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Application of novel distributed fibre optic sensing for slope deformation monitoring: a comprehensive review

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Author Contributions

All authors contributed to the study's conception and design. Ashis Acharya performed the literature search and prepared the first draft of the manuscript, and Tetsuya Kogure investigated, commented, and critically revised the manuscript. All authors read and approved the final manuscript.

ABSTRACT

Distributed fibre-optic sensing (DFOS) has developed expeditiously over recent decades in multiple technical fields, including slope engineering, as it furnishes several advantages over conventional landslide monitoring approaches. Fibre-optic (FO) cables can be embedded in a shallow trench or buried in a borehole to detect precursory signs of failure well before collapse. By measuring sent and backscattered light, FO systems detect mass movement from changes on the cable so that early warning measurements can be made. This review paper briefly discusses the fundamentals of optical fibres, followed by a compendious explanation of the sensing principle of various DFOS techniques (Rayleigh, Brillouin, and Raman backscattering). The significant considerations for installing an FO cable in a borehole/shallow trench for deformation sensing and the ground-anchor-cable coupling mechanism are emphasised. The most recent advancements of DFOS applications on slope deformation monitoring from the laboratory model size to the field scale are discussed in great detail, emphasising the progress made within the last ten years. Ultimately, some challenges associated with DFOS sensing and future development prospects are discussed. Engineering geologists and slope hazard mitigation planners are anticipated to benefit from the wide-ranging, in-depth information gathered here.

Keywords Slope failure. Distributed fibre-optic sensing. Strain monitoring. Landslide early warning

Introduction

Landslides are the most frequent and catastrophic natural phenomena responsible for the innumerable loss of human life and habitat and changes in the Earth's topography. Between 2004 and 2016, 4862 deadly landslides were recorded worldwide (excluding earthquake-triggered landslides), killing 55997 individuals, according to a global landslide database (Froude and Petley 2018). Landslides, which devastate the country's wealth and human resources, are significant impediments to development. For instance, every year in China, landslide-related disasters result in hundreds of deaths and economic losses of almost 20 billion yuan (Zhao et al. 2021).

Landslides can occur at various rates, from almost imperceptibly slow (mm/year) to incomprehensibly rapid (up to hundreds of km/hr); therefore, understanding their dynamics is critical to minimising the overall impact on an ecosystem. Landslide studies and analyses are in a period of exponential growth, concentrating mainly on techniques and solutions for stabilising, preventing, and categorising the most vulnerable hillslopes. Among the several landslide risk mitigation strategies, early warning (EW) systems are the most cost-effective and allow for better planning of mitigation measures for landslides (Piciullo et al. 2018). For many decades, several conventional and novel technologies have been applied to surface and subsurface slope monitoring, such as remote sensing (Šegina et al. 2020), geographic information systems, acoustic emission and microseismic (Weber et al. 2018), extensometers (Mentes 2015), and inclinometers (Segalini et al. 2019). These techniques have their benefits and drawbacks in measurement range or accuracy. In the case of complex geological and geohydrological conditions, the discrete point data obtained from the inclinometer can hardly reflect the overall stability of the slope. The durability and reliability of typical electrical-based equipment for long-term monitoring are likewise questionable (Zhu et al. 2014).

Optical fibres were primarily developed for the telecommunications industry, but during the past two decades, their application has dramatically risen in a wide range of technological disciplines, including structural health monitoring (Bado and Casas 2021; Gómez et al. 2020), geohazard assessment (Puzrin et al. 2020; Zhang et al. 2021), industrial engineering (Campanella et al. 2016), and environmental monitoring (Amer et al., 2021). However, distributed fibre optic sensing (DFOS) technologies have received much attention since they have unrivalled capabilities and unprecedented features. DFOS incorporates Rayleigh, Raman, or Brillouin scattering in the time or frequency domain to measure parameters such as temperature, stress, strain, and other acoustic properties (Kishida et al. 2014; Schenato et al. 2017). Compared to conventional geotechnical sensors, this sensing technology has been widely used due to a range of unique benefits, including easy and fast data transfer, high sensitivity to strain and temperature, long-term durability, long-distance and real-time monitoring, cost-effectiveness, compatibility, and resistibility (Barrias et al. 2016).

The DFOS technique has made tremendous progress in detecting ground movements and forecasting landslides over the last two decades, as it can operate as a "nervous system" for slopes by sensing the tensile strain of the soil/rock that they are embedded (Ye et al. 2022). Approximately 20 years ago, the Public Research Institute of Japan investigated the effectiveness of FO sensors in landslides in collaboration with various international research projects. However, they reported on issues such as measured and actual displacement and the direction of the landslide movement (Higuchi et al. 2007). Several studies have now been published in the literature that explore the applicability of these technologies as landslide monitoring techniques.

Most of the previous work has been carried out under controlled laboratory settings in a physical model slope to test the sensors' ability to detect strain changes (Minardo et al. 2021; Song et al. 2017). Considering various scenarios such as artificial rainfall, surcharge loading, toe cutting, and confining pressure (CP), previous investigators tracked the strain evolution until the slope failed and monitored the overall slope condition using various DFOS methods (Song et al. 2017; Sun et al. 2020; Zhang et al. 2021).

In field applications, FO cables can either be installed vertically in a borehole to localise shear zones (Kogure and Okuda 2018) or buried shallowly in a surface trench to detect cracks or fissures (Liu et al. 2017); sometimes, they can be readily integrated into artificial reinforcing structures so that they can fully reflect the overall deformation characteristics without missing any key features. To illustrate, in Yancheng city, Jiangsu Province, China, Zhang et al. (2021) employed optical fibre distributed strain sensing (DSS) technology in a 240 m deep borehole to examine the deformation characteristics of subsurface strata. More recently, Minardo et al. (2021) deployed a distributed FO sensor to monitor the Coroglio tuff cliff (Naples, Italy) over three years (May 2015–May 2018) and successively investigated the thermal dilations of the rock and the progressive deformation of the fracture. Recently, Arslan Kelam et al. (2022) presented the case of sensor installation in a shallow trench to detect landslide displacement.

Surprisingly, a critical review of DFOS applications regarding slope monitoring is rarely available in the literature; therefore, a comprehensive review of the studies on this issue is inevitable. Some reviews based on DFOS for civil engineering structural health monitoring and geoengineering, such as Ye et al. (2014), Barrias et al. (2016), Schenato (2017), and Bado and Casas (2021), have briefly attempted to incorporate the use of DFOS in slope stability assessment. However, a critical investigation on the topic is still lacking. Therefore, the present review attempts to analyse the issues in a single article, critically emphasising the recent developments made within the last decade.

Fundamentals of an optical fibre

Basic structure

An optical fibre is a thin, flexible, transparent fibre made of glass (silica) or plastic that serves as a light pipe for transmitting light from one end of the fibre to the other. Total internal reflection is the mechanism that governs light propagation through a fibre (Personick 1983). An optical fibre's basic structure comprises three coaxial layers: the core, the cladding, and the outer jacket or buffer (Fig. 1). A cylindrical rod comprised of a light-guiding dielectric substance makes up the core or innermost component. The core is encased in cladding, which has a lower refractive index (RI) than the core. Cladding prevents surface pollutants from soaking into the fibre and eliminates light leakage from the core into the atmosphere. The outermost protective layer also referred to as the outer jacket, shields the cladding from physical damage.

Single-mode fibre (SMF) and multimode fibre (MMF) are two types of optical fibres based on their mode number. An SMF can only propagate one mode of light, whereas an MMF has a large core that can propagate multiple light modes. SMF cores typically range from 5 to 10 µm in diameter, with 8 µm typical. Signals with wavelengths of 1310 or 1550 nm can propagate through an SMF core with a relatively small diameter. SMF cables are designed to maintain each optical signal's spatial and spectral integrity over long distances, allowing data to be delivered faster. In SMF, light propagation is only possible when $\nu < 2.405$, which is defined by Eq. (1) (Addanki et al. 2018):

$$v = \frac{2\pi a\sqrt{n_1^2 - n_1^2}}{\lambda_0} \quad (1)$$

where v is the normalised frequency, a is the fibre core diameter, λ_0 is the light propagation wavelength, and n_1 and n_2 are the RIs of the core and cladding, respectively.

MMFs have core sizes of 50-62.5 µm and can accommodate a variety of independent light modes within the core's width (Addanki et al. 2018). MMFs transmit high-bandwidth data across a small distance of less than 1 km. Multiple pathways convey a light signal through the MMF's core; the signal usually passes through the cable's core at a wavelength between 810 and 1300 nm (Nyarko-Boateng et al. 2020). Due to the slight RI difference and low coupling efficiency of the input power, the backscattered power of an SMF is approximately 10 dB lower than that of an MMF (Nakazawa 1983).

The step-index MMF has a large core with a diameter of 62.5 µm. As a result, light rays that make up the digital pulse may travel directly. In contrast, others may bounce off the cladding in a zigzag pattern (Fig. 2). The diverse groupings of light beams, referred to as modes arrive individually at the receiving point due to their unusual paths. The RI steadily decreases from the central axis towards the cladding in the core of the graded-index MMF. Light rays going down the axis advance more slowly with a greater RI than those near the cladding (Nyarko-Boateng et al. 2020).

