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# Recent development of advanced monitoring technologies in geotechnical engineering

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**ABSTRACT**

**Introduction.** The increasing demand for green and intelligent civil infrastructures necessitates high-precision Internet of Things (IoT) monitoring systems. Given the high sensitivity of geotechnical engineering to soil strains, it is essential to develop precise measurement approaches that can accurately capture soil strains ranging from micro-strain to large strains. In recent years, advancements in fibre optic sensing technology have enabled accurate measurements within geotechnical engineering. However, there is still a need to enhance measurement approaches for fibre optic sensing technologies across various strain levels. This study investigates several fibre optic sensing technologies, including point-distributed, array sensing, and distributed fibre optic sensors, and provides a comprehensive review of recent advancements in fibre optic sensing for the field of geotechnical engineering.

**Materials and methods.** Innovative methods and devices for high-precision small-strain fibre optic sensing are detailed. Additionally, a novel integrated fibre optic sensor device capable of measuring water pressure and total soil pressure using a signal transducer is introduced.

**Results.** The study also explores the use of 3D printing technology in fabricating these transducers. A fibre optic sensing method for monitoring cracks is presented, encompassing physical fabrication, calibration tests, and field engineering application verification.

**Conclusions.** The fibre optic sensing methods proposed in this study offer effective solutions for accurate measurement in geotechnical engineering across different environmental and disaster conditions.

**KEYWORDS:** fibre optic sensors, instrumentations, structure health monitoring, infrastructures

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# Последние разработки передовых технологий мониторинга в области инженерной геологии

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**АННОТАЦИЯ**

**Введение.** Возрастающий спрос на экологичную и «умную» гражданскую инфраструктуру требует высокоточных систем мониторинга Интернета вещей (IoT). Учитывая важность вопросов деформаций грунта для инженерной геологии, необходимо разработать методы измерения, способные точно фиксировать деформации грунта, начиная от микродеформаций и заканчивая существенными деформациями. В последние годы достижения в сфере волоконно-оптических технологий зондирования позволили проводить точные измерения в области инженерной геологии. Однако по-прежнему имеется необходимость усовершенствовать подходы к измерениям с использованием технологий волоконно-оптического зондирования различных деформаций. Рассматриваются несколько технологий волоконно-оптического зондирования, в том числе точечно-распределенные, массивные и распределенные волоконно-оптические датчики.

**Материалы и методы.** Приведен полный обзор последних достижений в области волоконно-оптических датчиков для целей инженерной геологии. Подробно описаны инновационные методы и устройства высокоточного измерения малых деформаций с помощью волоконно-оптических датчиков.

**Результаты.** Показан новый интегрированный волоконно-оптический датчик, способный измерять давление воды и общее давление грунта с помощью преобразователя сигнала. Проанализировано использование технологии 3D-печати для изготовления таких преобразователей.

**Выводы.** Представлен метод волоконно-оптического мониторинга трещин, включающий физическое изготовление, калибровочные испытания и верификацию в полевых инженерных условиях. Предложенные методы волоконно-оптического мониторинга основаны на эффективных способах точных измерений в области инженерной геологии для различных экологических и аварийных условий.

**КЛЮЧЕВЫЕ СЛОВА:** волоконно-оптические датчики, приборы, мониторинг состояния конструкций, инфраструктура

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## INTRODUCTION

Given the extended duration of infrastructure construction and usage, structural health monitoring (SHM) has emerged as a critical measure to ensure the stability and integrity of facilities [1–4]. Traditionally, electronic sensors have been predominantly utilized for monitoring purposes; however, these sensors often exhibit several limitations, such as vulnerability to electromagnetic interference, complex wiring requirements, and constrained timeliness. In contrast, fibre-optic sensors present significant advantages, including compact size, high sensitivity, and immunity to electromagnetic interference. These attributes render fibre-optic sensors highly suitable for specialized monitoring needs, and their application in engineering has become increasingly widespread [5–7].

