be kept in the stabilization phase for as long as possible. Indeed, in the acceleration stage of the EDZ, the tunnel support systems can be inefficient to withstand the rapid evolution of the strain rates. As such, the stability of tunnels can be seriously compromised and can lead to unforeseen partial or total failure. Although EDZ can be characterized by different techniques such as GPR, acoustic emission, microseismic monitoring system, borehole televiewer, borehole radar, and so on [51], continuous monitoring is highly required to control on real-time its health condition. For instance, in order to monitor the EDZ in a coal mine roadway, a bolt-based Fiber Bragg Grating (FBG) stress sensor which is able to capture the deformation of the EDZ and that of the undisturbed rocks, has been developed by Wan et al. [52]. Their monitoring results indicate that the stress change in the EDZ can be measured using the FBG sensors and, therefore, the stability of the mining tunnels can be well predicted. Fig. 6 shows a sketch of the monitoring situation provided by the bolt-based FBG sensor to monitor the health status of the EDZ.
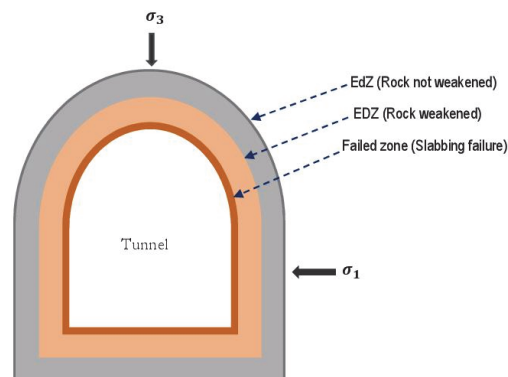

Figure 4: Typical position of the EDZ in a deep tunnel subjected to common principal stresses σ_1 and σ_3.
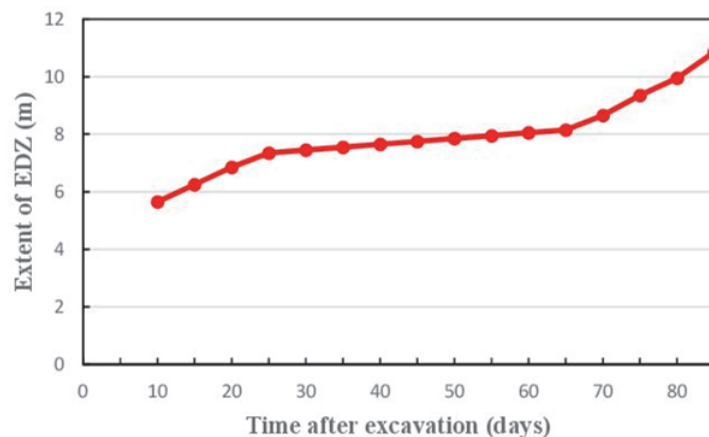

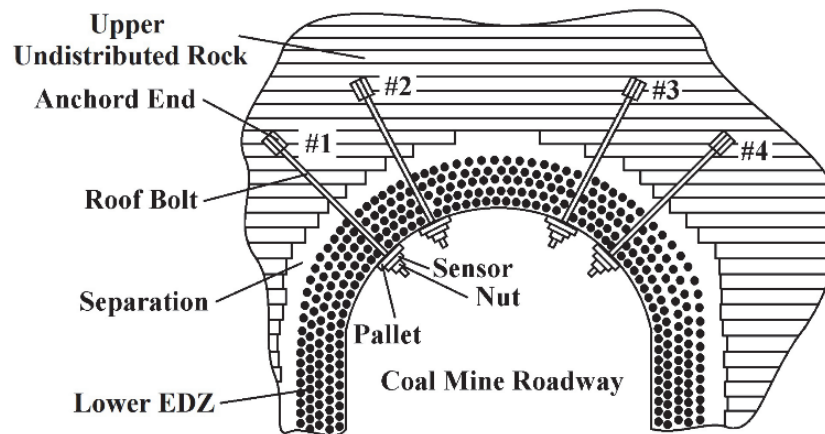Figure 5: Typical evolution of EDZ in deep articulated rocks

Figure 6: Sketch of the monitoring situation provided by the bolt-based FBG sensor to monitor the health status of the EDZ in mine roadway (adapted from Wan et al. [52])

The health status of rock bolts and cable bolts should also be conveniently monitored in deep rocky environments. In fact, rock bolts are essential to compensate for the weakened properties of the host rocks and to ensure the stability of the underground openings [53]. In severe rock conditions, cable bolts are installed to reinforce the rock bolts. Rocks and rock bolts are generally expected to behave like new materials where properties are sufficiently improved. Cement or resin grouting is habitually employed to install rock bolts [54, 55, 56], because the stability of the surrounding rocks largely depends on the durable performance of rock bolts in deep tunnels. Rock bolts are vital components of the tunnel structures and therefore should be sustainable [57]. Nevertheless, at great depth, various nocuous conditions generally affect the integrity and long-term performance of rock bolts. For example, after having exercised their function for a certain time, rock bolts and cable bolts may lose strength and fail prematurely. In addition, they can be attacked by corrosion, especially at great depths where groundwater can seep into the interstices of the surrounding rocks. Corrosion is frequent for all types of rock bolts [58], but it can be more severe for rock bolts and cable bolts made of steel. Therefore, health problems due to corrosion are common. As an electrochemical process which develops in slow manner [59], corrosion significantly affects the performance and service life of the aforesaid supports [60]. Moreover, losing strength is prevalent for any type of rock bolts and cable bolts after a certain time. Consequently, even for rock bolts capable of exhibiting significant corrosion resistance, their continuous monitoring is essential. It should be noted that depending on groundwater characteristics (temperature, flow rate, composition, pH, and so forth), the corrosion rate can be slow or rapid in rock bolts. In deep rock tunnels, the monitoring of rock bolts is strongly justified not only to control corrosion problem, but also to assess the strains which can be varied owing to load variation. Furthermore, especially for grouted rock bolts, the anchorage strength should also be properly assessed as it is greatly affected by the grout quality and the degree of delamination at the interface bolt-grout. For this purpose, it is also essential to monitor the grout quality and the degree of delamination between rock bolt and grout to ensure the stability of rock bolts.

Remote sensing techniques are widely utilized to monitor the state and conditions of rock bolts in tunnels. Nonetheless, it is critical to select or design the most suitable remote sensors that can accurately track rock bolt health status in real time. For example, most FBG sensors are not suitable for monitoring strain in rock bolts made of steel. Indeed, these sensors can generally deform up to 1%, while steel rock bolts can be elongated up to 20% in underground engineering [61]. In fact, Liu et al. [62] have previously demonstrated that FBG sensors can be installed in rock bolt heads to monitor the dynamic strains around underground excavations. According to them, very small strains of the order of 10^{-9} in rock bolt can be measured by the variation of the intensity supplied by the optical signal at a frequency of 1.7 kHz. Tab. 2 presents relevant information on existing sensors used to monitor rock bolt health in deep rock engineering.

In Table 2, the measurement performed can be classified as direct and indirect. It is considered direct when the sensors are directly connected to the rock bolts to be monitored. For example, FBGs are generally directly installed in instrumented rock bolts. In other situations, that is when the sensors are not directly connected to the rock bolts, the measurement is considered indirect. This last situation mainly occurs when the sensors are coated. Fig. 7 shows an instrumented rock bolts where fiber optic sensors are directly installed.

Study	Rock bolt type	Sensor	Sensor capability	Measurement type	Accuracy-Range	Monitoring outcomes
Stepinski [56]	Non-grouted and grouted rock bolts	Ultrasonic guided waves	Inspect the integrity of rock bolt using RBT	Direct	0.1 MHtz	By energy leakage at the interfaces rock and grout, guided waves are greatly reduced in grouted rock bolts. The effectiveness of guided waves relies on the low frequency mode.
Tang et al. [19]	Slotted and grouted rock bolt	FBG-Based Instrumented Rock Bolt and FBG temperature sensors	Detect the early failure of rock bolts	Direct	0 – 100 kN	The premature failure of the rock bolts can be alerted thanks to the evolution of the distribution of the axial forces along the bolts.
Vlachopoulos et al. [53]	Fully grouted rock bolts	DOS	Monitor the continuous strain profile of the rock bolts	Direct	1 Htz	Strain profiles are irregular and decrease from the borehole collar to the end of the embedded section of the rock bolts.
Huo et al. [63]	Grouted rock bolt	PZT	Monitor rock bolt pre-load based on ultrasonic transducers	Direct	54 – 0 MPa	Especially before saturation, the magnitude of the relevant signal decreases with the reduction of the preload in the bolt.
Forbes et al. [55]	Fully grouted rock bolts	ROFDR	Evaluate the distributed strain profile in the rock bolts subjected to shear at millimeter scale.	Direct	No data	The strain profile consists of coaxial and bending strains. A limit of 120 mm from the plane of continuity should be considered for nearly 90% of the shear-induced strain.
Wei et al. [59]	Grouted rock bolt	FOMI	Assess corrosion-induced strain in rock bolts	Direct and indirect	No data	Within the framework of accelerated tests, quasi- uniform strain evolutions were detected.
Buys et al. [64]	Grouted rock bolt	Ultrasonic guided waves	Assess the grout quality into rock bolts	Direct and indirect	No data	Minor echoes in the energy dissipation in the rock indicate that the quality of the grout is good.
He et al. [65]	Grouted rock bolt	Ultrasonic guided waves	Assess the degree of delamination at the rock bolt-grout interfaces.	Indirect	0.97 – 1.17 MHtz	The increase in wave amplitudes indicates the increase in the percentage of delamination in the rock bolts.