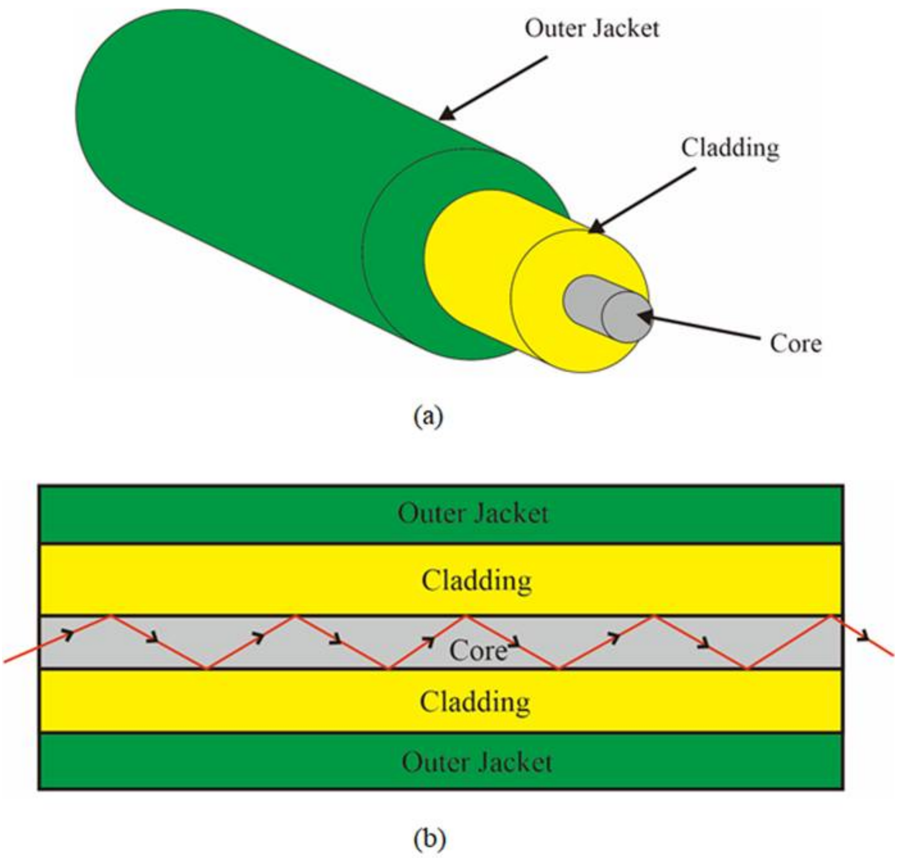


Fig. 1 Basics of an optical fibre **a** structure of an optical fibre and **b** cross-section of an optical fibre depicting the total internal reflection phenomenon along the fibre core

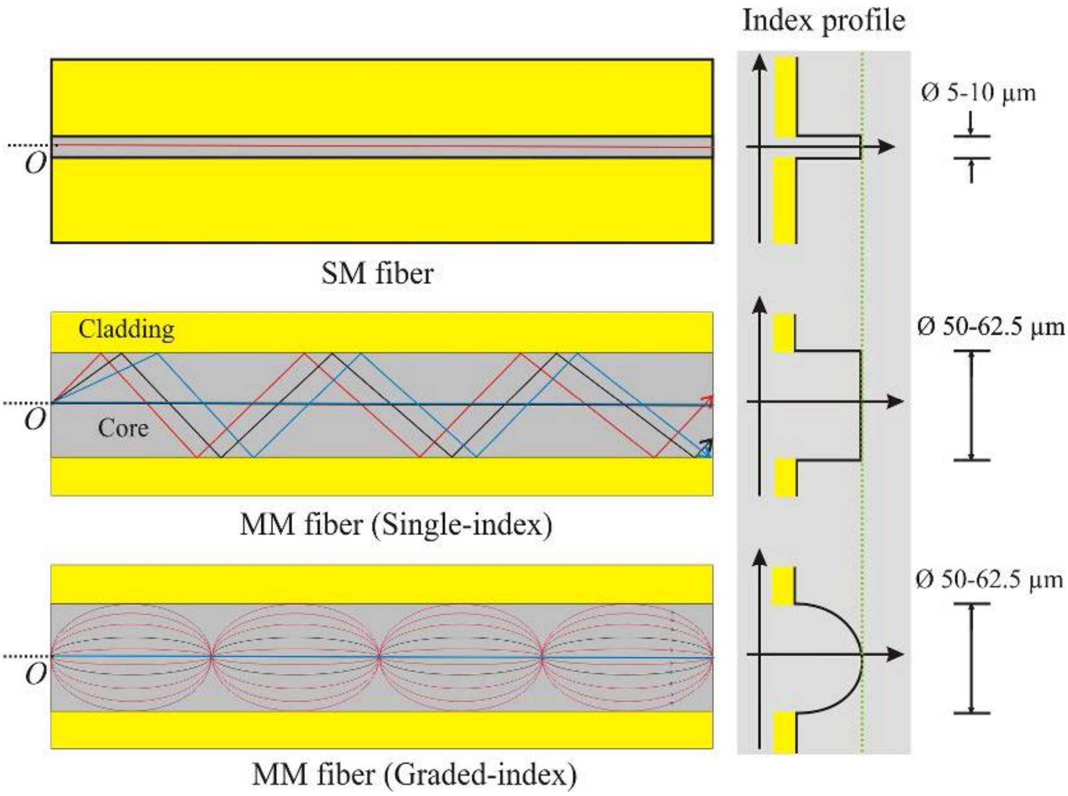


Fig. 2 Types of optical fibres based on the mode number

Backscattering phenomenon in optical fibres

Given that the angle of the incident light inside the core is greater than the critical angle, the function of the optical fibre is dependent on the theory of total internal reflection, which occurs at the interface between the core and cladding. A light wave interacts with the atoms and molecules as it travels through them. The electric field creates a time-dependent polarisation dipole when the light wave is far from a medium resonance. The induced dipole generates a secondary electromagnetic wave, which is light scattering (Bao and Wang 2021). Due to variations in density and composition, the light beam interacts with the fibre, and some photons return to the light source, causing backscattering. The elastic and inelastic back-propagating light helps to characterise fibre imperfections (Bao and Wang 2021; Barrias et al. 2016). The properties of the backscattered light can be characterised by phase, frequency, and amplitude to predict the changes in physical factors such as strain and temperature along the fibre. The energy ratio between the incident and backscattered light is significant for predicting fault location along the optical fibre.

Distributed fibre optic sensing (DFOS)

Since the entire length of the fibre functions as a sensor with DFOS sensing technology, information may be gathered from thousands of continuous sensing locations, which is impossible with conventional point-based sensing methods; therefore, the term ‘distributed’ is provided for DFOS. This sensing method is a unique monitoring solution that utilises the backscatter of optical pulses directed down an FO cable to monitor the temperature, stress, and strain affecting that cable. Elastic (Rayleigh) and nonelastic (Brillouin and Raman) scattering effects can be distinguished in the backscattering spectrum (Fig. 3). Only the Rayleigh and Brillouin scattering processes are affected by the medium's strain and temperature. In contrast, Raman-based systems are only temperature-sensitive (Monsberger et al. 2020). Table 1 illustrates the performance differences between the various DFOS techniques.

DFOS can be broadly categorised into two sensing systems: optical time-domain reflectometry (OTDR) and optical frequency-domain reflectometry (OFDR). In OTDR, the input pulse is launched into the fibre under test (FUT). The light that is transmitted through the fibre core will reflect and scatter to some extent. The same OTDR device detects the light from the input pulse that is back-reflected by Rayleigh backscattering or Fresnel reflection. Similarly, the OFDR sensing system is a sensitive and versatile technology that employs a tunable laser source (TLS) to detect the magnitude and phase response of an FUT. The OFDR sensing system is based on the fundamentals of swept wavelength interferometry (SWI). TLS produces a sinusoidal variation in output wavelength over time. The swept light is separated into two signals: probe and reference. The probe light is sent through an FUT, and the backscattered light is combined with the reference light and is detected coherently (Sun et al. 2021). Because of the time delay between the probe and reference signal, the beat frequency can be obtained. By performing a Fourier transform on the detected signal, one may determine the beat frequency value and map the location where the backscattered signal occurred (Dakin 1993).

Table 1 Relative performance characteristics of each type of distributed sensing (based on Barrias et al. 2016; Lu et al. 2019; Schenato 2017)

Distributed sensing technique	Sensing Range	Spatial resolution	Measurement time	T and ε	Fibre type
Coherent Rayleigh OFDR (COFDR)	10 m	1.3 mm	42 ms	Yes	SMF
	70 m	1 cm	10-20 s		
Coherent Rayleigh OTDR (COTDR)	Up to 40 km	4 m	20-500 µs	Yes	SMF
	100 km	5 m	n/a		
BOTDR	45 km	5 m	1800 s	Yes	SMF or few-mode
	20-50 km	1 m	n/a		
BOTDA	10 km	1.5 m	4 s	Yes	SMF or few-mode
	60 km	4 m	600 s		
Raman OTDR	1-37 km	1 cm-17 m	n/a	T only	SMF/MMF