Fibre optic sensors are principally categorized into two types: fibre Bragg grating (FBG) sensors and distributed fibre-optic sensors [8–11]. FBG sensors are typically employed to measure pressure, displacement, and temperature at specific locations within a building structure. Due to the thermal expansion and contraction effects inherent in optical fibres, FBG sensors exhibit high sensitivity to temperature fluctuations, facilitating precise and low-loss temperature monitoring. For instance, Hsiao et al. [12] measured extremely cold temperatures using metal-coated FBG sensors, while Liu et al. [13] enhanced the thermal expansion and contraction effects of optical fibres to enable real-time temperature measurement in high-temperature environments. Compared to conventional pressure measurement sensors, FBG pressure sensors demonstrate superior durability and stability. Li et al. [14] designed an FBG pressure sensor based on a cantilever beam structure, whereas Yang et al. [15] developed an FBG sensor utilizing an isosceles triangular cantilever beam structure for accurate pressure determination. Displacement in engineering is typically indicated by phenomena such as cracks, settlements, and misalignments, necessitating highly sensitive measurement tools. FBG displacement sensors are capable of accurately and in real-time monitoring such displacements. For instance, Shi et al. [16] proposed a compact FBG displacement sensor with robust micro-displacement measurement capability using a hyperbolic flexible hinge structure, and Ng et al. [17] developed a highly sensitive FBG displacement sensor based on the monitoring of FBG backward reflective power.

Given the intrinsic fragility of FBG sensors, encapsulation and protection are essential to ensure their reliability [18–20]. The advent and development of 3D printing technologies, especially fused deposition modeling (FDM), have introduced innovative methods for sensor fabrication and production [21, 22]. In FDM technology, a printer nozzle, guided by computer modeling, heats and melts the print material, depositing it layer by layer until the final product is formed [23]. For example, Hong et al. [24] designed an FBG-embedded pressure sensor utilizing FDM technology, while Hassan et al. [25] demonstrated the potential of 3D printing technology in designing soft pressure sensors, thereby highlighting the flexibility of 3D printed production.

Distributed fibre-optic sensors are classified based on their measurement principles into point-distributed, quasi-distributed, and fully distributed systems [26–28]. Point-distributed and quasi-distributed sensors usually employ FBGs as the measurement unit [29, 30]. For instance, Pei et al. [31] developed a sensor based on point-distributed fibre optics specifically designed for monitoring landslide displacements; Xu et al. [32] proposed a novel sensor based on quasi-distributed fibre optics for soil pressure measurements of earth slopes; and Luo et al. [33] proposed an ultra-weak FBG (WFBG) array sensing system for long-distance monitoring. In fully distributed fibre measurements, the entire fibre serves as the sensing element [34–36]. Li et al. [37] used an optical backscatter meter for concrete crack monitoring, confirming the effectiveness of distributed fibre optics in this application; Wang et al. [38] implemented distributed temperature measurements (DTS) for real-time monitoring based on the Brillouin scattering slow-light delay time; Ravet et al. [39] monitored continuous tunnel displacement using distributed fibre-optic strain sensing, highlighting the potential of distributed fibre optics in tunnel detection; and Prabodh et al. [40] proposed dynamic strain measurements using Brillouin optical time domain analyzer (BOTDA), providing a reference for the measurement of vibration-based physical quantities such as sound.

In summary, fibre-optic sensing exhibits substantial developmental potential in the realm of structural health monitoring. It is adaptable to a variety of monitoring conditions and is suitable for monitoring temperature, strain, and stress at structural vulnerable points, as well as for long-distance real-time monitoring. This study elucidates the measurement principles of various fibre-optic sensors and, in conjunction with FDM technology, details the production, calibration, and application of two types of FBG sensors. Furthermore, it analyzes the application of a distributed fibre-optic sensing system, offering guidance for the implementation of fibre-optic sensing systems in engineering.

## Working principle of fibre optic sensors

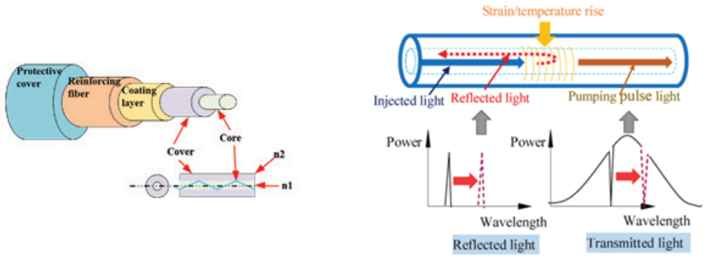
Fig. 1 shows structure of the optical fibre and the working principle of the fibre optical sensors. The core, being the innermost component, is responsible for light transmission. The outer protective layers safeguard the optical fibre from environmental damage and mechanical stress, thereby enhancing its durability and performance. The FBG sensor exhibit a high sensitivity to variations in external environmental conditions. When broadband light is incident upon a FBG, the FBG selectively reflects a specific wavelength while transmitting all other wavelengths. This particular reflected wavelength, known as the Bragg wavelength, is sensitive to variations in temperature and strain. The relationship between the Bragg wavelength and these external factors can be expressed as follows:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - P_{eff})\varepsilon + (\alpha + \xi)\Delta T, \qquad (1)$$