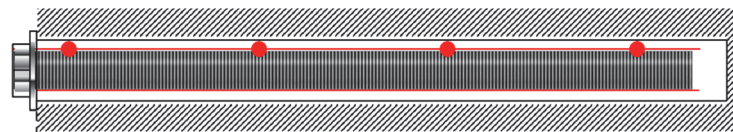Table 2: Monitoring of rock bolts with diverse sensors.

Figure 7: Illustration of direct installation and direct measurement of FBG in an instrumented rock bolts: red point traduces FBG sensors; red line is optical fiber

It is crucial to properly monitor the excavation damaged and the rock bolts/cable bolts to ensure the long-term stability of deep rock tunnels. In fact, one factor affecting the durability of rock bolts is the bolt length which should be sufficient and exceed the plastic zone of deep rock tunnels [57]. The plastic zone can generally be thought of as the EDZ [66]. For circular

tunnels, the radius of the plastic zone is generally calculated on the basis of support conditions, crustal stress and mechanical properties of rocks as follows [67]:

$$R_p = R_0 \left[\frac{(P - c \times cotg\varphi)(1 - sin\varphi)}{P_i + c \times cotg\varphi} \right]^{\frac{1-sin\varphi}{2sin\varphi}} \tag{1}$$

where R_p is the plastic radius; R_0 is tunnel radius; P: original stress of rocks; c: cohesion factor; φ: angle of internal friction; P_i: resistance of the support.

Ordinarily, the evaluation of plastic zone radius is extremely important in design of rock bolts and cable bolts in deep rock engineering. However, as times passes, the extent of the plastic zone or EDZ is increased over time, as already shown in Fig. 5. One reason that can explain such evolution is that parameters such as rock stresses can be augmented over time. It is crucial to adequately monitor the EDZ in order to take timely decision preventing its expansion. In fact, the worst case which could consist in large scope of EDZ to the point to overtake the limit of the support length should be strongly avoided in order to maintain reasonable structural integrity and ensure long-term stability of deep tunnels.

Secondary lining and its necessity for monitoring

In addition to the primary support generally formed by rock bolts, cable bolts, shotcrete and steel arch, the secondary lining is also a key component of the tunnel support structures. The secondary lining plays the role of structural corrector and waterproofing structures. Its exposure conditions can generally vary from medium to high at great depths where the rocks surrounding the tunnels mostly suffer complex conditions. The secondary lining is generally the superficial part of the tunnel structures (Fig. 8). It is mostly made in concrete. With regard to the stability of tunnels, it is a fundamental factor [14], as its conditions may also reflect the conditions of the primary supports. Due to different exposure conditions, the mechanical properties of the secondary lining typically degrade over time [68], in addition to coping with the time-dependent behavior of its own material and that of tunnel face advance [69]. It should be noted that the integrity of the secondary lining mainly depends on the resistance of the primary lining which directly secure the surrounding rocks. Indeed, the stronger the primary lining, the safer the integrity of the secondary lining. In the Minxian tunnel (northwest China), for example, as reported by Wang et al. [70], the strength of the primary support was the main cause of cracking of the secondary lining. In complex rock masses, suitable sensors are even necessary between the primary and secondary linings to monitor the pressures exerted inside them. Indeed, particularly in deep tunnels where mainly large deformations occur, the contact pressure between these supports has to be carefully monitored [71]. As an example, to monitor pressures between the two linings in the Minxian tunnel, pressure sensors have been installed [70].
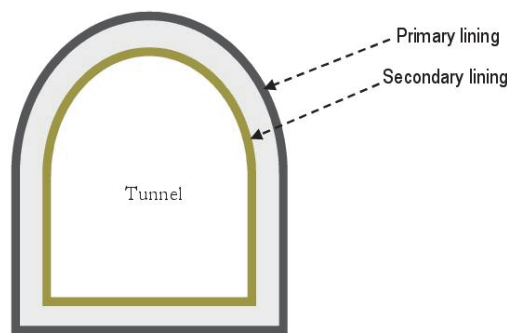

Figure 8: General position of the secondary tunnel lining.

The initial health problem of secondary tunnel linings is mainly cracks. In fact, they are generally signs of damage and also proofs of changes of existing stress [39, 72-74]. According to Farrar and Worden [75], failure usually occurs due to the critical evolution of damage that can cause partial or total loss of capacity of a given system. It should be noted that the severity of the damage can be related to the depth and the operating age of the tunnels. In fact, the deeper and older the tunnel, the greater the extent of its damage [76]. Thereby, adequate control of damage evolution is a mandatory and difficult task that re-quire thorough attentions. Importantly, in their early stage, some cracks cannot be detected by simple visual inspections. Unexpected failures of the secondary tunnel lining automatically lead to considerable human and economic

losses. In order to better control critical damage in the Kaidagu tunnel project (China), a monitoring program was operated by distributed fiber optic sensors installed in the damaged lining [77]. After nearly a year of monitoring, the distributed deformations recorded by the fiber optic sensors have made it possible to highlight the vertical and oblique ovalizations of the tunnel lining [77]. Fig. 9 illustrates the installation of fiber optic sensors in the Kaidagu tunnel lining.

Figure 9: A view of fiber optic sensors installed in the Kaidagu tunnel lining (after Sui et al. [77], with permission from Elsevier).

Study	Study case	Location	Sensor	Sensor Capability	Accuracy-Range	Tunnel operating age when monitoring assessment	Monitoring Results
Liu et al. [78]	Lianchengshan Tunnel	China	Vibrating wire sensors, surface strain gauges, concrete strain gauges, pressure cells	Identification and collection of monitoring information, control the structural stress in tunnel.	No data	30 years	Tendency of support pressure transfer from the primary to secondary lining. Unstable structural stress.
Puntu et al. [79]	Tunnels in South-link Line Railway of Taiwan	China	VMGPR system	Detection of lining conditions in tunnels: thickness of first and second lining, boundary between the linings, identification of void layer and Rebar.	1000 MHz	20 years	Decreased secondary lining thickness by 19.39% in one tunnel, and in the others it is between 0 and 1.71%.
Wang et al. [70]	Minxian Tunnel	China	Pressure sensors	Evaluation of the contact pressure between surrounding rocks, primary and secondary linings.	0.01MPa - 5 MPa	> 3 months	The bearing capacity of the tunnel can withstand the contact pressure between surrounding rocks, supports and linings
Gue et al. [80]	Royal Mail Tunnel	United Kingdom	BOTDR system, and LPDT	Measurement of strains in lining in bending mode, Measurement of shear strain amount in linings and its joints	$\pm 30\,\mu\varepsilon$ (BOTDR)	97 years	Peak bending strains detected, the linings underwent rotation, and then significant compressive strains. Peak shear strains measured

Table 3: A summary of common sensors used in primary and secondary tunnel lining monitoring

Continuous effective monitoring of the linings is essential to ensure safe operation throughout the lifetime of the tunnels. Indeed, the selection or the design of any remote sensing technique should be the most suitable or optimal in order to properly satisfy the monitoring objectives. The most common sensors utilized in the monitoring of the primary and secondary lining of tunnels are presented in Tab. 3.

Monitoring results are related to the effectiveness of the monitoring system and also to the period over which the monitoring data is processed and interpreted. As already stated, continuous monitoring is extremely important for all parts of deep tunnels. However, it is even more important for lining structures which are majoritary made of fragile materials such as concrete. Thus, even if the monitoring results indicate that the health conditions of the linings are normal with regard to the monitoring period, it remains crucial that monitoring of these be continued. For instance, in the Mixian tunnel, the monitoring results show that the linings behave normally after more than 3 months [70]. Nevertheless, ensuring the safety and stability of this tunnel at all times requires effective continuous monitoring systems. For illustration (Fig. 10), in the Bai Ni-jin No. 3 tunnel where a monitoring program was carried out by 10 encapsulated FBGs, considerable deformation changes were recorded in the secondary lining for 3 consecutive years [14].
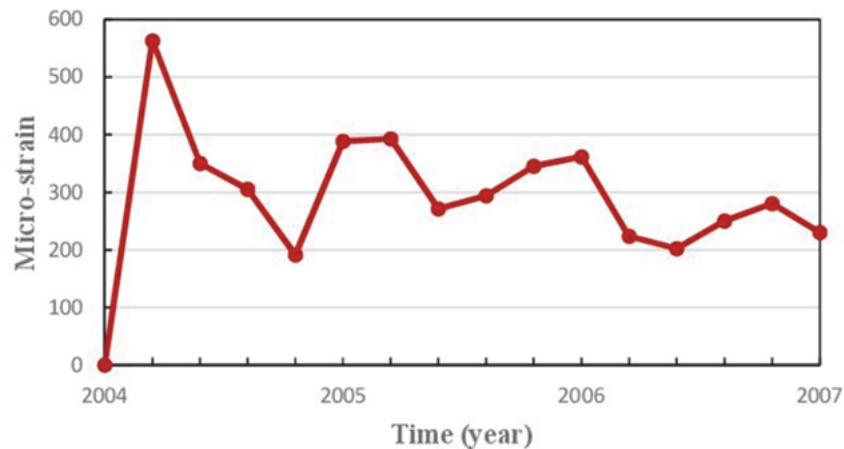

Figure 10: Variation of strains monitored by FBG sensors in a section of a secondary tunnel lining (Data from Li et al. [14].