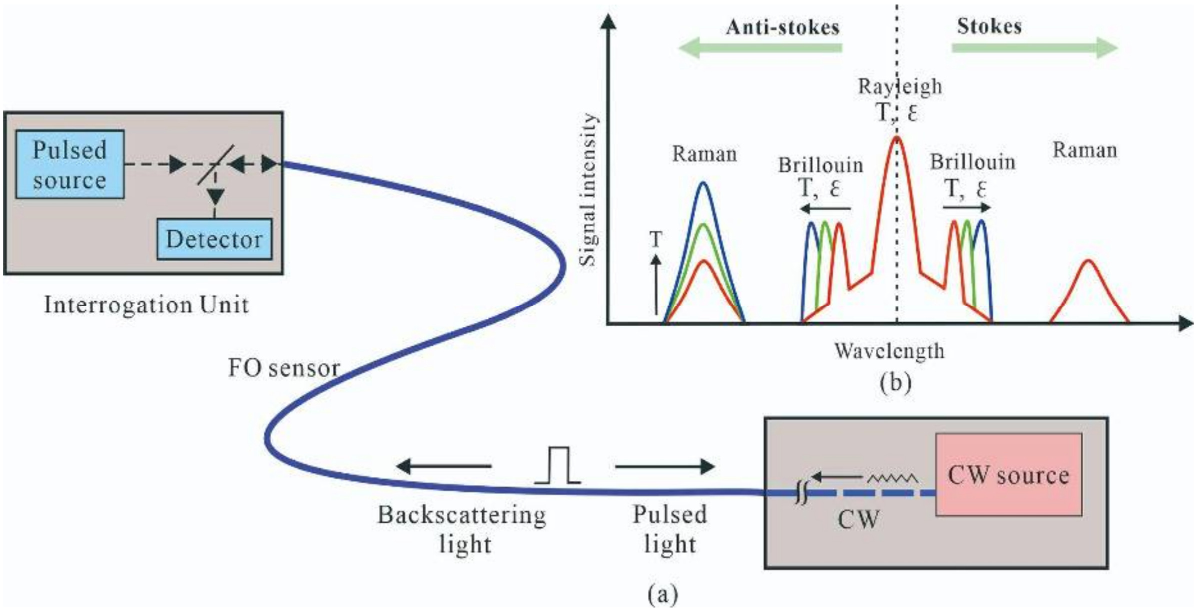


Fig. 3 Distributed FO sensing techniques **a** basic scheme of the sensing setup and **b** different scattering components in optical fibres (*T*: temperature, *ε*: strain) (modified from Monsberger et al. 2020)

Rayleigh backscattering

Lord Rayleigh was the first to study how air molecules scatter light. Rayleigh scattering distributed sensing is the elastic distribution of light induced by the interaction of incident photons with particles smaller than the wavelength of the light itself along the optical cable. Local environmental perturbations, such as changes in temperature, pressure, or strain, can be detected along the optical fibre by monitoring the variations in the amplitude, frequency, or phase of the backscattered light. Despite having a limited sensing range, this method has the highest spatial resolution (almost 1 mm), making it excellent for monitoring the characteristics listed above (Bado and Casas 2021). The fourth power of the wavelength is inversely related to the degree of scattering (Di Sante 2015).

A typical arrangement for Rayleigh backscattering is illustrated in Fig. 4. The random ordering of the molecules creates localised differences in density and, as a result, fluctuations in the refractive index (Bao and Wang 2021). The amount of power spectral shift before and after environmental changes ($\Delta\nu_R$) is proportional to changes in strain or temperature and can be stated as Eq. (2):

$$\Delta\nu_R = C_{11}\Delta\varepsilon + C_{12}\Delta T \tag{2}$$

where $\Delta\varepsilon$ and ΔT denote strain and temperature changes, respectively. C_{11} and C_{12} are two constant coefficients corresponding to strain and temperature change, respectively. These parameters should be evaluated in the laboratory calibration test for each type of cable.

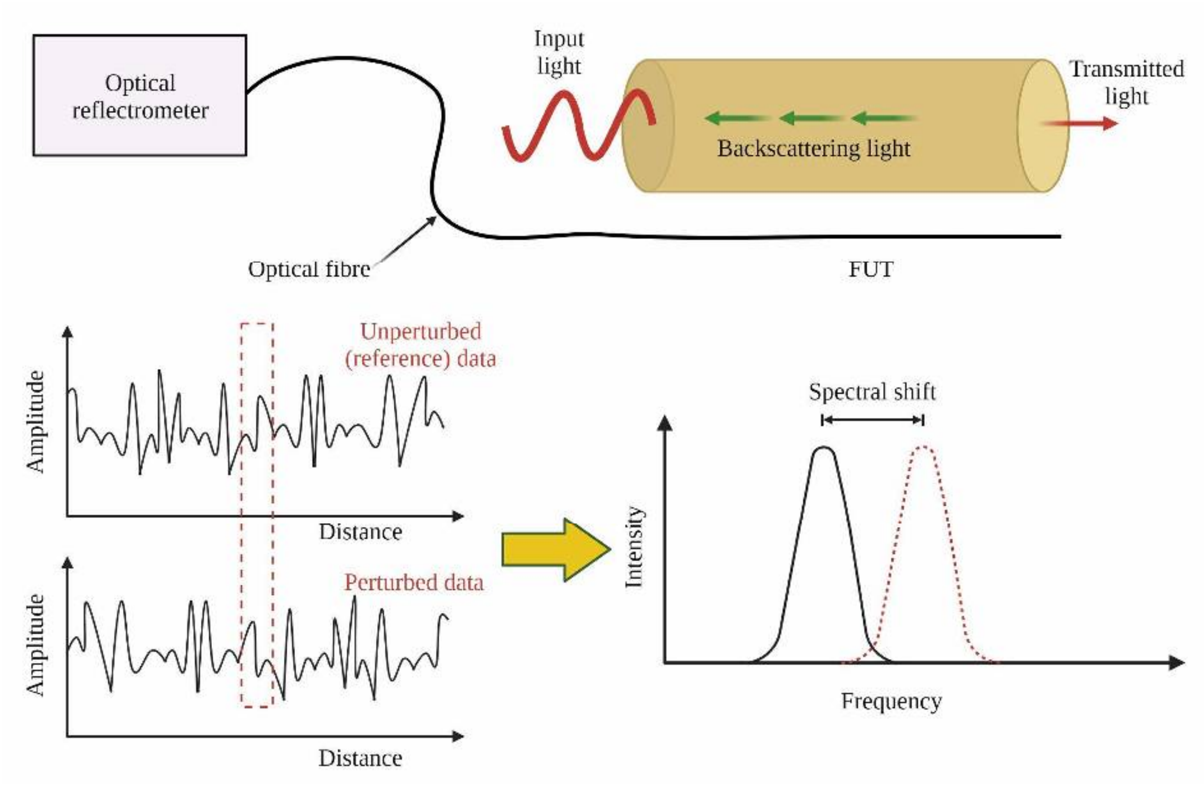


Fig. 4 Schematic representation of the Rayleigh-based OFDR sensing technique (modified from Berrocal et al. 2021)

Brillouin backscattering

The Brillouin scattering technique has recently sparked considerable interest because of its strain and temperature sensing potential. As in Raman backscattering, light is scattered in Brillouin sensing as a result of the interaction between incident light and thermally generated material density fluctuations (acoustic photons), resulting in Stokes (longer wavelength than the pump) and anti-Stokes (shorter wavelength than the pump) wavelengths (Rogers 1999). Commonly used Brillouin backscattering sensing techniques are standard Brillouin optical time-domain reflectometry (BOTDR) or Brillouin optical time-domain analysis (BOTDA) based on spontaneous and stimulated Brillouin scattering, respectively. Due to the stimulated amplification of Brillouin spectra, BOTDA technology can obtain higher spatial resolution and accuracy than BOTDR technology (Zhao et al. 2021).

A typical configuration for Brillouin backscattering is presented in Fig. 5. Mathematically, the amount of Brillouin frequency shift ($\Delta\nu_B$) can be expressed by Eq. (3):

$$\Delta\nu_B = \frac{2\mu\nu_a}{\lambda} \tag{3}$$

where μ depicts the effective RI of the fibre, ν_a denotes the acoustic wave velocity of the fibre core, and λ is the wavelength of incident light waves. For instance, ν_B takes values from 11.5-13 GHz (Nikles et al. 1996) and 10-13 GHz (Rui et al. 2017) depending on the fibre RI profile at pump wavelengths of 1300 nm and 1550 nm, respectively.

The Brillouin central frequency depends very linearly on either temperature or strain over an extended range (-30 °C < T < 100 °C, 0 < ε < 1%) (Nikles et al. 1995). This linear dependency can be expressed by Eq. (4) (Hong et al. 2016):

$$\Delta\nu_B = C_{21}\Delta\varepsilon + C_{22}\Delta T \quad (4)$$

where $\Delta\varepsilon$ and ΔT denote the strain and temperature changes, respectively. C_{21} and C_{22} are two constant coefficients corresponding to the strain and temperature changes, respectively. These coefficients depend on the material composition and geometry of the optical fibre. For standard telecommunication SM fibres, C_{21} and C_{22} will vary slightly at approximately 500 MHz/% and 1 MHz/°C, respectively, at an operating wavelength of 1550 nm (Rui et al., 2017).