where $\Delta\lambda_B$ is the center wavelength drift of the FBG due to stress strain or temperature change; $\lambda_B$ is the initial wavelength of the FBG without external influence; $P_{eff}$ is the optical elasticity coefficient, for the commonly used quartz optical fibre to take 0.22; $\varepsilon$ is the fibre grating strain; $\alpha$ and $\xi$ are the coefficient of thermal expansion of the optical fibre grating and the thermo-optical coefficient, generally take $\alpha + \xi = 6.67 \cdot 10^{-6}$/°C; $\Delta T$ is the temperature change.

Distributed sensing technology can be categorized into three distinct types based on the underlying monitoring principles. Fig. 2 provides a comprehensive overview of the various types of distributed fibre optic sensors, categorizing them into point-distributed, quasi-distributed, and fully distributed. Point-distributed sensors measure strain and temperature variations by detecting changes in reflected wavelength. Quasi-distributed sensors utilize multiple measurement points along the fibre, each corresponding to a distinct wavelength shift, thereby enabling long-distance monitoring across multiple locations. Fully distributed sensors use the entire optical fibre as a continuous measurement point, allowing for the measurement of physical quantities along the entire length of the fibre.

The principles underlying point-distributed and quasi-distributed sensors align with those used in FBG monitoring systems, which are not reiterated here. In the upper right corner of the figure, the internal structure of the optical fibre and FBG details, such as the core,



*a* *b*

**Fig. 1.** Structure of the optical fibre (*a*); working principle of fibre optic sensors (*b*)

**Рис. 1.** Состав оптического волокна (*a*); принцип работы волоконно-оптических датчиков (*b*)

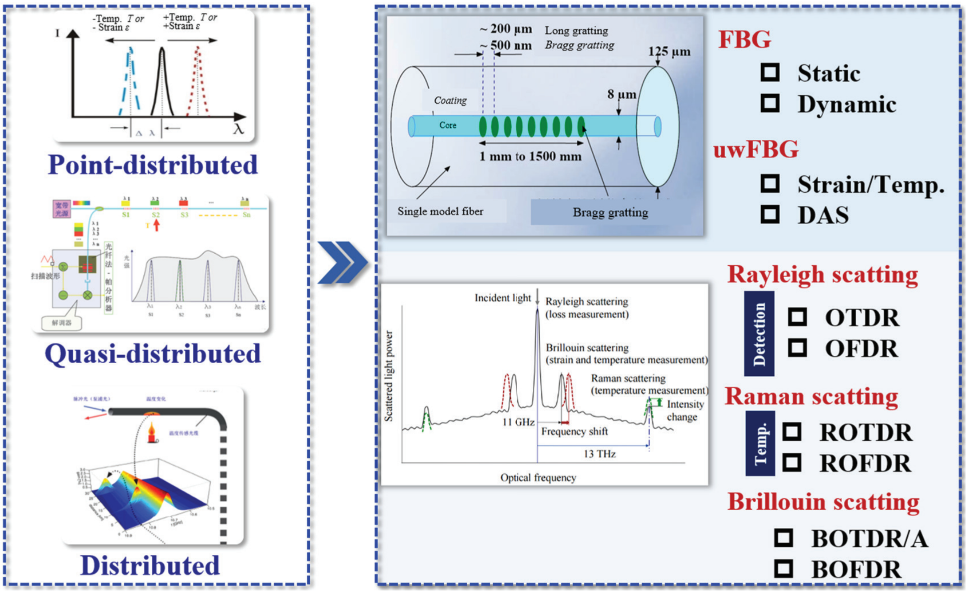


**Fig. 2.** Distributed fibre optic measurement principle and application

**Рис. 2.** Принцип и применение распределенных волоконно-оптических измерений cladding, and various grating periods, are depicted. FBGs are widely utilized for both static and dynamic measurements, with ultra-weak FBGs (uwFBGs) being particularly effective for monitoring strain, temperature, and distributed acoustic sensing (DAS).