Groundwater leak monitoring

Ensuring the continued structural health of deep rock tunnels cannot be done without proper monitoring of groundwater leakage. In fact, over time, groundwater infiltration problems are almost unavoidable during the lifetime of tunnels due to the inevitable reduction in the stiffness of the linings [81]. In operated tunnels, groundwater leaks are mainly found at structural joints in existing cracks. When their flows are very low in their initial states, it is generally difficult to detect them by simple inspection, especially in deep tunnels. At the same time, they can gradually increase the loads in tunnel linings, grow rapidly and be responsible for numerous cracks that seriously affect the structural integrity of tunnels. It has been reported by Sun et al. [82] that the structural and functional constituents of tunnels can be degenerated by the effects of water leakage. Any deterioration has the consequence of reducing the performance and durability of the structures, in particular when it is not treated in real time. As such, early warnings about groundwater leaks are necessary in order to adopt adequate measures to address groundwater infiltration issues as quickly as possible. Indeed, the longevity of the tunnels is considerably threatened by groundwater leaks. This is because the spreading of cracks in the concrete lining is facilitated by groundwater leaks [83]. Many structural health issues such as corrosion, voids, spalling and cracking are mainly due by water ingress in tunnels [84]. Grouting techniques are typically utilized to diminish groundwater leaks in tunnel [66, 85, 86]. However, over time, even if the most adequate grouting techniques are employed, groundwater leakage can appear inside a given deep rock tunnel [66]. For instance, groundwater leakage was one of the major diseases causing liner cracking in Jizhao Tunnel (Guizhou, China), and although adequate treatments were applied, long-term monitoring was adopted mainly in the most damaged sections [87].

Groundwater leakage not only accelerates the deterioration of the lining structures, but also reduces the mechanical properties of the rocks surrounding the tunnels. If it is not detected and addressed in its early stages, it can become more severe and increase the risk of unforeseen partial or complete tunnel failures. Therefore, to continuously ensure safe operation of tunnels, reliable monitoring of groundwater infiltration is strongly required [39]. In fact, groundwater seepage must be detected and diagnosed quickly and accurately [88], owing to its enormous consequences. In addition to

conventional methods, remote sensing techniques are employed to monitor groundwater seepage inside rock tunnels. Tab. 4 presents a summary of the salient techniques used to monitor groundwater leaks in deep rock tunnels.

Study	Study case	Location	Sensor	Sensor Capability	Accuracy-Range	Tunnel operating age when monitoring assessment (years)	Monitoring Results
Wang et al. (2021) [23]	Yuelongmen tunnel	China	Seepage pressure Gauges, Single-point displacement gauges, Rock stress gauges	Monitor the variation in the mechanical parameters of the surrounding rock in the tunnel.	0.1 kPa, 0.01 mm, 1 kPa	4 – 5	In a section of the tunnel, there was a steady increase in the probability of occurrence of water inrush. Grouting has been applied to solve the problem.
Lin et al. (2020) [24]	Kaiyuan Tunnel	China	Ground Penetrating Radar (GPR)	Combined with the high-density electric method and the TEM method, the GPR can accurately detect water leaks in the tunnel lining structure.	10–1000 MHz	10 – 13	Various water leak points are distributed in the lining, and are mainly due to the presence of fractured rocks and water diversion zones. Appropriate grouting treatments are applied for that.
Xu et al. (2018) [88]	Underground Tunnel at Fengtai District	China	Terrestrial Laser Scanning (TLS)	Detection of water leakage in underground tunnels by means of intensity data and 3D point cloud.	5 mm	No data	Water leakage area detected in the tunnel wall at a percentage of 10.76%.

Table 4: Monitoring details of groundwater leak in some deep rock tunnels.

It is important to note that even when the groundwater leak problem is detected and resolved, the deployment of monitoring techniques should be continued. In fact, since deep rock tunnels are generally built below the groundwater table, the risk of groundwater leaking inside them is considerable. Consequently, groundwater leaks can be detected and triggered at any time during the life of a given rock tunnel. As it can be seen in Table 4, according to the TLS results, nearly 10.76% of groundwater leaks have been detected in the walls of an underground tunnels at Fengtai District of China [88]. Even after applying proper measures to solve the groundwater leaks in such a tunnel, continuous monitoring is still required.
Note that, depending on how the permeability of rocks is increased after heavy rains, groundwater could enter the tunnels afterwards. Generally, groundwater inflows are triggered inside tunnels following sufficient increases in rock permeability [66]. Early warnings are always needed to thwart their triggering into tunnels. Hence, adequate remote sensors must be continuously designed in accordance with the challenges faced by deep rock tunnels. When monitoring groundwater infiltration in tunnels, each situation is unique. The actual conditions of tunnels related to the buried depth should be taken into account in the design of sensors to accurately monitor groundwater leakage.

Convergence deformation and the need for its monitoring
After rock tunneling, there are always in-situ stress redistributions that lead to new stress equilibrium states [57]. The consequences of rock excavations are generally significant around tunnels [37]. For instance, as already stated, the hydromechanical, physical and chemical properties are perennially degraded in the inevitable damaged zone of the excavation [47, 49, 72]. The tendency for tunnels to converge within excavated areas is therefore inexorable and evolves over time, and is considered to be a very marked effect of excavation [57]. In fact, convergence is considered as the progressive closure of the excavated areas of the tunnels [72]. It is the result of two processes namely advancement of the tunnel front and creep deformations [72, 89-91]. However, the higher contribution of the tunnel convergence is that of due to creep deformations [72, 90, 91]. As such, as one of a significant mechanism of rock degradation, rock creep control is of paramount importance to mastering convergence deformation and ensuring the long-term stability of tunnels. Notably,

convergence strain is a crucial indicator of tunnel stability. It is ordinarily argued that tunnels become unstable from a certain range of convergence deformation. According to Zhao et al. [92], convergence deformation is considered large around a tunnel from a value of 400 cm. At great depth, convergence deformations can be larger [93, 94], and over time, are mostly unbearable in soft and weak rock tunnels [95]. Large convergences are undesirable because they often lead to sudden failures which can cause enormous human and economic losses. It is crucial to ensure safe operation throughout the lifetime of the tunnel by effectively monitoring the convergence deformation [96]. A minor error in the observation or measurement of convergence strain could lead to a major tunnel safety concern. Note that extreme convergence, which is one of the main causes of tunnel failure [97], should be prevented as soon as possible by means of appropriate monitoring techniques.

The necessity to use adequate and reliable remote sensing techniques to continuously monitor tunnel convergence deformation is urgent. Important decisions on the continued operation, maintenance or abandonment of a tunnel largely depend on the data collected from the monitoring systems. Since deep rock tunnels are generally confronted with complex hydrogeological conditions, monitoring their convergence deformation is more difficult than shallow tunnels. In fact, in such tunnels, the convergence deformation should be monitored before the installation of the primary supports and also after the creep deformation has been stabilized by the installation of the secondary lining [13]. Additionally, to ensure safe operation at all times, convergence strain must be continuously monitored. For example, in India, through continuous monitoring of a deep cavern which has revealed a displacement rate of 0.024 mm/month, the appropriate decision was to install adequate additional rock bolts in the roof to resolve the problem [98]. It was experienced that the convergence rate decreased from 1.74 mm/d to 0.3 mm/d after the installation of the linings in the deep tunnel of the Jinchuan No. 2 mine in China [20], which also illustrates the need for continued monitoring. Adopting the most suitable sensors to monitor deformation of tunnels is essential. As such, presenting a relevant summary of most used sensors to this end is very interesting. This could inspire further progress in the field of tunnel structural health monitoring. Tab. 5 provides the most widely used sensors for monitoring convergence deformation in deep tunnels.

Study	Study case	Location	Sensor	Sensor Capability	Accuracy-Range	Tunnel operating age when monitoring assessment (year)	Monitoring Results
Jiang et al. [20]	Deep tunnel in the Jinchuan No. 2 Mine	China	3D laser scanner	Assessment of convergence deformation of tunnel surrounding rocks.	1.2 mm + 10 ppm	> 10	Surrounding rocks deformed, but structural integrity maintained.
Zhang et al. [98]	Deep cavern of Shuangjiangkou Hydropower Station	China	Fiber Bragg Grating; Digital photogrammetric; Multi-point extensometer	Measure the convergence deformation of the deep cavern	0.1 μm ; 0.012 mm	4 − 6	Stable cavern with a maximum displacement of almost 42 mm.
Li et al. [96]	A gold mine in Shandong	China	Draw-wire displacement sensors and tilt sensors	Continuous monitoring of convergence deformation of tunnel cross-sections. An alarm is triggered when displacement overtakes the alarm limit value.	0.01 mm	No data	After 2 months, displacement up to 1 mm, 3 mm, and presence of cracks.

Table 5: A summary of deep tunnel convergence deformation monitoring.

It can be seen that, different remote sensors are required to effectively monitor the structural health of deep rock tunnels. Indeed, any health problem must be treated in real time to prevent its development. The evolution of any health problem in deep rock engineering will inevitably reduce the performance, safety conditions and ultimately the life of the constructed structures. Consequently, remote sensing techniques are of utmost importance to monitor the various relevant components of tunnel structures to ensure reliability and safety at all times. It is important to emphasize that effective monitoring must be maintained consistently even if the surveillance results do not detect any health issues at a given time. For example, as shown in Table 5, periodic monitoring results from the deep tunnel of the Jinchuan No. 2 mine show that the structural integrity is not affected by the deformation of the surrounding rocks. Figs. 11, 12 and 13 illustrate the situation of tunnels monitored by 3D laser scanner, FBG sensors, and Digital photogrammetric System. However, due to several factors, these

results monitoring could be modified after a certain time of tunnel operation. Hence, effectively predicting the safe operation of tunnels at any time based on convergence deformation requires effective continuous monitoring systems.
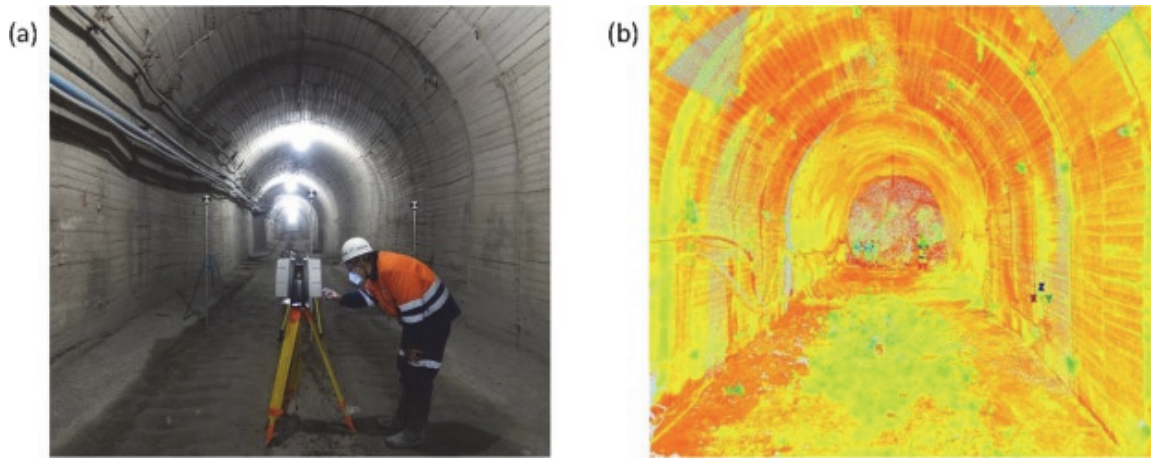