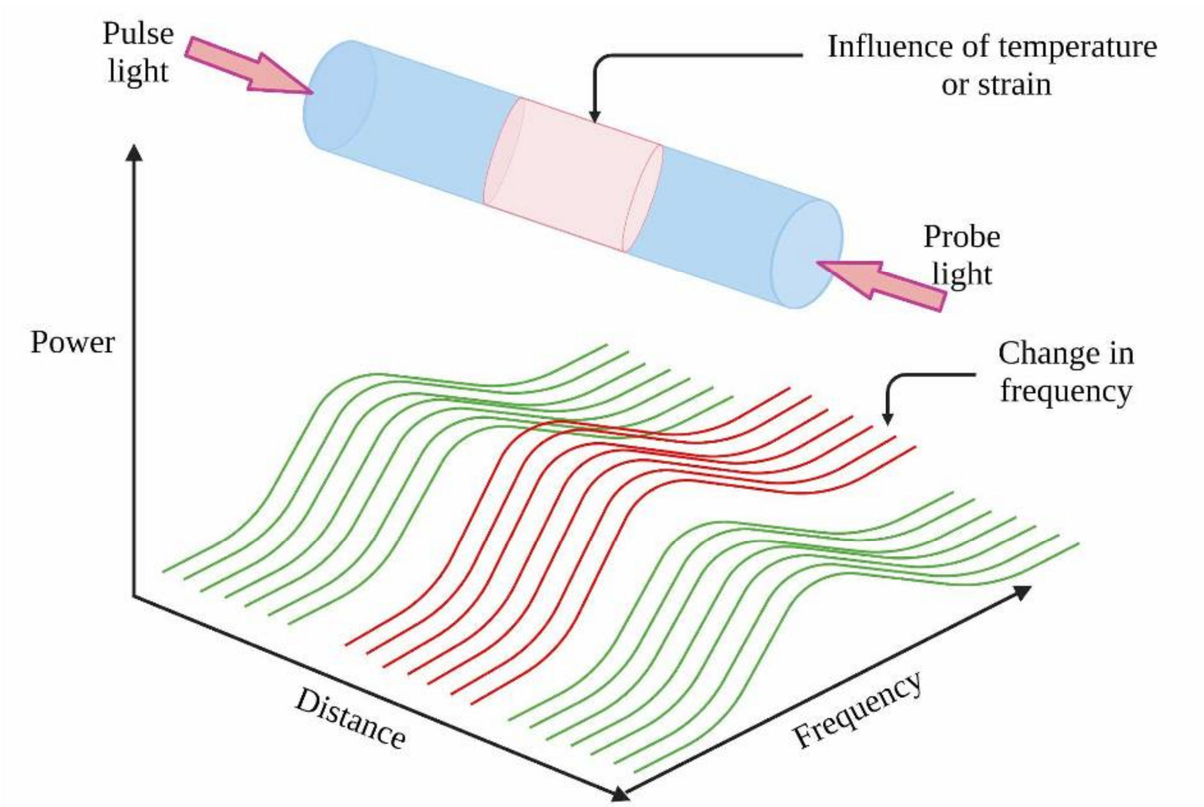


Fig. 5 Schematic representation of temperature and strain sensing using the BOTDR technique (modified from (modified from Tang and Cheng 2018)

Raman backscattering

Raman scattering is based on detecting the signal reflected (backscattered) directed towards the laser source after an incoming light pulse from a laser is transmitted via an optical fibre. Raman scattering is inelastic, resulting in anti-Stokes and Stokes components. Eqs. (5) and (6), respectively, express the anti-Stokes and Stokes Raman photons as follows (Li and Zhang 2022):

$$h\nu_s = h(\nu_0 - \Delta\nu) \quad (5)$$

$$h\nu_{as} = h(\nu_0 + \Delta\nu) \quad (6)$$

where h stands for the Planck constant, ν_0 depicts the initial frequency of the incident light, and ν_s and ν_{as} are the frequencies of the Raman Stokes and anti-Stokes signals, respectively.

The Stokes band is the portion of the light that has been shifted to a higher wavelength. The anti-Stokes band is the part of the light that has been moved to a lower wavelength and is temperature sensitive (as sketched in Fig. 6). As a result, Raman scattering is exclusively employed to measure distributed temperature (Wijaya et al. 2021). The amplitude of the anti-Stokes component is proportional to the average number of thermally generated phonons ($\bar{n}$) in the medium, which is expressed by Eq. (7):

$$\bar{n} = \frac{1}{e^{h\Omega/KT} - 1} \quad (7)$$

where h is the Planck constant, Ω is the optical frequency shift, K is the Boltzmann constant, and T is the absolute temperature. In contrast, the amplitude of the Stokes part is proportional to $\bar{n} + 1$ (Lu et al. 2019).

For distance ranges of several kilometres and a spatial resolution of 1 m, the repeatability of Raman dispersed temperature devices is on the order of 0.1 °C. It declines with increasing distance but can be maintained by increasing the device acquisition time. The maximum range is 30 km (Henault et al. 2010).

The Raman-based distributed temperature sensing (DTS) approach has been widely employed in many engineering applications since it was initially tried in a solid-core optical fibre utilising a solid-state source and detector (Dakin et al. 1985). This method has a spatial resolution of 0.25 m and a sensing range of 0. l °C, allowing temperature measurements over a 20 km fibre scope. Standard germanium-doped telecommunications grade fibres are utilised for Raman scattering.

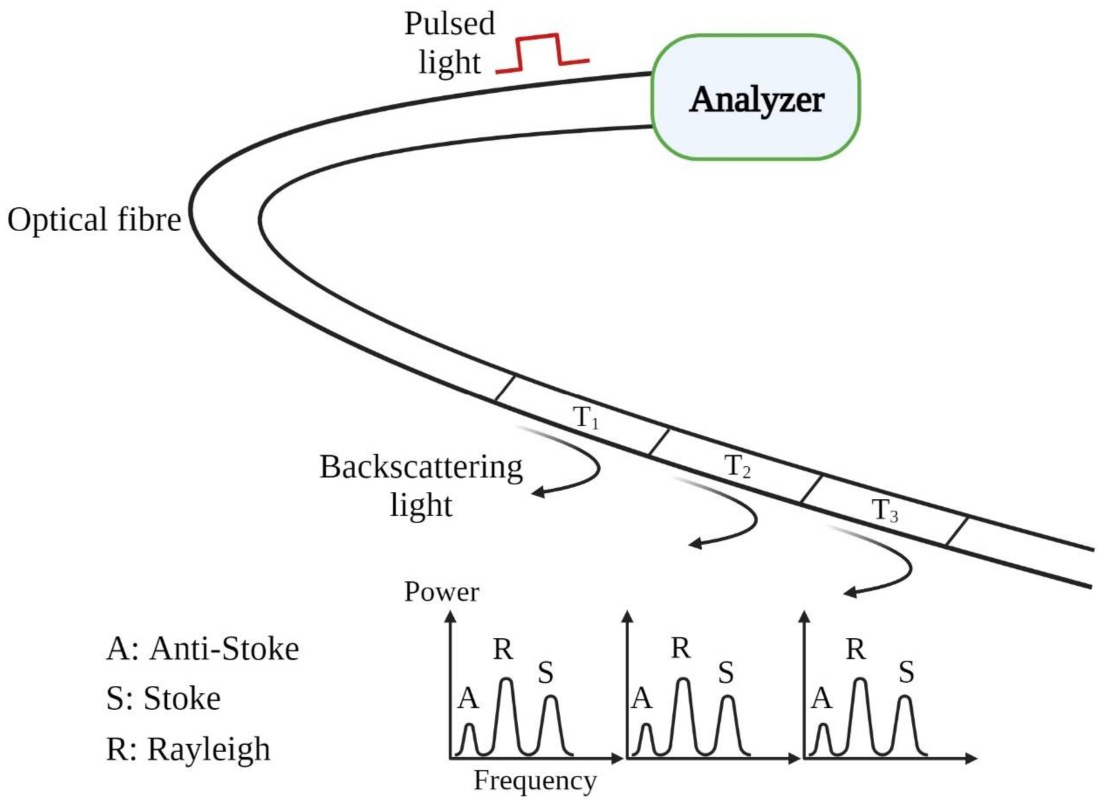


Fig. 6 Schematic representation of distributed temperature sensing using the Raman-based DFOS technique (reproduced from Soga and Luo 2018)

Basics of FO cable deformation

An optical fibre transmits the wavelength information of the reflected wave to the ground receiver to obtain the multifield information within the landslide mass and the mechanism for the deformation of the slip surface (Peng et al. 2020). The preimplanted fibre is hypothesised to deform and exert strain when the rock or soil body inside the landslide deforms vertically or horizontally, resulting in a change in the wavelength of the reflected wave (Chai et al. 2019. This is the basic principle of ground strain measurement employing distributed FO sensors. Eqs. (2) and (4) are simplified general equations that can be summed up to obtain the entire fibre's strain distribution by computing the backscattering light's frequency/spectral shift.

Let us consider an installed FO cable in a vertical borehole extending from the slip surface to the deep stable layer. The cable's displacement vector is assumed to parallel the slope at the sliding surface, where substantial shear strains are expected to cause permanent landslides. At the slope surface, the horizontal and vertical components of the displacement vector (Δx_0, Δz_0) are geodetically measured. These components can be divided into two orthogonal segments, $u_{0\beta}$ and $w_{0\beta}$ (Eqs. 8 and 9), one parallel to the sliding surface and the other perpendicular to it (Puzrin et al. 2020):

$$u_{0\beta} = \Delta x_0 cos\beta - \Delta z_0 sin\beta, \quad (8)$$

$$w_{0\beta} = \Delta x_0 sin\beta + \Delta z_0 cos\beta. \quad (9)$$

Fig. 7 illustrates the deformation of an initially vertical cable segment. The top of the segment undergoes displacement relative to its bottom. As a result, the FO cable element deforms (elongates or shortens), resulting in the measured strain of:

$$\varepsilon = \frac{dz - dz_0}{dz_0} \quad (10)$$

where dz_0 is the initial vertical cable segment, and dz is the length of the segment after deformation.