Distributed measurement techniques are further classified based on their underlying monitoring principles, such as Rayleigh Scattering-Based Sensors, which is primarily used for high-resolution strain; the optical time domain reflectometry (OTDR) and optical frequency domain reflectometry (OFDR) are used for temperature measurement; the Brillouin Scattering-Based Sensors of Brillouin optical time domain reflectometry/analyzers (BOTDR/A) and Brillouin optical frequency domain reflectometry (BOFDR) are commonly used to measure distributed strains and temperatures.

### Newly designed effective soil stress transducer

In engineering applications, FBGs are frequently affixed to sensing units to measure various parameters. Given the complexity of the operational environment, it is often necessary to monitor multiple variables simultaneously. To address this challenge, the encapsulation and integration of FBGs is essential. In this study, an FBG sensor capable of simultaneously measuring earth pressure and water pressure was developed. As illustrated in Fig. 3, the FBGs for measuring earth and water pressures were embedded into the grooves of the upper and lower layers of the sensor, respectively. The upper structure is completely sealed, while the lower structure contains micropores that permit only water or air to pass through, ensuring measurement accuracy. The sensors were fabricated using the 3D FDM method, which allows the fibre grating sensing unit to be embedded directly during the printing process, thus preserving the sensor's integrity and sealing. FDM-fabricated sensors can be better matched to the modulus of the soil, ensuring synchronized deformation with the soil. Additionally, the flexibility of FDM enables the design of package structures that can integrate various measurement functions within a single sensor, thereby simplifying the measurement process.

Prior to deployment, the sensor must be calibrated to determine its static coefficient. As depicted in Fig. 4, the upper right part of the figure demonstrates the setup for the calibration test. The sensor's soil pressure measurement was calibrated using overlying pressure with a gradient of 0.01 MPa, applying corresponding weights to the sensor's sensing surface. The sensitivity of the sensor to soil pressure was calculated to be 12.633 nm/MPa through linear fitting. For the calibration of water pressure, air pressure was used in place of water pressure with a gradient of 0.05 MPa. The corresponding air pressure was increased in the water pressure sensor chamber, and the sensitivity of the sensor to water pressure was calculated to be 6.282 nm/MPa, also through linear fitting. These findings confirm that the sensor possesses sufficient sensitivity to both earth and water pressures to meet the necessary engineering specifications.

### Newly designed crack measurement sensors

Engineering structures are often susceptible to small cracks, necessitating the use of sensors with high measurement accuracy to monitor these small displacements. To meet this requirement, a high-accuracy, small-range FBG displacement sensor was developed and packaged using FDM technology. The design and structure of the sensor are shown in Fig. 5, with the sensor designed to have an overall length of 10 cm and a cross-sectional dimension of 8 mm.

The newly designed crack measurement sensors can measure micro-cracks under various conditions. The relationship between the slit displacement $\Delta x$ and the FBG wavelength drift $\Delta\lambda_B$ is shown in Eq. (2), where $K_\varepsilon$ is the fibre grating strain sensitivity coefficient, $K_1$ and $K_2$ are the elasticity coefficients of the fibre grat-