Figure 11: (a) A scanning operation at a tunnel site; (b) Gained point cloud for tunnel 3D surface (After Jiang et al. [20], with permission from Elsevier).
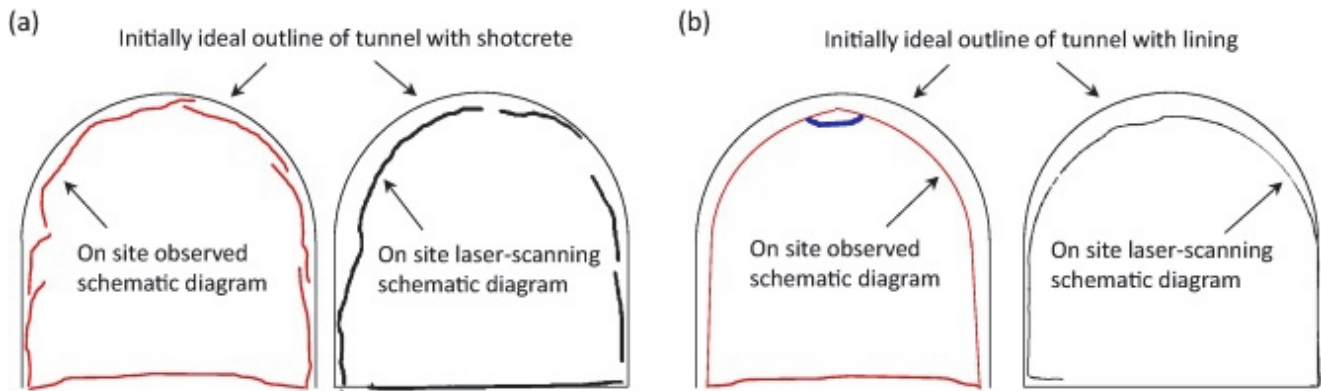

Figure 12: Illustration of tunnel failure generated by convergence deformation: (a) cracks on shotcrete; (b) partial closure on the secondary lining (from [20], with permission from Elsevier).
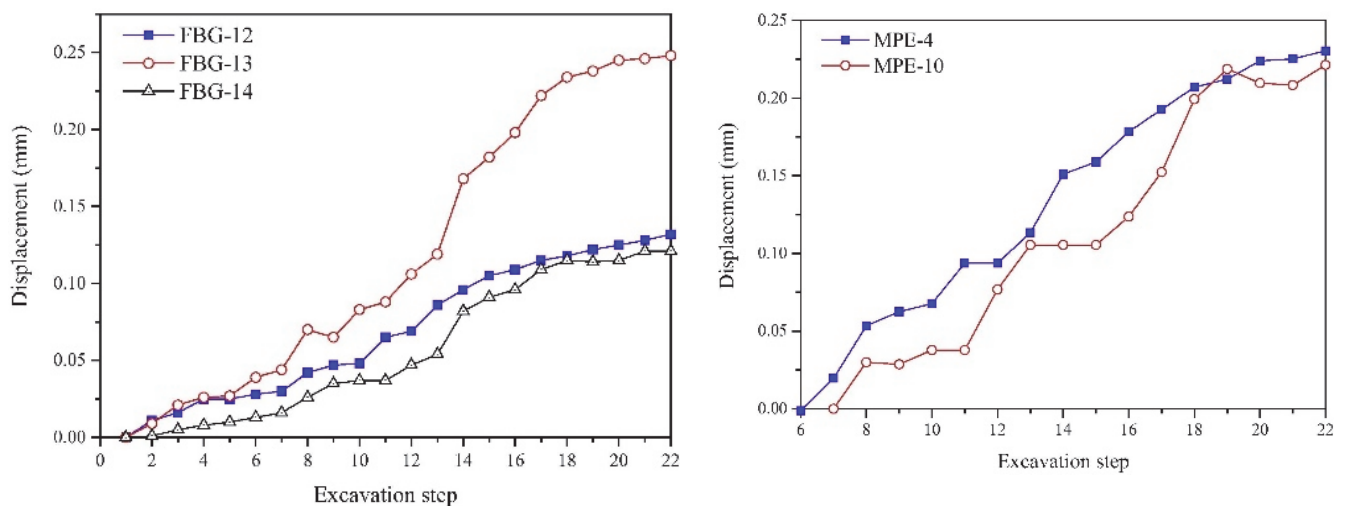

Figure 13: Convergence deformation measured at the Shuangjiangkou Hydropower Station by: (a) FBG sensors; (b) Digital photogrammetric System (From Zhang et al. [98], with permission from Elsevier).

Figs. 11, 12 and 13 show that remote sensors are employed to monitor and assess the convergence deformation of deep rock tunnels. In Fig. 14, as the monitoring results display a peak displacement which is not small and not compromising the safety of the deep cavern, the stability of the Shuangjiangkou Hydropower Station is ensured. However, as the convergence evolves with time and its rate depends on several factors including the characteristics and conditions of deep rocks, its long-term monitoring is required. For reminder, the evolution of the tunnel convergence can be expressed via the following mathematical function [91, 92]:

$$C(x,t) = C_{\infty x}\left[1 - \left(\frac{X}{x+X}\right)^2\right]\left\{1 + m\left[1 - \left(\frac{T}{t+T}\right)^n\right]\right\} \tag{2}$$

Here $C(x,t)$ traduces the total convergence in a section of a given tunnel at a distance x from the face, and after a time t ; $C_{\infty x}$ stands for the instant closure and can be estimated at remote distance from the face; X is a reference distance controlling the effect of the tunnel face; T is time characteristic related to the time-dependent response of the system rock/support; n is the exponent taking into account the time-dependent contribution of the convergence and it generally considered as 0.3; m is a parameter taking into account the ratio between the instant convergence and ultimate total convergence. According to Jiang et al. [20], the maximum convergence (d_{max}) of deep rock tunnel with an excavation length l can be estimated as follows:

$$d_{max} = 0.006253e^{0.06576l} \tag{3}$$

Generally, as time passes, there is strong evolution of the deformation of surrounding rocks in deep tunnels. Since the scope of convergence deformation usually reveals the degree of integrity and stability of tunnel structure, it is of paramount importance to regularly monitor and assess it on real-time.

The need for fire monitoring in deep rock tunnels
Ensuring the safety and stability at all times of deep rock tunnels cannot be fully satisfied without proper monitoring or detection systems for fires. In fact, fire is a frequent event that can break out in operated tunnels [99-101]. Ordinarily, as stated by Kim et al. [102], when an average annual of 4 fires occurs in a given tunnel, such a tunnel is considered dangerous. The main causes of tunnel fire are multiple and are mostly electrical fault, cable, fuel, breaks jamming, engine breakdown, engine problem, Front-back collision [103]; friction from drilling and cutting, welding, blasting, explosion, and so on [104]. When fire occurs inside tunnels, it generally provokes structural health problems. Indeed, fire hazards are major issues affecting the structures of tunnels [105, 106], and habitually engender huge damage such as casualties and financial losses [101, 105-111]. These huge consequences of fires are mainly due to the typical compact space and complex structures of tunnels [108, 112].
The effects of fires on the structure of tunnels, and in particular on the linings are well recognized [101, 103, 106, 111, 113-116], and spalling damage is mostly the predominant process of failure in concrete structures [111, 117]. As examples, serious damage has been recorded in north section of the Central Park North-110th Street Subway station of Manhattan owing to a fire that occurred on 27 March 2020 [105]. The concrete lining of a tunnel was damaged up to two-thirds due to several hours of fires accompanied with a temperature of 800℃ [118]. As reported by Hua et al. [110], due to severe damage, the lining of the UK-France Tunnel had to be repaired after an extensive fire occurred on 11 September 2008. Likewise, the lining of the Mont Blanc tunnel were hugely damaged following a fire that lasted several hours and generated high temperatures of up to 1000℃ [119]. Generally, high temperatures are unfavorable to tunnel structures. They affect the tunnel linings by deteriorating the bond existing between the host rocks and the lining materials [120]. For instance, one reason of the degradation of concrete in Tokaanu Tunnel in New Zealand is the excessive temperature overtaking 100℃ [120]. As explained by Wasantha et al. [114], increased temperature can be rapid during fires in tunnels. Note that near the fire source, local high temperature is ordinarily common during tunnel fire [112]. It is well known that high temperature is among the pertinent characteristics of deep rock engineering. For tunnels located in complex high-temperature geothermal environments, temperatures will rise even faster during a fire. In addition, in such tunnels, the risk of fire occurrence may be higher. This is mainly due to the fact that fire itself can be resulted from high temperatures that imply the constituents of electrical systems [121]. Fig. 14 illustrates some tunnels around the world built in high temperature environments. Depending on the duration of fire and the temperature level, the severity of damage to the tunnel lining can be more and

more serious. Another severe effect of fire in tunnel is that the anchorage system and rock bolts can considerably lost their capacity due to their exposition to the heat [115]. Also, rock mechanical properties are altered as a result of high temperatures [72, 115].