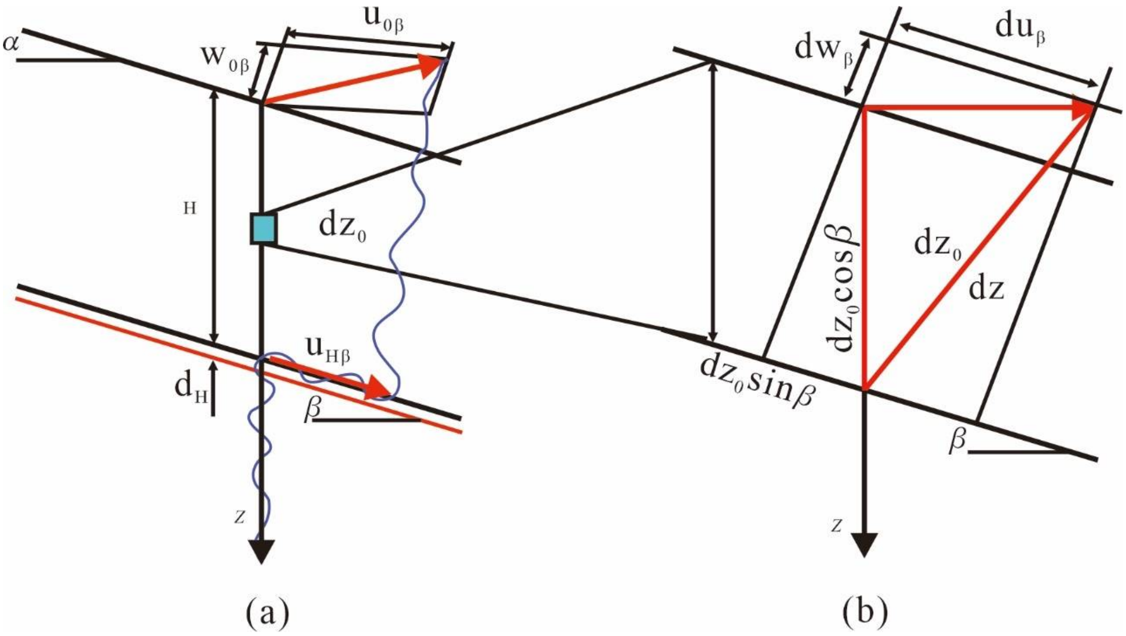


Fig. 7 a Showing the geometry of the FO cable installed sliding slope (*H* represents the thickness of the sliding layer and α is its inclination; d_H is the thickness of the sliding surface; β quantifies the inclination of the sliding surface; $u_{H\beta}$ depicts the displacement vector of the FO cable) and **b** schematic deformation of the cable's element (reproduced from Puzrin et al. 2020)

Strain is distributed along the optical fibre's axial direction. As a result, the strain data from the DFOS interrogator may be combined along the fibre length to obtain stratum deformation (Gu et al. 2018; Liu et al. 2019). The equation is as follows:

$$\Delta D = \int_{h_1}^{h_2} \varepsilon(h)\, dh \quad (11)$$

where ΔD is the deformation from h_1 to h_2 and $\varepsilon(h)$ quantifies the strain distributed along the depth.

It should be emphasised that the shear deformation of the sliding zone in the lower, middle, and toe portions of the landslide differs (Sang et al. 2019). The strain distribution is affected by the angle between the optical cables and the sliding zone and the position of the main slip surface in the sliding zone (Fig. 8).

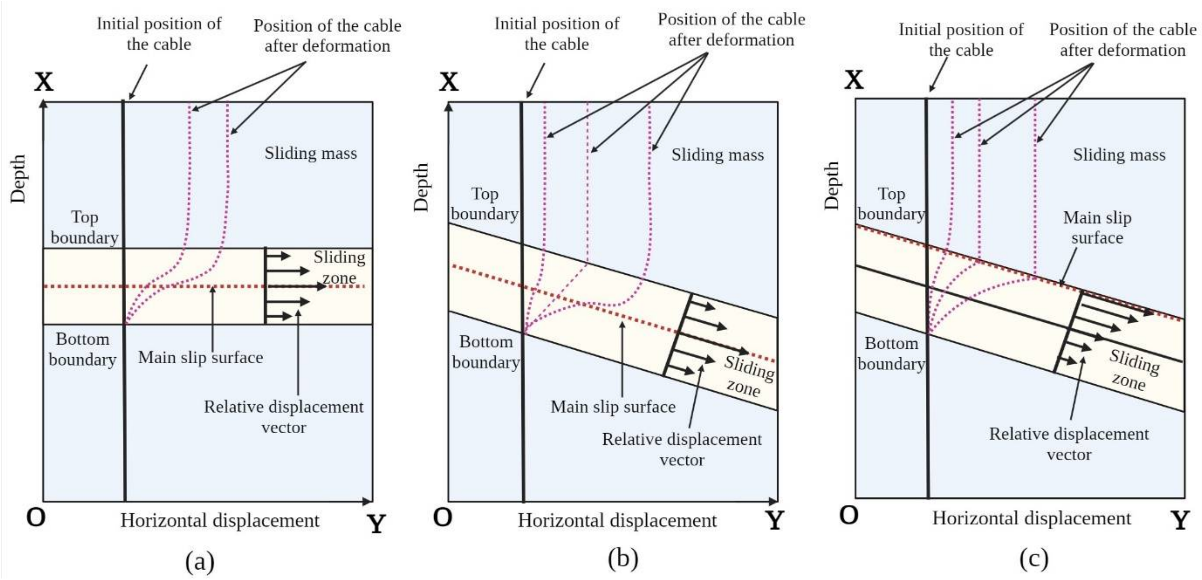


Fig. 8 Spatial relationship between the sliding zone and cable **a** at the lower portion of the landslide where the angle between the sliding zone and the cable is 90° and the main slip surface is located in the middle of sliding zone **b** at the middle portion of the landslide where the main slip surface is located in the middle of the sliding zone, and **c** at the toe portion of the landslide where the main slip surface is located at the top boundary of the sliding zone (modified from Sang et al. 2019)

FO sensor installation

DFOS sensors are directly inserted into a borehole that extends to the bedrock below the slip surface or is laid inside a shallow trench to detect small settlements or shear zones to monitor the vertical deformation profiles. Table 2 compares the installation techniques for shallow trenches and boreholes.

A change in the frequency of light induced by strata compaction or rebound can be detected using an optical fibre inserted vertically inside the borehole. The sequential steps for borehole-embedded FO slope monitoring include drilling a vertical borehole, washing the hole with clean water, installing optical fibre, backfilling the hole, and sealing it. The monitoring objectives and site conditions determine the borehole size. Zhang et al. (2021) installed an optical cable in a monitoring borehole with a depth of ~200 m and a diameter of 129 mm. Sun et al. (2016) designed six boreholes with depths ranging from 14.2 m to 40 m.

Ducting and trenching were previously investigated methods for laying optical fibres on shallow surfaces. This methodology performs well in sandy, gravel, and cobbles. For instance, Schenato et al. (2017) successfully demonstrated that the shallow installation of FO sensors on a landslide mass is practical and more relevant for detecting shallow landslide triggering. Liu et al. (2017) embedded the optical fibre in a 75 cm deep and 40 cm wide trench in Wuxi City, China, to detect the ground fissures developed due to subsidence using the BOTDA-based sensing method. Measurements were carried out for 5.5 years and successfully detected two deformation areas. During the whole measurement period, the entire optical cable was stretched by 11.3 mm due to the ground subsidence. Amer et al. (2021) installed an FO cable with a total length of approximately 2.9 km in a trench less than 50 cm deep for ground subsidence-uplift deformation monitoring. It should be emphasised that to simplify the measuring system and reduce measurement time, different segments of the optical fibre lines need to be connected into a complete loop after they are laid in a trench (Zhang et al. 2021).

There are currently no trench or borehole design specifications for ground sensing. Large-diameter boreholes cannot guarantee the entire strain transfer within the formation. Large-scale trench excavation can disturb the surrounding area. Therefore, cable installation on the shallow soil surface can be accomplished by employing mini-trenching techniques. The microtrenching (slot-cut) installation technique could be a suitable option for asphalt surfaces that cross landslide boundaries.

Table 2 Comparison between the borehole and trench installation of the optical cable

Borehole	Shallow trench
A borehole is drilled in a creeping landslide mass to determine the subsurface profile.	A trench is excavated in continuously moving shallow landslides where drilling a borehole might create a risk (Arslan Kelam et al. 2022).
Deformation of large deep-seated seated landslides, settlements, shear zones, and overall groundwater and seepage phenomena could be monitored.	Landslide boundaries (Sang et al. 2019), local settlements, shear zones, and shallow temperatures could be detected and monitored.
The vertically installed optical fibre inside a borehole can monitor multiple strata's stress state, multiple slip surfaces, and collapse activity (Zhu et al. 2017).	The horizontally installed optical fibre can monitor a specific stratum's movement and stress condition (Zhu et al. 2017).
Main requirements: (a) ensure the sensor's optimal performance and long-term durability under physicochemical conditions (b) prevent the cable from being lost or damaged during the installation (Choi et al. 2021) (c) decrease borehole radius and increase cable gauge length (Zhang et al. 2020).	Main requirements: (a) prestraining of the cable and ensuring the proper attachment of the cable to the bottom of the trench (usually epoxy adhesives are used) (b) preventing slippage at the fixation point.
Backfilling materials must have a stiffness similar to the surrounding geology.	Microanchors must have a bearing capacity similar to the cable.
If the main target is deep deformation monitoring, the influence of atmospheric temperature can be neglected if it is in the range of 5 ℃.	Since we deploy cables close to the surface, the cable could detect the influence of the atmospheric temperature change, ultimately affecting the measurement. However, this contradicts the results revealed by (Arslan Kelam et al. 2022).
Type of cable to be installed, borehole diameter, and target depth are other essential considerations.	Evaluating ground-cable coupling in shallow, loose sediments is challenging under low confining pressure. Cable types and trench dimensions are other important considerations.
Cement grout is preferred for backfilling rather than in situ soil, sand, and gravel to ensure the crucial coupling between sensors and the surrounding geologic body.	The cable is laid and fixed to the ground by microanchors at a certain distance to achieve overall bonding and point fixation (Iten et al. 2011; Sang et al. 2019).
Cable requirements:	Cable requirements:

Highly protected cable, low stiffness, high tensile strain for shear zone and low tensile strain for settlement monitoring, cables fabricated with microanchors to ensure better coupling, steel and wire encapsulation.	High tensile strain, highly protected with coatings, cables fabricated with microanchors.