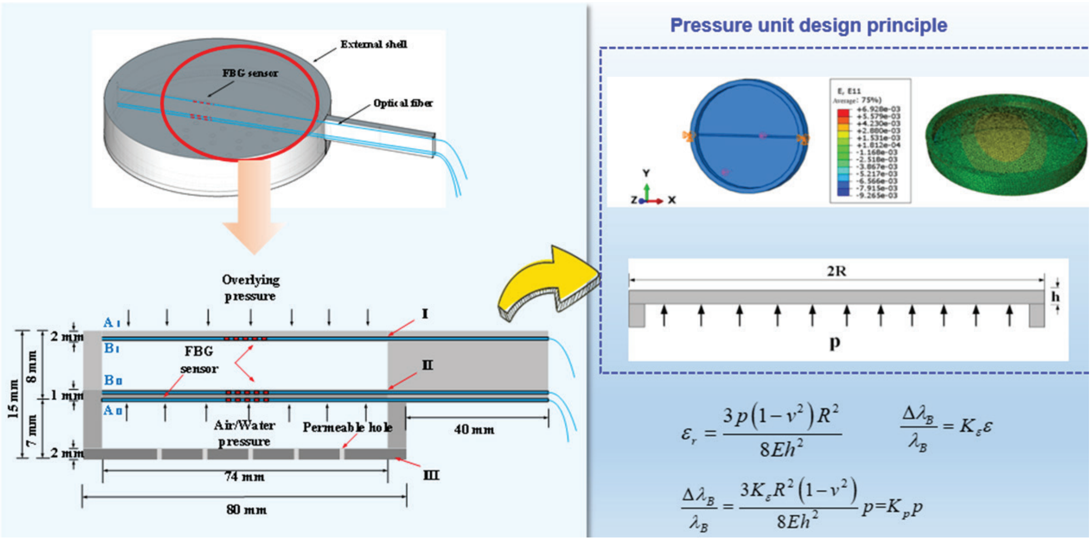


**Fig. 3.** Structure of soil – water pressure sensor

**Рис. 3.** Схема датчика давления грунт – вода

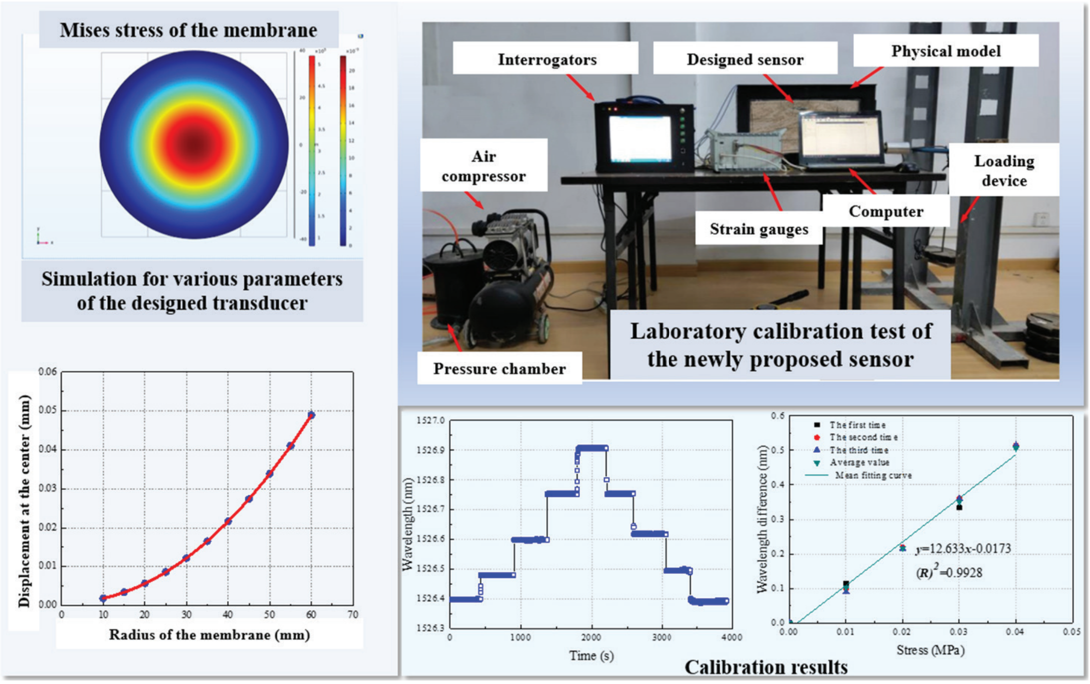


**Fig. 4.** Calibration of soil – water pressure sensor

**Рис. 4.** Калибровка датчика давления грунт – вода

ing and the spring, respectively, and $L$ is the length of the stretched fibre:

$$\Delta\lambda_B \approx K_\varepsilon \frac{K_2}{K_1}\frac{\Delta x}{L}. \tag{2}$$

The calibration tests were carried out in laboratory. The results are depicted in Fig. 5. It can be found that the displacement sensitivity of the proposed transducer was 2.301 nm/mm with a fitting coefficient of 0.992. The temperature sensitivity was 0.0208 nm/°C with a fitting coefficient of 0.9917. Based on the small-range FBG displacement measurement device, a hardware and software system was developed for long-term stable real-time monitoring of geotechnical bodies.

## Field application cases of newly designed fibre optic sensors

Structural damage in engineering typically begins with the initiation of cracks, followed by crack propagation and eventual structural failure. High-accuracy, small-range sensors with high sensitivity are suitable for real-time monitoring of crack propagation. In this study, newly designed fibre-optic sensors were applied to monitor crack displacement in rock bodies at the top of caves.