Figure 14: A view of geothermal extent in some tunnels in the world (Data from [119]).

In general, during a fire, the rapid change in temperature is very harmful to tunnel structures. Depending on its extent, the temperature change may even cause some components of the tunnel structures to break. Indeed, a compression failure can occur in the lining of the tunnels following a temperature variation around the tunnels [122]. It should be noted that temperature distribution, heat release rate (HRR), fire size, fire growth rates, and fire duration are among relevant characteristics of tunnel fires [123]. However, high temperatures and smoke are the strongest consequences of fires in rock tunnels [101]. The heat release rate (HRR) is usually estimated to assess the danger and intensity of fires and can be expressed as following [116]:

$$HRR = \chi \dot{m}_F \Delta H_c \qquad (4)$$

Here χ represents efficiency of combustion which is often equal to 0.75 in typical tunnel fire schemes; $\dot{m}_F$ stands for fuel of the mass loss rate caused by the burning (kg/s); ΔH_c denotes the heat of full combustion (kJ/kg).
The temperature can be calculated by taking into account an appropriate tunnel fire heating curve [123]. Generally, it can be determined as follows [106]:

$$T = T_0 + A\left(1 - 0.325 e^{\alpha t} - 0.675 e^{\beta t}\right) \qquad (5)$$

Here T is temperature provided by the typical curve ($\mathrm{^\circ C}$); T_0 represents the temperature initial ($\mathrm{^\circ C}$); A, α, β stand for parameters related to the fire curves considered; t is the duration of fire expressed in minutes.
Consideration should be given to the exposure of the tunnel ceiling to the peak gas temperature which can be estimated as follows for small fire [107, 124]:

$$\Delta T_{max} = \begin{cases} \dfrac{17.5 Q^{2/3}}{H_{ef}^{5/3}}, & V' \le 0.19 \\[4mm] \dfrac{Q}{V b_{f_0}^{1/3} H_{ef}^{5/3}}, & V' > 0.19 \end{cases} \qquad (6)$$

Here ΔT_{max} represents peak extra temperature under the ceiling (K); Q is Full heat release rate (kW); H_{ef} stands for vertical distance existing between the fire source bottom and the tunnel ceiling (m); b_{f_0}: fire source radius; V' is a dimensionless fan speed.

In the case of large fires, the peak gas temperature below tunnel ceiling can be expressed as following [107, 124]:

$$\text{if } V' \leq 0.19, \quad \Delta T_{max} = \begin{cases} \dfrac{17.5\,Q^{2/3}}{H_{ef}^{5/3}} \\ \\ Constant \end{cases} \tag{7}$$

$$\text{if } V' > 0.19, \quad \Delta T_{max} = \begin{cases} \dfrac{Q}{V b_{f_0}^{1/3} H_{ef}^{5/3}} \\ \\ Constant \end{cases} \tag{8}$$

According to Hua et al. [111], based on temperature level (T), fire can mainly spread in three ways: low-intensity (T<300°C) which is generally not dangerous to tunnel structures, intermediate intensity which can damage the tunnel lining at certain extent, and high intensity (T≥1200°C) which usually cause severe damage to tunnel lining. To prevent fire, tunnels should be equipped with reliable and suitable monitoring systems. Precisely, monitoring the temperature distribution in the surrounding of tunnels is mandatory in order to be able to provide appropriate warnings at the earliest [125]. Thus, adequate actions can be taken at real-time to control the fire situation before it develops significantly. Smoke movements in tunnels depend on the time required for fire detection and the time for starting any emergency system [126]. In tunnel fires, time plays a key role as it influences the efficiency of decision-making [100]. When a fire is discovered in a tunnel, it must be fought and extinguished within a short period of time to avoid enormous loss of human life and economic, and considerable structural damage. Therefore, it is necessary to quickly identify the exact location of the fire in order to take appropriate actions [127]. This can help in remedial measures in a timely manner, or reducing the fire impacts as fast as possible. Regarding the structural health of tunnel, detecting the early stage of fire in tunnels should be a priory and time for decision-making remains a crucial factor. It is true lining collapse can result from long duration fire [114], but a short fire duration is also detrimental for the tunnel structures. An example, the Shanghai Metro Line 8 tunnel lining was damaged by a fire lasting only 10 minutes in 2005 [113]. In fact, the effectiveness of rescue plans depends on the ability to identify the emplacement of fire in tunnel [128]. Knowing that it remains a challenging task to evaluate the damage caused by fire in tunnel structures [119], real-time monitoring of fire and adopting efficient decision capable of reducing its effects are deeply necessary.

Remote sensing techniques can be used to detect the early stage of a fire outbreak in tunnels. Indeed, tunnel fires can be monitored by using several types of sensors [102]. Nevertheless, due to their characteristics, Raman sensors are very promising for fire monitoring in tunnels [125, 129-131]. In fact, such sensors have the capability of taking into account the different structural environment to assess the temperature distribution throughout the tunnel route [125]. For instance, to monitor fire hazard in the Xuanwu Lake Tunnel of China, Raman optical time domain reflectometry were served as the basis for distributed temperature sensing system [126]. Fire source can be detected in tunnels by using a suitable method of localization based on Raman distributed optical fiber sensors [131]. Adequate monitoring of fire in tunnel is of paramount importance. This can prevent considerable damage on tunnel lining.

Durability of sensors

Successful long-term monitoring of the structural health of tunnels does not rely solely on the adequacy and effectiveness of sensors. It also depends on the durability of all the components of the adopted monitoring system, and in particular on the sensors. It is important to continuously monitor the health conditions of installed sensors to ensure that they are continually effective in providing real-time feedback of the structural parameters they monitor. In fact, after working for a long time, the detecting ability of a sensor may be reduced. Additionally, due to the inevitable time-dependent behavior of natural rocks [72], the capacity of sensors can be diminished by fatigue and ageing. When the capacity decreases, the performance of the sensors is automatically reduced. The structural health monitoring can no longer be effective under such conditions. It is always urgent to ensure that the sensing capacity of sensors is normal at all times. For tunnels monitored by fiber sensors, when necessary, the decision to replace these sensors must be made in real time. Indeed, the fragility of fiber optic cables is recognized and their breakage is frequent in severe rocky conditions [80]. As such, suitable coatings should be considered for such sensors. It has been revealed that such sensors have reduced performance after exposing to

difficult conditions [132]. Therefore, ongoing monitoring is necessary in order to know when the coatings of such sensors need to be replaced [132]. Overall, it is extremely important to check the health status of sensors at all times and identify faulty sensors in order to make appropriate decisions.

For instance, among the 872 FBG sensors installed in the Rossio tunnel in Portugal, several of them proved to be faulty over time, and the wavelength of a broken sensor suddenly and dramatically changed [133]. To allow the monitoring system to continue to be effective in the Rossio tunnel, the replacement of the defective sensor had to be rapid [133]. In the Lee tunnel project located in London, United Kingdom, some cables of a BOTDA installation were removed owing to damage [134]. In the Creighton mine in Canada, as reported by Forbes et al. [135], due to two locally broken fiber optic sensors which failed to correctly register the expected strains, instrumented cable bolts were later installed to improve the monitoring systems. Since sensors are essential components of the structural health monitoring, their long-term integrity play a vital role. Especially for fiber optic sensors, their constituents should not be broken promptly [74], when they are exposed to common harsh situations during their service life [136]. Therefore, to provide safe long-term monitoring, it is extremely important that sensors are robust and effective during tunnel excavation and operation. Owing to the complex behavior of deep rocks, different types of sensors can provide more interesting data regarding the structural health of tunnels. Indeed, networks of different sensors may be better suited to monitor different parts of the structural health of deep rock tunnels. Although wired sensors are expensive and time-consuming to install [137], their use cannot be avoided in many situations. In very complex environments, wireless sensors can be mainly used, but they can be combined with wired sensors to increase monitoring capacity and durability. However, regardless of the types of sensors employed, their continuous monitoring is necessary. As reported by Haque et al. [44], monitoring of sensor networks is also necessary to reduce the extent of power utilization in nodes. It should be noted that, as the burial depth of underground structures increase more and more, it is important to verify, within a reasonable time, the reliability and efficiency of the selected and designed monitoring systems. At deeper and deeper depth, surrounding rock parameters vary greatly over time, and the overall properties and conditions of rocks are increasingly complex. Robust, efficient and sustainable monitoring systems are needed to provide accurate and real-time monitoring data.