Coupling mechanism

Although the use of the DFOS sensing method has been increasingly used to monitor slopes, the overall coupling and interaction mechanisms between the installed FO cable and the formation remain unclear. Since the FO cable is a manifold composite, the entire strain transfer mechanism can be viewed as consisting of two aspects (Zhang et al. 2020):

(i) the strain transfer between the cable, backfilling materials (anchors), and geologic formation and
(ii) the strain transfer within the multiple layers of the FO cable (core, cladding and outer jacket)

The strain transfers from the Earth to the core are accomplished through shearing at the strongly bonded interfaces between the ground, outer jacket, cladding, and core when optical fibres are implanted in a trench or borehole to quantify the axial and shear strains (Fig. 9) (Soga and Luo 2018). The abovementioned two aspects of strain transfer are primarily due to the lack of standardised cable installation and backfilling procedures. In an ideal situation, the measured strain of the cable would correspond to the actual strain generated in the ground. However, the strain registered by the optical analyser is not entirely representative of that experienced by the ground because of the interface slippage. The possible reasons for slippage could be as follows:

- Alterations in CP from the shallow ground layers to deep layers
- Modulus difference among the cable, backfill, and formation

The deformation of the FO cable is only considered compatible with the formation only when there is no interface slippage, which occurs when the backfill-cable interface shear stress is lower than the peak interface shear strength (Zhang et al. 2020). However, to achieve such conditions, one should pay careful attention to various factors such as ground property, borehole and backfill property, ground-borehole interface adhesion coefficient, cable property, gauge length, and borehole-cable interface parameters (Ansari and Libo 1998; Zhang et al. 2020). According to a recent study, by carefully considering the following two crucial parameters, the quality of strain delivered to the cable from the surrounding ground can be enhanced (Zhang et al. 2020):

- Increasing the backfill modulus and cable gauge length, and
- Decreasing the borehole radius and cable stiffness

The progressive failure of a fibre/soil interface has been highlighted by many publications that have studied the interaction between FO cables and soil by utilising pullout tests on small-scale soil samples (Zhang et al. 2014, 2015; Zhu et al. 2015). These studies focused on how an increase in overburden pressure significantly strengthens the binding between an optical fibre and soil, allowing for the measurement of more significant ground deformation. Nevertheless, it is still unknown how different environmental factors affect the cable-soil contact and what kinds of inaccuracies in coatings and jackets contribute to strain measurements. For the first time, Zhang et al. (2016) reported that the cable-soil interface is susceptible to not only CP but also environmental changes (density and moisture content of the soil). They observed that low moisture contents and high soil density ensure strong cable-soil interfacial behaviour. The same research group proposed an index to quantitatively evaluate the cable-soil coupling condition, which is given in Eq. 12 (Zhang et al. 2018):

$$\xi_{c-s} = \left(\frac{\int \varepsilon(l)dl}{u_0}\right) \times 100 \quad (12)$$

where $\varepsilon(l)$ is the strain distribution along the FO cable and u_0 is the pullout displacement applied at the cable head. The above equation shows that a significant index value corresponds to strong cable-soil coupling. However, how this index correlates with actual strain measurements is still unclear. Furthermore, they proposed a CP threshold of ~0.36 MPa, where an excellent cable-coupling condition can be achieved.

The studies mentioned above demonstrate that pullout tests can comprehend the cable-soil interaction efficiently; however, it is still challenging to achieve total coupling between the cable and soil on a natural slope. In a field application, sand, gravel, in situ soil, clay, or a combination of them, as well as cement grout, can be used to fill boreholes and trenches. Backfilling with loose soil materials cannot ensure the coupling between backfilled material and ground because soils are loose porous media that are particularly subject to environmental perturbations (seasonal groundwater variation and precipitation infiltration). Therefore, the backfilling technique with cement grout is increasing these days as cementing the cable to the borehole wall provides optimal coupling in terms of strain data quality resulting in a higher SNR. The rock strata deformation causes the deformation and fracture of solidified cement mortar, which are then transferred to the optical fibre to generate strain changes. The strain of the optical fibre can reflect the deformation and failure of rock strata; however, it is challenging to use in shallow boreholes. In addition to ensuring strong coupling, cement backfilling facilitates the monitoring of seepage flow. By introducing heat along the heating cable installed inside the borehole during cement slurry pouring, we can detect the changes in the local temperature field because of the seepage flow. Ultimately, the quantitative relationship between groundwater flow, amount of bedrock deformation, and the influence of seasonal variation can also be determined.

Kogure and Okuda (2018) followed a similar concept presented in Fig. 9 and achieved a good coupling between the borehole wall and optical cable interfaces in which the borehole was sealed with cement grout. Hu et al. (2020) also followed similar procedures employed by Kogure and Okuda (2018) in a mining project for roof strata monitoring. They agreed that the grouted cement paste inside a borehole increases the coupling between cables, rock strata, and cement mortar anchorage and can more accurately reflect the law of rock movement. Nevertheless, some measurement noise related to cement grouting was documented. This noise might be due to the decoupling between the cable and grout. One should pay careful attention to this issue while installing the cable and pumping grout. Grouting materials with low elasticity may reduce the noise. A good coupling effect between backfilled material and the surrounding ground was reported by Wu et al. (2015), in which researchers used a mixture of sand, gravel, and bentonite for sealing the borehole. In such a method, the volume of bentonite expands due to the influence of water, causing sand and gravel to extrude all around by filling the fissures with serum. This mechanism increases the coupling performance between the ground and anchorage. Table 3 summarises the coupling efficiency between the FO cable and geologic materials in laboratory and in-situ studies carried out by previous investigators.

Table 3 Comparison between previous studies carried out to achieve better coupling performance

DFOS method	Coupling between FO cable and geologic material	Typical measuring parameters	Remarks	References
BOTDR	Depends upon the strength of geosynthetics and the type of jacket/buffer (Laboratory experiment)	Spatial resolution: 1 m Strain measurement accuracy: ±0.003%	Cables were affixed on geosynthetics by epoxy resin.	Wang et al. (2009)
BOTDA	Not assured (Field experiment)	Strain accuracy: ±10 με Temperature accuracy: ±1 °C	Borehole was sealed with cement grout.	Minardo et al. (2014)
BOTDA	Not assured (Laboratory experiment)	Spatial resolution: 5 cm Strain measurement accuracy: ± 7-15 με	3 mm outer-diameter heat shrink tube was used to ensure the deformation compatibility using epoxy resin.	Zhu et al. (2014)
BOTDR	Assured (Laboratory monitoring)		-Coupling performance between the sand–gravel–bentonite and the sensors -Curing time, CP, and the type of optical fibre govern coupling performance.	Wu et al. (2015)
COTDR	Assured (Field experiment)	Spatial resolution: 10 cm Strain resolution: 1.87 με	-Borehole was sealed with cement grout to achieve coupling with the borehole wall	Kogure and Okuda (2018)
BOTDR/BOTDA	Assured (Lab and field experiment)	BOTDR in laboratory: Readout resolution: 0.05 m, spatial resolution: 1 m BOTDA in field: Readout resolution: 0.05 m, spatial resolution: 0.1	-Coupling efficiency depends upon the CP -Borehole was filled with a mixture of sand, clay, and gravel.	Zhang et al. (2018)
BOTDR	Assured (Field experiment)	Spatial resolution: 1 m Sampling resolution: 0.2 m	-Borehole was sealed with concrete slurry and showed good coupling performance.	Hu et al. (2020)
BOTDA	Assured (Laboratory experiment)	Sampling interval: 5 cm Spatial resolution: 10 cm Strain measurement accuracy: ± 7.5 με	-A new parameter called the strain propagation depth (d_ε) was proposed. When d_ε=0, the cable solidifies in the soil. -CP governs codeformation ability.	Zhang et al. (2021)
BOTDR	Assured (Lab and field experiment)	Readout resolution: 0.05 m, spatial resolution: 1 m	-Borehole was backfilled with a mixture of sand, gravel, and bentonite.	Zhang et al. (2021)
BOTDA	Not assured (Field experiment for shallow ground movement)	Strain resolution: 0.1 με Measurement interval: 0.5 m	-FO cables were coiled with anchorage metal stakes. Backfilling material is not mentioned.	Arslan Kelam et al. (2022)