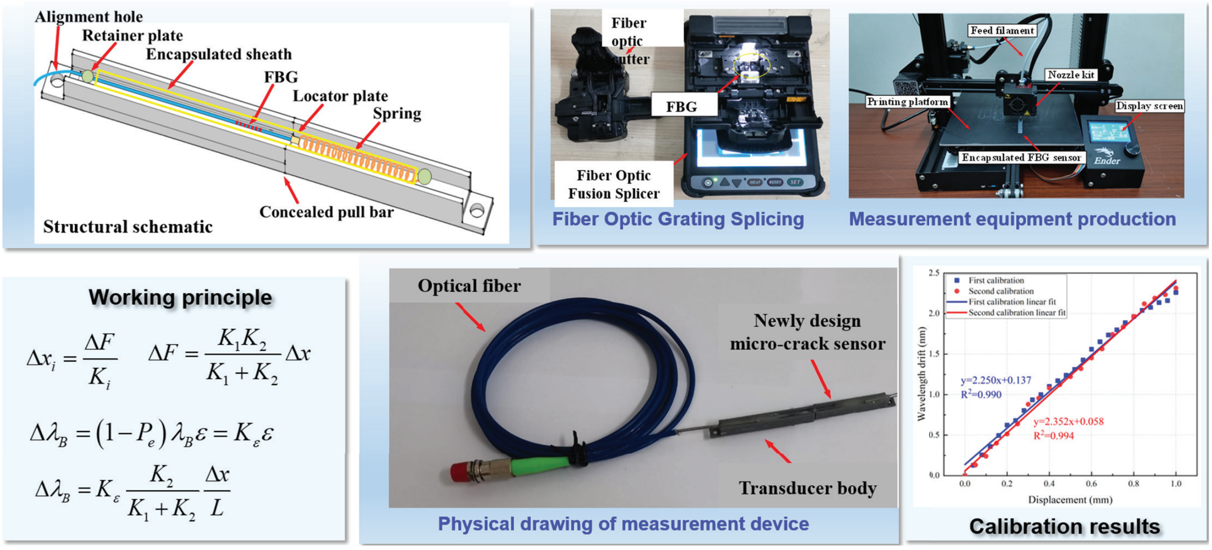
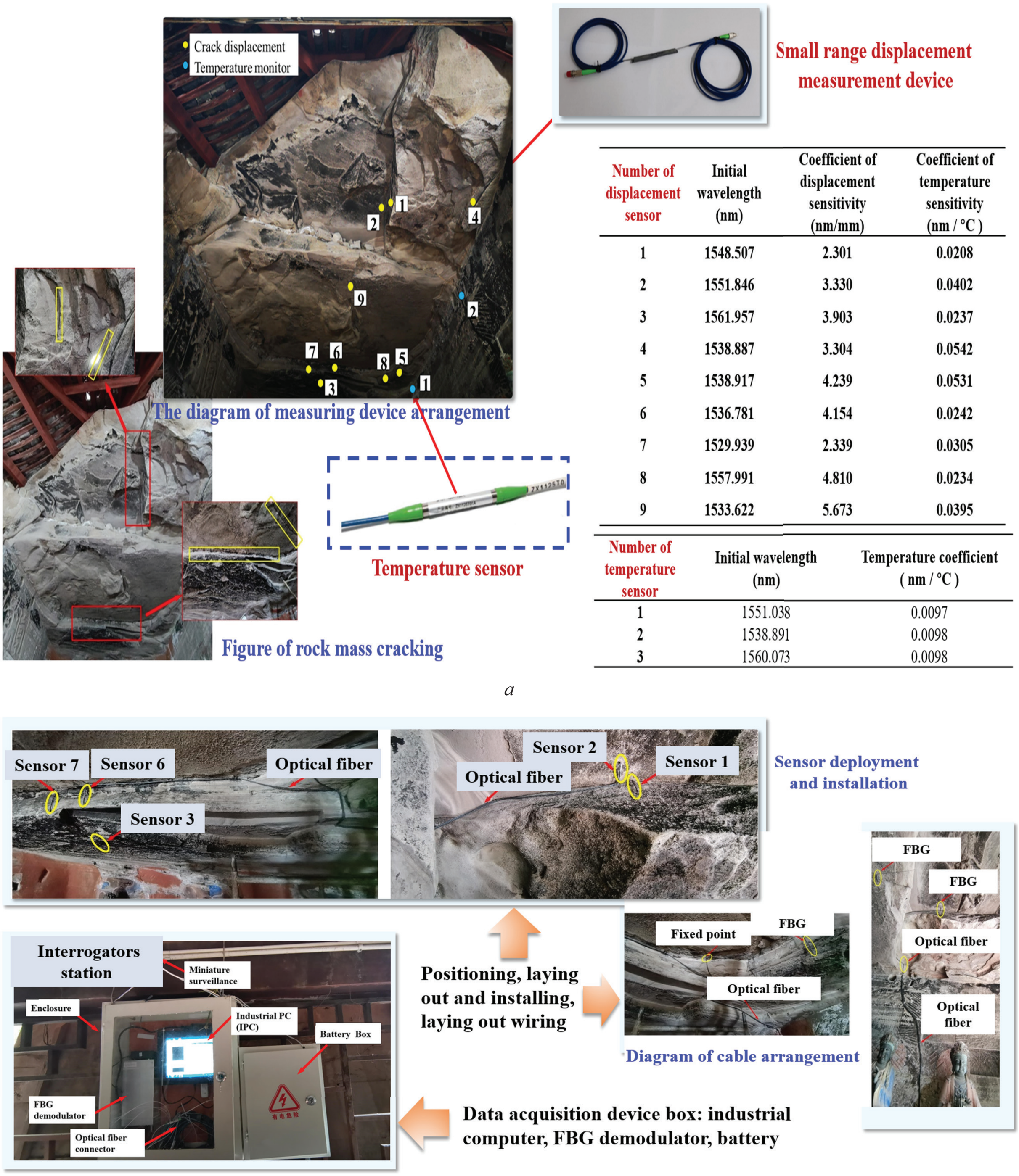