ON THE DESIGN OF A NEW FBG DETECTOR FOR GROUNDWATER LEAKS IN DEEP SOFT ROCK TUNNEL

Study area and engineering context

Belonged to the National Highway G357, the Weilai tunnel is situated in the Weilai Village, Bada Town, Xilin County, in Guangxi Province, China. The Weilai tunnel is part of the Tianxi Expressway project and has a burial depth of 105 m. Huge mountains, intersecting ridges and valleys surround the tunnel site. Fig. 15 provides the location map of the Weilai Tunnel in Guangxi province and a view of the tunnel site before excavation.
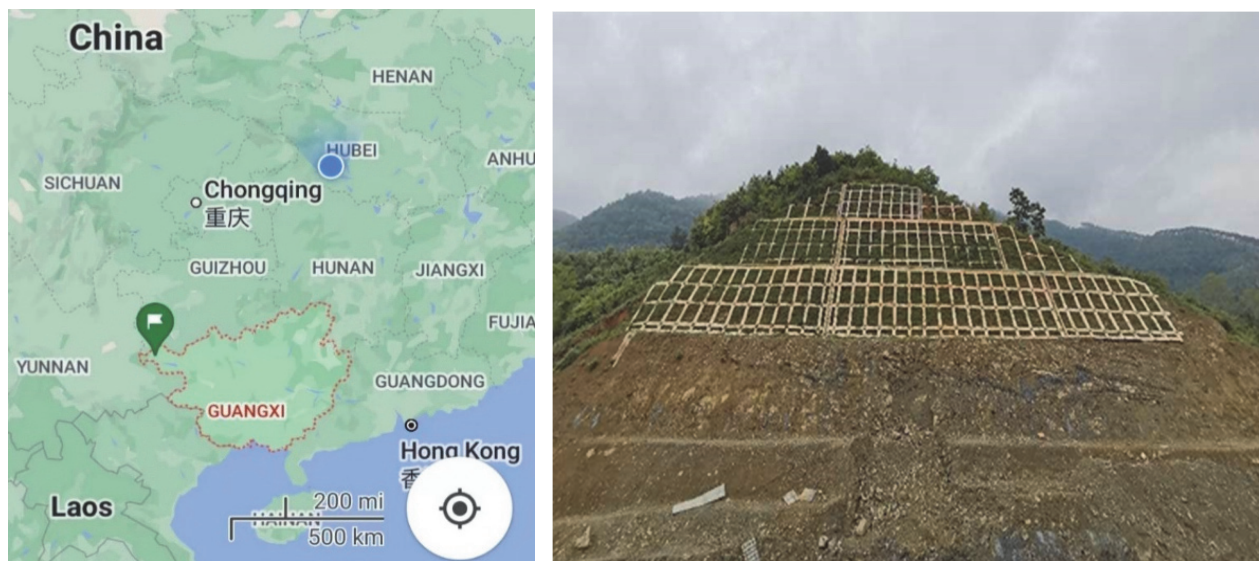

Figure 15: Location Map of Weilai Tunnel Project in Guangxi Province (left); A view of the tunnel site before excavation (right)

The lithology along the tunnel alignment is mainly composed of argillaceous sandstone and sandstone. However, the argillaceous sandstone is more predominant and is initially broken with many spectacular fractures. The surrounding environment of the tunnel is classified as soft rocks because of its low uniaxial compressive strength which is less than 10 MPa. In spite of drill-and-blast excavation method provokes more additional damage to the host rocks than those caused the TBM [37], it was adopted with reasonable sequence to excavate the Weilai tunnel, due to complexity associated with the site. Groundwater is relatively abundant in aquifers close to the surrounding rocks. As a result, geohazards such as groundwater inflows occurred during the construction of the tunnel. On top of that, the tunnel experiences strong creep and exhibits large convergence deformations. To assess the convergence deformation of the tunnel, traditional monitoring method was carried out with the Total station and convergence gauges where monitoring data were taken for 27 days. The final cross-section size of the tunnel, the disposition of the monitoring points, and an illustration of monitoring operation are illustrated in Fig. 16. Thereby, based on the on-site monitoring data, the evolution of tunnel convergence deformation is shown in Fig. 17.
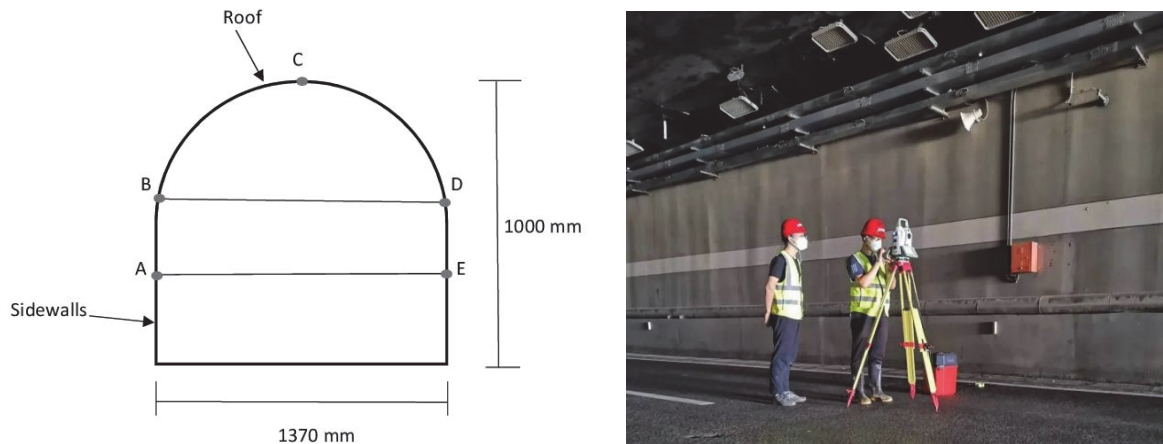

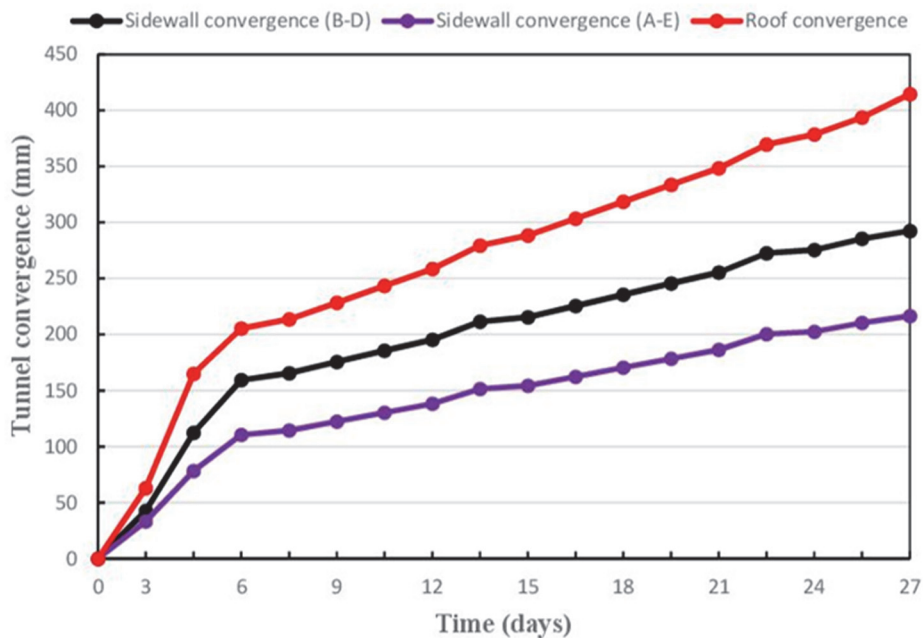Figure 16: Tunnel cross-section size, monitoring arrangement and illustration

Figure 17: Convergence deformation of the tunnel based on-site monitoring data

A robust support scheme has been designed to ensure the long-term safety and stability of the tunnel. It is composed of "Pressure aid + deep grouting + fully grouted rock bolts + fully grouted cable bolts + steel arch + secondary lining". Nevertheless, due to the overall severe conditions of the tunnel environment, in order to effectively guarantee long-term

structural health, long-term monitoring with suitable and effective remote sensors is required. This is justified by the fact that considerable deformation of tunnel can be durable as the strength of the surrounding rocks is weak [138].

Although many sensors have been designed to monitor critical health issues in various sections of deep tunnels, there is still a need to design new sensors to improve monitoring capability and applicability in tunnel engineering. In fact, as already explained, the behavior of deep rock engineering is increasingly complex with the long-term effects of high stress, elevated temperature and considerable groundwater flows and pressures. Remote sensors should have strong capability in order to effectively monitor the structural health of deep rock engineering and provide accurate monitoring information in a timely manner.

As previously mentioned, groundwater leakage is a serious adverse events jeopardizing all tunnel components. Its effects on all components of tunnel structures are very detrimental. Indeed, as soon as it appears, even at very low flow or pressure, it must be detected and treated as quickly as possible. Thus, the speed and simplicity of detecting the early onset of groundwater leaks is of great benefit to the structural health of tunnels. The first ideas for the design of a fiber optic groundwater leak detector are presented herein.

Relevant basis and working principle of FBG sensors
The major interests in FBG sensors are associated with their relevant characteristics such as light weight, small size, corrosion resistance, durability, multiplexing, resistance to electromagnetic interference and ease of installation [139]. Diverse parameters related to the health conditions of tunnel structure can be monitored by such sensors. Accordingly, the design of a new FBG sensor for detecting groundwater leak is of paramount importance. It is well known that many FBG sensors are designed to detect cracks, strain and temperature. This situation can be exploited to design new FBGs capable of detecting groundwater leaks in the Weilai tunnel. Broadly speaking, before groundwater leaks appear into the secondary lining of the tunnel, permeability of surrounding rocks and linings are augmented. Specifically, when the permeability of the secondary lining exceeds a tolerable limit, groundwater leaks may occur into the tunnel. A proper FBG can monitor the increase in secondary lining permeability and provide accurate data that will help in developing timely maintenance plans to resolve the issue as quickly as possible. Thought the FBG, humidity can be converted into strains, and by this, early warnings can be provided. In fact, the idea is that as permeability increases, strain can be increased in the FBG. This is of particular significance as an appropriate FBG sensor can also help to prevent the evolution of cracks and fractures in the secondary lining of the deep soft rock tunnel. It should be reminded that many cracks, fractures, and damage in tunnel secondary lining are the consequences of the triggering of groundwater inflows.