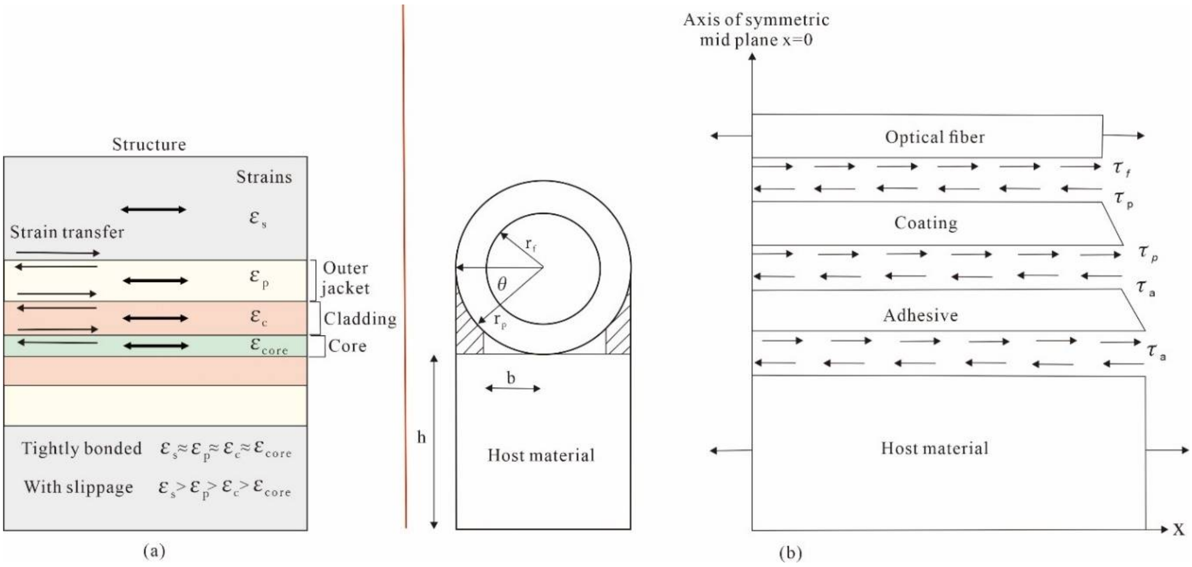


Fig. 9 a Strain transfer from the structure to the ore (the strain exerted by all layers will be approximately equal if they are perfectly anchored, which is desired in civil engineering applications; however, sensing actual strain developed in the structure is challenging when there is slippage between interfaces) (Soga and Luo 2018), and **b** analytical model of surface-bonded optical fibre (where all layers behave as linear elastic isotropic materials, all interfaces are perfectly bonded, and the protective coating and adhesive are subjected to shear deformation only) (Her and Huang 2011)

Applications of DFOS in slope deformation monitoring

The simplest and most fundamental physical characteristic for determining the behaviour of landslide masses is deformation. Accurate measurement of strains locates a layer undergoing compaction or rebound. Using typical slope deformation monitoring tools such as inclinometers, interpreting the precise positions of slip surfaces is time-consuming. Therefore, the investigations of DFOS in slope deformation surveillance have been increasing rapidly during the last decade. Following a technical literature survey, we discovered that the majority of previous studies focused on slope deformation monitoring.

Experimental study

An optical system may fail if the breakpoint occurs in the middle of the fibre; therefore, a closed loop must be established during a test measurement (Chai et al. 2019). Moreover, the lack of control of measurement conditions in the natural slope is another significant hindrance. Therefore, most of the work has been carried out under controlled laboratory settings under artificial rainfall, surcharge loading and toe cutting to test the sensors' ability to detect changes in displacement.

Nearly a decade ago, an instrumented flume equipped with Brillouin scattering-based sensors was built to investigate the mechanics of rainfall-induced slope failure (from prefailure to postfailure) and flow slide initiation in unsaturated granular soils (Olivares et al. 2009). They demonstrated the advantage of stimulated Brillouin scattering (SBS) as a reduced acquisition time and high processing speed despite poor spatial resolution (2 m). Considering the resolution of the Brillouin scattering, Minardo et al. (2015) detected a clear-cut profile of soil deformation in a small-scale soil slope subjected to artificial rainfall using BOTDA at a spatial resolution of 20 cm and an acquisition rate of approximately 2 min. In their study, an artificial rainfall intensity of 35 mm/h was reproduced above the ground surface until slope failure was triggered after approximately 60 min. Soil movements and uphill and downhill soil deformations were clearly detected before slope failure.

A large-scale physical model of a slope for monitoring landslide progressive deformation and collapse patterns was devised by Schenato et al. (2017). The model was constructed inside a 6×2 m reinforced concrete structure with a 32° slope. The top porous layer was 60 cm thick and prone to collapse. A strain placed on the cable by the landslide was measured with a spatial precision of 10 mm using the OFDR technique (OBR4600 from Luna Innovation Inc.), and the strain evolution was tracked until the slope failed. These researchers also stated that the optimal position for detecting landslide triggering would be at the sliding interface, but a shallower installation might also be practical and more relevant.

The strains measured by the optical fibre are local axial strains, which reflect the stability condition of the monitoring layers. For instance, Zhu et al. (2014) employed BOTDA sensing methods to measure the horizontal strain distributions inside a medium-scale model slope (3.5×1.5×1.5 m) under different surcharge loadings and explored the relationship between the soil strain field and the overall slope condition. The combination of the point-based sensor (FBG) and distributed sensor (COFDR) was investigated for the monitoring of the geo-grid reinforced model slope (0.8×0.4×0.45 m) under different surcharge loading (Sun et al. 2020). However, these studies haven not considered the influence of CP on the coupling between cable and soil, and it is still unclear at what CP the reliability of the measured strain can be ensured. Therefore, to fill this research gap, Zhang et al. (2021) devised a BOTDA-based sensing system in a model slope (3×1.5×1.5 m) and evaluated the slope evolution process under the combined effect of surcharge loading and toe cutting. They clarified that the CP governs the cable and soil coupling. They also introduced a new parameter called the 'strain propagation depth (d_ε) to characterise the coupling between the soil and the strain sensing cable. In brief, d_ε is the maximum distance the axial strain propagates along the cable in a pullout test. When d_ε=0, the cable solidifies with the soil. This study provides valuable information for assessing the surcharge loading generated by dense roadway construction.

Pulse-prepump Brillouin optical time-domain analysis (PPP-BOTDA) technology is a recently developed sensing method by Neubrex Co., Ltd., in Kobe, Japan, with obvious advantages in strain precision (25 με), cost-effectiveness and improved spatial resolution (10 cm) over traditional BOTDA technology (Kishida and Li 2006). This sensing method has a negligible temperature influence on the strain measurement precision (Zhao et al. 2021). Both strain and temperature-compensated fibres can be installed in the borehole, and strain data given by both fibres can be obtained simultaneously by a single measurement. Song et al. (2017) exploited the PPP-BOTDA technique to assess strain developed in a model slope (3×1.5×1 m) during slope surface loading and cutting with a sampling resolution of 5 cm, strain measurement accuracy of 7.5 με, and temperature measurement accuracy of 0.75 °C. The results showed that the specially designed strain sensing cable was satisfactorily co-deformed with the soil after 225 kPa loading, which is closely equal to the value estimated by (Zhang et al. 2021) (that is, 220 kPa).

Research on monitoring techniques for fast-moving landslides, which have a potentially significant impact on the environment, is still in its infancy because developing efficient systems for field monitoring is challenging. Most studies have concentrated on monitoring the long-term motion of slow-moving landslides that creep at rates ranging from millimetres to several metres per year. A step towards a complete knowledge of rapid rockfall and debris flow behaviour has been investigated recently in a small-scale flume model using the DFOS technique by some researchers in Italy. For instance, for the first time, Darban et al. (2019) developed steep model slopes made with unsaturated pyroclastic soils subjected to artificial rainfall. They used both BOTDA and BOFDA sensing techniques to investigate the mechanism of progressive failure of slopes. Minardo et al. (2021) designed a physical slope model (length and width were 110 cm and 50 cm, respectively) with granular cohesionless volcanic sand. An artificial rainfall intensity of 100 mm/hr was reproduced above the ground surface to induce slope failure. A digital camera and BOFDA with a spatial resolution of 5 cm at the expense of a time resolution of approximately 3 min were used to monitor the sudden increase in soil strain. Compared with digital cameras, a clearer precursory signal of incoming failure was detected with optical fibres. These physical model tests are believed to help further in-depth investigations and analyses of sudden and rapid slope movements.

In situ study

In the past three decades, several distributed FO sensors have been proposed for in situ strain monitoring. The effectiveness of FO sensors in different landslides in Japan was explored approximately 20 years ago by a joint project between the Public Research Institute of Japan and other international research projects. After Aulakh et al. (2004) demonstrated the applicability of the OTDR technique for sensing landslide activity as a cost-effective alternative to conventional monitoring techniques, Higuchi et al. (2007) investigated a similar OTDR-based sensor in the Takisaka Landslide in Fukushima Prefecture in eastern Japan. Using this approach, tensile displacement was detected precisely. Nevertheless, some measurement errors were recorded because of hysteresis in the relation between the amount of loss of travelling light and the ground displacement observed in the laboratory. Several studies have now been published in the literature that explore the applicability of these technologies as landslide monitoring techniques.

A team of researchers in Switzerland have employed road-embedded DFOS sensing techniques to localise slip surface and ground displacement. For instance, Iten and Puzrin (2009) investigated the displacements of two landslides, namely, the Brattas and Laret landslides, for a few months using a road-embedded optical fibre. They embedded an FO cable into a trench in asphalt (with trench dimensions of 89 × 10 × 70 mm) and successfully identified the stable part-transition zone-moving part. Details of the theory and practical experiences of the same team regarding strains of the FO cable, deformations in the sliding body and slip surface, and the sliding surface inclination can be found in Puzrin et al. (2020). After Kogure and Okuda (2018) implanted an optical cable into a 16 m deep borehole to investigate landslides, our traditional thoughts regarding landslides in which rocks below a slip plane are fixed, stable, and impermeable need to be changed. They detected the deformation of the lower section of the landslide under the slip plane composed of mudstone employing a Rayleigh backscattering-based FO sensor (with a spatial resolution of 10 cm and a strain resolution of 1.87 με). Their study inspected strain changes at three different depths of 2, 8, and 14.3 m, each representing the uppermost section, the slip plane, and the bottom section, respectively.