**Fig. 5.** Structure and object of sensor with high-precision, small-range

**Рис. 5.** Схема датчика с высокой точностью и малым радиусом действия



| Number of displacement sensor | Initial wavelength (nm) | Coefficient of displacement sensitivity (nm/mm) | Coefficient of temperature sensitivity (nm / °C ) |
|---|---|---|---|
| 1 | 1548.507 | 2.301 | 0.0208 |
| 2 | 1551.846 | 3.330 | 0.0402 |
| 3 | 1561.957 | 3.903 | 0.0237 |
| 4 | 1538.887 | 3.304 | 0.0542 |
| 5 | 1538.917 | 4.239 | 0.0531 |
| 6 | 1536.781 | 4.154 | 0.0242 |
| 7 | 1529.939 | 2.339 | 0.0305 |
| 8 | 1557.991 | 4.810 | 0.0234 |
| 9 | 1533.622 | 5.673 | 0.0395 |

| Number of temperature sensor | Initial wavelength (nm) | Temperature coefficient ( nm / °C ) |
|---|---|---|
| 1 | 1551.038 | 0.0097 |
| 2 | 1538.891 | 0.0098 |
| 3 | 1560.073 | 0.0098 |

*a*

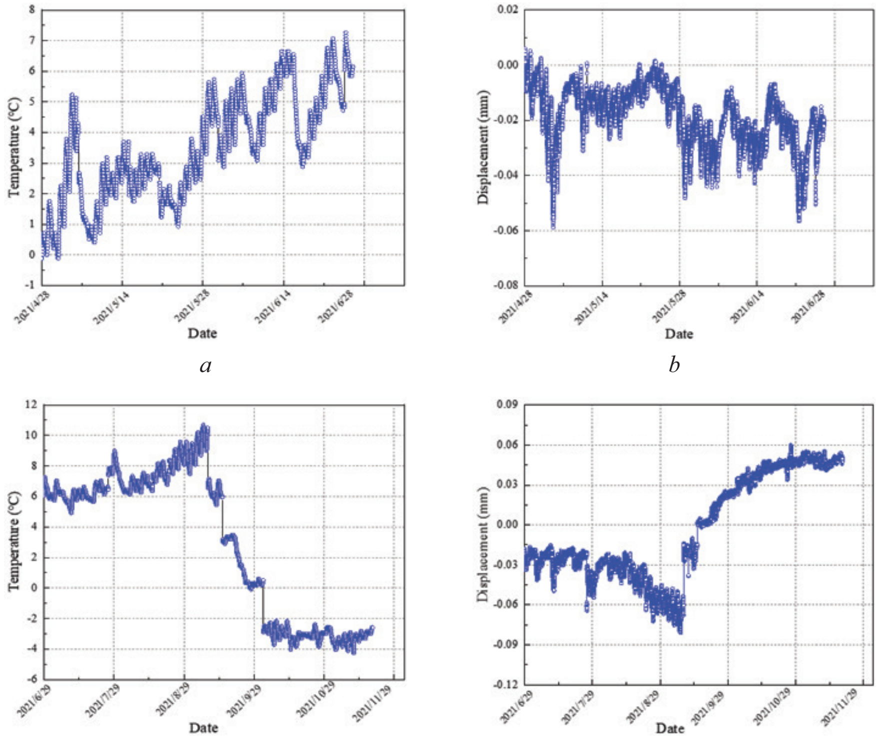
*b*

**Fig. 6.** Field application of newly designed fibre optical sensors: *a* — sensor arrangement; *b* — field instrumentation system

**Рис. 6.** Применение в полевых условиях новых волоконно-оптических датчиков: *a* — расположение датчиков; *b* — система полевых приборов

These rock bodies are subjected to significant bearing pressure and are disturbed by water spray erosion, wind, and seismic activities, all of which exacerbate crack propagation. To maintain the stability of the top rock body of the cave, real-time monitoring of crack displacement is essential. The arrangement of the top rock body and sensors is shown in Fig. 6. To ensure the accuracy of crack displacement monitoring, temperature sensors were also installed around the displacement sensors to compensate for temperature variations.

Cracks in the rock at the top of the cave were monitored over a one-year period, with time as the intermediate variable. Fig. 7 illustrates the results of crack displacement monitoring at point 1. Fig. 7, *a*, *c* show the temperature variations over the year, indicating a fluctuating pattern that aligns with seasonal atmospheric tem-



*a* *b*

*c* *d*

**Fig. 7.** Typical results of field cracks: *a* — April – June temperature monitor; *b* — April – June crack displacement monitor; *c* — June – November temperature monitor; *d* — June – November crack displacement monitor

**Рис. 7.