The working principle of FBG sensors is illustrated in Fig. 18. Typically, the intensified spontaneous emission light, through a coupler, illuminates the set of installed sensors. The wavelength shift which is generated by external disturbance is habitually detected by means of an interrogator. The latter is utilized for appropriate demodulation. When the pertinent parameters (cracks, temperature, pressure, stress, strain, and so on) vary, the FBG sensors are subjected to traction or compression. Hence, as a pertinent response, the wavelength shift of the FBG is displayed by a reflective spectrum.
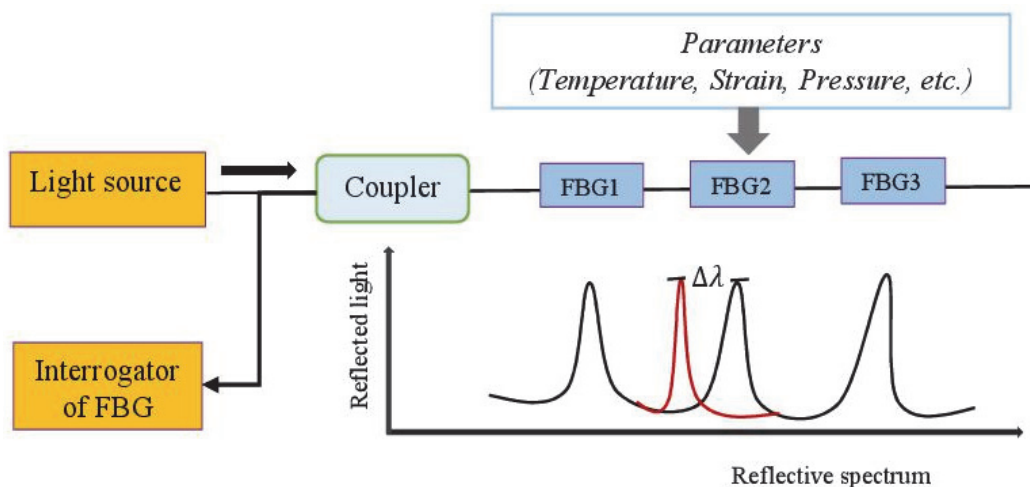

Figure 18: General working principle of FGB sensors

The Bragg wavelength (λ_B) which is the interaction between light from a broadband source and the grating ($\wedge$), can be determined as below [31, 139, 140]:

$$\lambda_B = 2 \wedge n_{eff} \tag{9}$$

Here n_{eff} represents the refractive index of the fiber.

A linear relationship is used to represent the offset of the reflected Bragg wavelength ($\Delta\lambda_B$) as follows [31]:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - p_e)\varepsilon + (\alpha + \xi)\Delta T \tag{10}$$

Here $\Delta\lambda_B$ stands for Bragg wavelength offset which is induced by the strain (ε) and temperature change (ΔT); p_e is effective photo-elastic coefficient of the FBG; α is the thermal expansion constant of grating; ξ represents thermo-elastic constant of the fiber. For typical values, $\alpha = 1.2\ pm/\mu\varepsilon$ and $\xi = 13\ pm/\text{°C}$ for an FBG deploying 1550 nm as central wavelength [38].

Relevant requirements and design
The critical requirement of the new FBG sensor is identified. Indeed, as noted by Kerrouche et al. [140], the critical requirement of the sensor network must be determined in order to properly design a monitoring system. The new FBG should be of high resistance which can resist difficult conditions of the aforementioned deep soft rock tunnel. Concretely, it will be a FBG semi-coated with a kind of material capable of absorbing of water and humidity, as shown in Fig. 19.
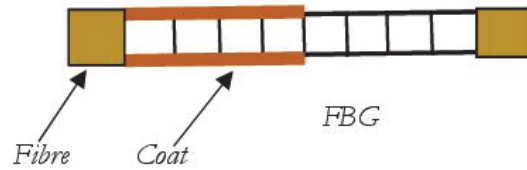

Figure 19: Illustration of the semi-coated FGB sensor

The rapid reaction of FBG will allow it to convert the absorption of water and humidity into strains. Indeed, on the basis its adsorption ability, polyimide is selected to coat the FBG. Temperature variation will be assessed by using the uncovered part of the FBG. Such a consideration is made because in deep rock engineering, temperature fluctuation cannot be overlooked. The FGB will be able to control the variation in deformation due to the increase in permeability or the early appearance of groundwater leaks. In order to better evaluate the performance of the sensor, it is suggested that strains and temperature be evaluated separately. Thereby, with regard to Equation (10), the wavelength shift related only to strain is determined as below:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - p_e)\varepsilon \tag{11}$$

Similarly, the wavelength shift related only to temperature is estimated as follows:

$$\frac{\Delta\lambda_B}{\lambda_B} = (\alpha + \xi)\Delta T \tag{12}$$

The FBG will be applied to control the early onset of groundwater into the Weilai tunnel. Consequently, strains will be detected in the secondary lining of the tunnel, and real-time decisions will help for continuously maintaining the structural integrity of the tunnel. Since the surrounding rock conditions are complicated, the sensitivity of the new FBG sensor will be amplified accordingly. Ordinarily, to adequately improve the sensitivity of the FBG sensor, an amplification factor q can be considered and is determined as below [141]:

$$q = \frac{\varepsilon_{FBG}}{\varepsilon} \tag{13}$$

Here ε_{FBG} represents the strain of the fiber material in the area concerned by the FBG. Consequently, the enhanced wavelength shift related to strain can be defined as follows [141]:

$$\frac{\Delta\lambda_B}{\lambda_B} = \left(1 - p_e\right)q\varepsilon \tag{14}$$

It should be noted that, especially for deep soft rock tunnels built in severe rock conditions, the sensitivity of any FBG should be properly enhanced. In Guangxi province, it is known that the failure of some tunnels occurs even after a short time of operation. This can be explained by two main reasons: the general adverse conditions of the region, and insufficient monitoring systems. Therefore, the project to design suitable sensors to monitor each structural element of the Weilai tunnel is of huge significance.

DISCUSSIONS

In this article, monitoring the structural health of deep rock tunnels based on remote sensing techniques is comprehensively highlighted. The use of various sensors is emphasized in the field of tunnel engineering. Indeed, at great depths where rock characteristics and conditions remain complex while at the same time long-term safety and stability are required for the tunnels therein, appropriate and effective monitoring systems are essential. Due to their relevant characteristics, remote sensing techniques have well found their applications in deep rock engineering and are increasingly becoming a cutting edge research topic in this field.

For optimal monitoring performance, the selection and the design of the most suitable remote sensing techniques is required for a given tunnel. In addition to being suitable for the situations they are monitoring, sensors must also ensure sustainable performance over the life of the tunnels. For instance, owing to their durability and their ability to monitor continuously deformation at diverse points of their lengths in rocky media, distributed fiber optic sensors are ordinarily employed [142]. Nonetheless, for real results, adequate consideration must be made on the proper calibration and accuracy of the optical sensors [143]. Additionally, it is of huge significance to ensure that the performance of the monitoring systems is durable. Strategies leading to continuous monitoring of detection systems should therefore be strongly considered in the planning and installation of any monitoring system of deep tunnel structural conditions.

Due to the existence of several health problems, different sensors are generally employed to monitor them. For instance, strain sensors generally installed to control cracks which can be provoked by damage evolution or to measure strain evolution. Temperature sensors are mounted to control variation of temperature. For instance, in order to control their temperature change, the surrounding rocks and the lining of the tunnels can appropriately house temperature sensors [144]. Yet, it is recognized that temperature change can also induce deformation in tunnel [145]. In fact, to monitor various health issues, various suitable sensors can be adequately mounted in critical areas of tunnels. Installing and deploying multiple sensors to monitor various health parameters can provide more reliable and accurate monitoring data, if they are properly established. Nonetheless, in most situations, the associated economic constraints are not negligible. As shown in Figure 2, a comprehensive approach to monitoring in deep tunnels can include different elements, namely:

- Monitoring the evolution of deformation in the Excavation Damaged Zone (EDZ).
- Monitoring the health conditions in the rock bolts and cable bolts (deformation, corrosion, stability loss, etc.)
- Monitoring the health status of the secondary lining (crack expansion, evolution of damage and deformations, etc.).
- Monitoring groundwater leakage to prevent surrounding rock deterioration, corrosion in rock bolts and cable bolts, lining instability, etc. In fact, in particular in concrete lining structure, groundwater leakage is very harmful.
- Monitoring the convergence deformation to prevent tunnel instability and premature closure.
- Fire monitoring to prevent spalling damage in tunnel lining and loss of bond between supports and host rocks.

It can be seen that effectively ensuring safety and stability at all times in deep tunnels is a difficult and costly task, as various sensors are required to monitor various health issues. At present, in engineering practice, this remains very difficult. One solution is that monitoring systems can be designed so that their sensors are able to monitor and measure multiple health parameters. For example, an FBG capable of measuring strain, vibration, and temperature was designed by Yao et al. [146]. It has been reported by Li and Zhang [124] that in tunnels, real-time monitoring of both cracks and temperature is even required for distributed fiber optic sensors.

Other sensors able at measuring different parameters may also be designed. However, in deep rock engineering where complex situations may include adverse geological and hydrogeological conditions, high in situ stresses, high temperatures, etc., there is a great need for high sensor performance and durability. Since any sensor has its peculiarities and limitations, in-depth investigations on the performance of various remote sensors in monitoring different parameters of deep tunnels are needed in order to further deepen the discussions. The suitability of detectors in relation to the depth of structures and their types of health problems should also be further investigated.