** Стандартные варианты трещин, образовавшихся в полевых условиях: *a* — монитор температуры апрель – июнь; *b* — монитор смещения трещин апрель – июнь; *c* — монитор температуры июнь – ноябрь; *d* — монитор смещения трещин июнь – ноябрь

perature changes. The monitoring data reveal significant daily temperature variations, reflecting large diurnal temperature differences. Fig. 7, *b*, *d* depict the changes in crack displacement. After removing the effect of temperature on the wavelength, a positive increase indicates crack expansion, while a negative increase may be due to minor sensor rebound and the thermal expansion and contraction of the cracks due to temperature changes.

## CONCLUSIONS

This study provides a comprehensive discussion on the current state of optical fibre sensing technology. Some newly designed optical fibre sensors for effective stress and micro-cracks measurement in geotechnical engineering were also presented. The working principle, sensor design and advanced 3D FDM fabrication approach were elaborated. A typical field application case of the newly designed optical fibre sensors was discussed. Major conclusions are summarized as follows:

1. Optical fibre sensing technology could offer a new approach for health monitoring in civil engineering in good accuracy and long-term stability especially in harsh environment, such as low temperature, electro magnetic interference conditions and corrosion environment.

2. The proposed fibre optic transducer could measure the effective stress of earth pressure in high accuracy. The pressure sensitivity of the soil pressure diaphragm is 12.633 nm/MPa with a linear fitting coefficient of 0.9928. The pressure sensitivity coefficient of the water pressure diaphragm is 6.282 nm/MPa with a fitting coefficient of 0.992. The physical model results proved the accuracy of the newly designed fibre optical sensor.

3. A high-precision small range FBG displacement measurement device was proposed to measure micro-cracks in different conditions. The sensitivity of the proposed transducer was 2.301 nm/mm with a fitting coefficient of 0.992; the temperature sensitivity is 0.0208 nm/°C with a fitting coefficient of 0.9917. In addition, a hardware and software system was developed for long-term stable real-time monitoring of geotechnical bodies, which could provide beneficial guidance for actual engineering displacement, temperature changes, and disaster warning.

4. The outcome of this study provides newly approach investigating the displacement and strain patterns of models after stress deformation, offering practical monitoring means for subsequent engineering applications.

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