It is important to note that, any health problem can affect the structural integrity and longevity of tunnels. However, the heath conditions of the EDZ could be an upstream factor influencing the longevity of tunnels, as can be seen in Fig. 4. Indeed, to some extent, the instability conditions of the EDZ can provoke instability conditions of the rock bolts, cable bolts and the linings. Indeed, as reported by Gao et al. [47], the risk of instability around deep tunnels can be favored by the appearance of groundwater flows which are facilitated by the EDZ. As such, when the latter are really stable, the probability of triggering groundwater leaks in tunnels can be minimized. Moreover, the convergence rate may also be low over time. On this basis, effective monitoring of excavation damaged areas could be very fruitful for the overall structural health of deep tunnels built especially in very complex rock conditions. In such conditions, although adapted support schemes can be designed to better ensure the safety and stability of deep tunnels, improvements or new support schemes are required when the rock conditions become more complicated [57]. It is essential to reinforce in real time the support schemes of deep tunnels built in very complicated rock conditions, and in particular when these conditions become increasingly difficult. To this end, suitable and continuous monitoring systems using remote sensing techniques are very promising for real-time decision-making.

If all structural components and typical diseases are well monitored, monitoring systems can effectively provide real-time alerts regarding the health status of different parts of deep rock tunnels. Fig. 20 illustrates comprehensive monitoring scheme which could be extremely beneficial for effective real-time decision-making on the current conditions of deep tunnels in severe rock conditions.
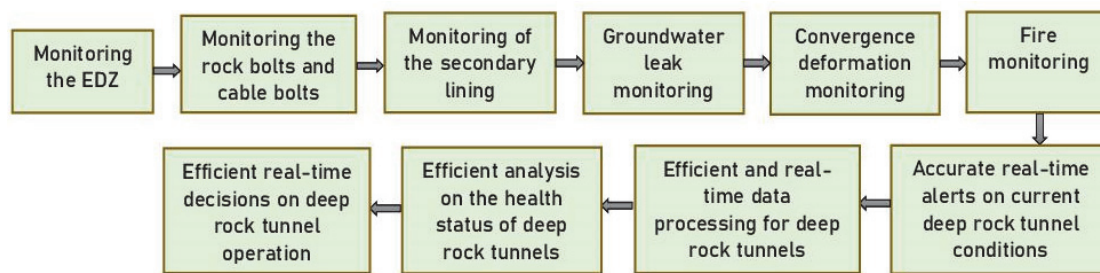

Figure 20: Comprehensive structural health monitoring for deep rock tunnels

The global monitoring scheme depicted in Fig. 20 can be very attractive to properly ensure safe operation of deep rock tunnels at all times. It can be seen that, if a monitoring system is applied to control structural diseases only in superficial sections of deep tunnels, any disease detected should be dealt with faster than expected. In fact, if a disease occurs in a superficial section, it could originate from deeper sections such as EDZ, therefore, it could not be in its early stage, and may quickly threaten the safety and stability of tunnels. For example, due to the growth of numerous cracks in its secondary lining after only three years of operation, the Xuecheng Tunnel of China's National Highway 317 was temporarily taken out of service, and its repair took two years [147]. Generally, as in any engineering structure, in the majority of tunnels, the duration of maintenance is all the greater as the extent of the damage is greater. Notably, the longer the maintenance period, the greater the economic expenditure. Comprehensive monitoring systems employing effective remote sensing techniques can enable early detection of tunnel diseases, and their treatment may require shorter lead times. Accordingly, when properly applied, comprehensive monitoring systems with suitable remote sensing techniques can have the merit of helping to reduce economic expenditure in deep tunnels.

As tunnels are buried deeper and deeper, there is an urgent need to design ever more efficient remote sensors. In addition, the durability of monitoring systems and sensors is increasingly affected at great depths. Factors such as monitoring region and sensing effectiveness cannot be neglected in the design of monitoring systems for deep tunnels. It is essential to ensure that the number of sensors is sufficient so that the monitoring regions are properly covered. In addition, the sensing performance of sensors should be sufficiently efficient. Care should be taken for weakened detections as they may be inaccurate. Since accuracy degrades as detection distance increases [36], sensors should be positioned appropriately. It should be noted that despite the high precision that remote sensing techniques systems can provide, it is always necessary to seek to improve the degree of surveillance of tunnels built in very complicated rocky environments. Therefore, in particular in

concrete structures where cracks are very frequent, at the same time as remote monitoring is operational, periodic visual inspections can also be carried out [147]. It should be noted, for instance, that improvements are still needed for wider applications of distributed fiber optic sensors [148, 149], despite the recognition of their colossal advances in tunnel engineering. Periodic visual inspections could not only help monitor remote sensing systems, but also critical parts of tunnels. In fact, in deep underground engineering, as expressed by Zhang et al. [150], some basic limitations of the employed sensors should be addressed to warrant more efficient operation of the applied monitoring systems. Due to the increasing number of deteriorated tunnels in use [151] and the often missed optimal maintenance time to ensure stability [152], there remains a great urgency to apply robust and efficient remote sensing techniques for real-time monitoring. As simulated by Xu et al. [15], deformation features of deep surrounding rocks can be well depicted by distributed fiber optic sensors. However, the great necessity to enhance the capability and durability of such sensors is required in deep underground engineering where soft rocks are predominant. In fact, robust and efficient sensors are of tremendous importance to guarantee long-term monitoring in deep rock tunnels where various stress states can be found. For instance, changes in stress regimes and presence of groundwater near the tunnels could broke some FBGs employed for the monitoring [153], and the results can be affected. Considerable attentions should be given to the health status of sensors in deep rock tunnels. Inefficient sensors generally provide inefficient monitoring data and the decision made in such conditions will be inaccurate. Poor monitoring should always be prevented as it is generally dangerous for the overall safety of deep rock tunnels. A study conducted by Zhu et al. [154] has revealed that poor monitoring is among the causes of 60% tunnel accidents in China from 2010 to 2020. It is thus more than urgent to enhance the capability and efficiency of the monitoring systems for deep rock tunnels. This should be prioritized since structures such as deep rock tunnels are expected to have long operational lifespan that can exceed 100 years. Moreover, it is crucial to ensure long-term monitoring for underground structures [154, 155], and especially for those built at great depth [37].

CONCLUSIONS

I n this article, comprehensive monitoring of deep rock tunnels using remote sensing techniques has been discussed. Monitoring is shown to be the premise for controlling the structural health and durability of deep rock tunnels. The main conclusions drawn from this article are as follows:

1. Deep rock tunnels are affected by many health problems that can evolve over time. The development of such problems have serious impacts on the safety, stability and longevity of tunnels. To prevent significant growth of such health issues and ensure safety and stability of tunnels at all times, adequate and reliable monitoring systems are required. Then, real-time decision-making and suitable actions are imposed to effectively guarantee the longevity of deep rock tunnels.

2. The structural health issues in deep rock tunnels are diverse. They are mainly: evolution of degradation in the excavation damaged areas, corrosion of rock bolts, cracks, fractures and strains in primary and secondary lining, groundwater leaks in secondary lining, convergence deformation and damage caused by fires. Most typical structural diseases generally provoke other health issues. Moreover, major hazards such as groundwater leaks and fires are causes of many structural problems in deep rock tunnels. For instance, the occurrence of fire in tunnels affect structural components such as the anchorage systems, the rock bolts and linings. The secondary lining of tunnels usually suffers spalling damage after being exposed to fire. Overall, reliable and adequate sensors are required to monitor any structural disease and hazard in tunnels in order to take remedial measures at the earliest prospect.

3. Remote sensing techniques are widely employed for structural health monitoring of deep rock tunnels. Nonetheless, at present, ground-based remote sensing is more utilized than satellite remote sensing in structural health monitoring of deep rock tunnels. Both wired and wireless sensors are very promising in deep underground engineering, and are applied singly or combined in hybrid or multiple manner. The combination of these two types of sensors can be more interesting for adequate long-term monitoring in deep rock tunnels. This is strongly suggested for deep tunnels particularly built in severe rock conditions. In fact, if one sensor system fails unexpectedly over time, at least the other one can provide usable real-time monitoring information. Above all, long-term monitoring of deep rock tunnels must be properly ensured. Thereby, the structural integrity of these structures can always be assessed and maintained for as long as possible.

4. The effectiveness of monitoring the structural condition of deep tunnels mainly depends on the performance and durability of the sensors. Therefore, continuous monitoring of sensor performance is necessary to obtain accurate and efficient monitoring data at all times. All components of monitoring systems must be adequately controlled.

Real-time decision-making relies on the capability and efficiency of sensors. Given the complexity of deep rock engineering, robust, adaptive, and durable sensors are preferred for long-term monitoring of deep tunnels.

5. Since various health issues are typically encountered in deep rock tunnels where unforeseen partial or total failures are common, it is of utmost importance to continuously improve monitoring performance by opting for the optimum combination of various suitable sensors. Indeed, the sensors can be designed for different situations with regard to the complexity linked to the typical health problems according to the geological, geotechnical, hydrogeological and the excavation conditions of the constructed tunnels. Comprehensive monitoring operated by effective remote sensing techniques to control all typical health issues can be adopted for more effective real-time decisions regarding the operation of deep tunnels.

6. For future research in this domain, in order to establish reliable databases that can help in the selection of appropriate remote sensing techniques for deep rock tunnels, it is crucial to deeply compare the performance of various sensors for different structural diseases commonly found in these structures.

NOMENCLATURE

DOS	Distributed optical strain sensing
CCFPI	Coaxial cable Fabry-Perot interferometric sensors
EDZ	Excavation Damaged Zone
GPR	Ground Penetrating Radar
VMGPR	Vehicle-mounted Ground Penetrating Radar
ROFDR	Rayleigh Optical frequency domain reflectometer
FOMI	Fiber Optic Michelson Interferometer
RBT	Rock bolt Tester
PZT	Lead Zirconate Titanate
TLS	Terrestrial Laser Scanning
FBG	Fiber Bragg Grating
OTDR	Optical Time Domain Reflectrometer
OFDR	Optical Frequency Domain Reflectrometer
OECST	Optical-electric co-sensing tape
TEM	Transient Electromagnetic Method
TBM	Tunnel Boring Machine
LPDT	Linear Potentiometric Displacement Transducers
SHM	Structural Health Monitoring

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