In the last decade, researchers have developed FO-based inclinometers for slope monitoring. Table 4 emphasises how superior FO-inclinometers are to conventional inclinometers, although there are still urgent concerns that must be overcome in the future. Minardo et al. (2014) proposed an FO-inclinometer exploiting the BOTDA sensing method and traditional inclinometers on a natural slope, demonstrating the sufficient accuracy of the previous method. This sensing technique mainly consists of two parts, namely, a test tube and a strain sensing fibre. Specifically, four optical fibres are installed on the surface of the test tube at four positions orthogonal to each other (as depicted in the figure in the right column of Table 4); however, three fibres would be sufficient to reconstruct pipe deformation. It is believed that introducing the fourth fibre allows for more significant precision in strain. Based on the classic Euler beam theory, the lateral displacement of the tube can be calculated with optical fibre strain data. Fig. 10 illustrates the relationships among the bending displacement, $\omega(z)$; rotation angle, $\theta(z)$; and tube strain, ε. Similar research was carried out by Sun et al. (2016), who presented an in-place FO-inclinometer based on BOTDR to obtain the long-term internal deformation of the slope. The results show that the BOTDR-based inclinometer measurement is consistent with the traditional inclinometer measurement, with a difference of less than 4 mm. However, these investigators reported issues such as the lack of standardised procedures for sensing cable installation in large areas and difficulty in data interpretation and modelling coupling mechanisms.

Because the bottom of the inclinometer tube is immersed in bedrock, the abovementioned researchers presumptively assumed that there is no displacement and no rotation angle there. However, the theoretical approach based on this assumption is in question now after Kogure and Okuda (2018) detected strain development inside the deep bedrock below the slip surface.

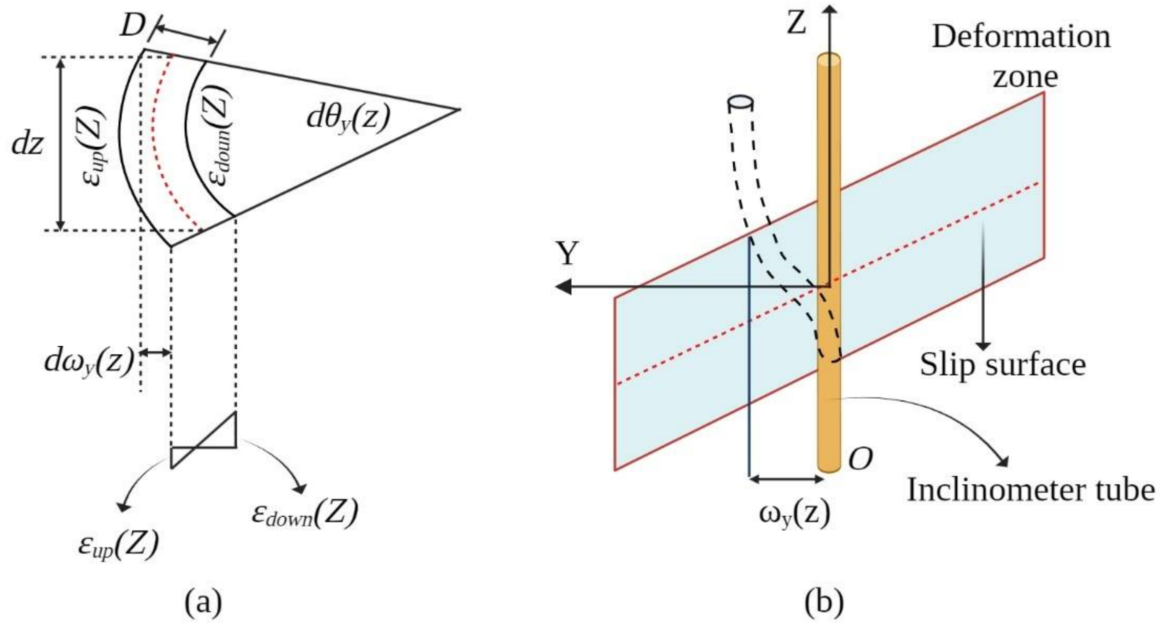
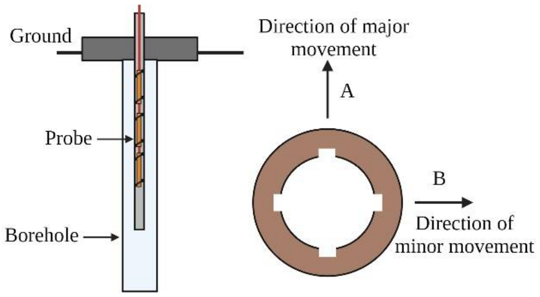
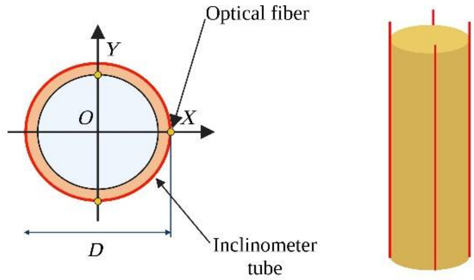


Fig. 10 a BOTDR-based inclinometer, and **b** principle of the displacement calculation (measurement of the bending displacement, rotation angle, and strain of the tube) (modified from Sun et al. 2016)

Table 4 Comparison between conventional and FO-based slope inclinometers

Conventional inclinometers	Novel FO-inclinometers





Advantages: -Measurement of rate, magnitude, direction, and depth of moving slope mass - Derive whether the deformations are speeding, decelerating, or steadily developing	Advantages: -Measurement of 3D deformation of soil -Continuous monitoring from a remote site -Multiplexing capability -Self-compensation against temperature variations -Displacement sensitivity as high as 1 mm over 1 m
Limitations: -Periodic inspection is necessary -Become ineffective if the displacement reaches levels that make it impossible for the measuring head to slide along the inclinometer tube itself -Electromagnetic interference, poor durability, poor stability, a limited number of measurement points	Limitations: -Difficult installation procedure (especially for the proper orientation of the sensor over borehole depth) -Lack of understanding of the tube deformation -Lack of norms and standard guidelines for cable installation

Many researchers have focused on monitoring the deformation behaviour of landslides in the Three Gorges Reservoir in China, a hot spot of landslide hazards, using various FOS approaches. For instance, in Block-1 of the Majiagou landslide of the reservoir, integrated FO sensing technology (IFOST), including BOTDR/A, Raman optical time domain reflectometry (ROTDR), and a fibre Bragg grating (FBG) were employed to test the surface and deep deformation of the slope, especially the shearing deformation of the slipping zone, and a kinematic model was proposed (Zhang et al. 2018; Zhang et al. 2015). These researchers embedded an FO cable in a 43 m deep borehole and captured the variation in strain distribution from September 2012 to September 2013, detecting two major slip surfaces at approximately 12.5 m (contact between surface and bedrock) and 34 m (within bedrock). Again, the same team deployed FO cables based on Brillouin scattering in a borehole to elucidate the compaction and rebound phenomenon for two years (from November 2014 to December 2016) in Shengze, southern Yangtze Delta, China (Zhang et al. 2018). These authors discovered a 7.6 m thick zone compaction and a confining pressure threshold (~0.36 MPa) to achieve a robust cable-soil interaction. All of the abovementioned research focused on locating the overall deformation along the borehole locating major and some minor slip surfaces, and enabling a better understanding of the deformation helps to establish a better slope stability analysis based on the strain profiles. However, how the optical cable exerts strain within the sliding zone at a different location of the main slip surface is still unknown.

To fill in the abovementioned research gaps, Sang et al. (2019) adopted the BOTDR technique for Majiagou landslide monitoring. They presented three geometric models to evaluate the evolutionary stages of the sliding zone (orthogonal, Skew-I, and Skew-II). They discovered that two skew models can more accurately depict the shear deformation of the sliding zone in the middle and upper parts of the landslide and that the orthogonal model can reveal the deformation of the sliding zone in the lower toe section of the landslide. Additionally, they provided a compelling rationale for the normal and sinusoidal strain distribution throughout the cable within the sliding zone, which was lacking in earlier investigations. However, these investigators encountered difficulties with the costly optical analyser and the arduous cable installation process.

Wang et al. (2017) developed the FOS-LW, a landslide early warning system. In summary, the FO cable's change in light energy intensity allows the FOS-LW to detect the deformation of the soil and rock masses. When the displacement resulting from the deformation of the slope increases, the system identifies movements in the soil and rock from the change in signal energy intensity caused by localised microbending in the cable. After almost a year of observation, it was discovered that the slope's maximum displacement was minimum (< 1 mm), or "green level," which was consistent with the values given by the inclinometer. Recently, for the first time in Turkey, Arslan Kelam et al. (2022) demonstrated an FO system for tracking large-scale movements that are easily transformable into an EW system by taking into account a strain threshold value. Data collected over six months revealed a direct correlation between the strain variations and the groundwater level, precipitation, and temperature variation. During the measurements, these researchers encountered two significant problems: (1) an electrical interruption; and (2) an optical cable break. The abovementioned research is expected to contribute to mass movement hazard and risk assessment studies.

Table 5 Absolute threshold values for alarm system development (Wang et al. 2017)

Alarm level	Horizontal displacement	Vertical displacement	Crack width
Green	< 5 mm	< 3 mm	< 3 mm
Yellow	5-10 mm	3-10 mm	3-7 mm
Red	> 10 mm	> 10 mm	> 7 mm

Important considerations

Cables and devices

The current generation of DFOS devices represents a technological revolution regarding the number of sensing points compared to conventional single-point sensing techniques. However, there is currently research on improving their spatial resolution, sensing range, and acquisition time. The complexity of the discrete optoelectronic components used in current FO sensor technology, including pulsed lasers, PDs, modulators, switches, optical filters, electrical current, and voltage amplifiers, compounds the bulkiness of the system (Lu et al. 2019).

The main issue with cables deployed in underground environments is their durability. For many in-situ monitoring applications, optical cables must endure extreme weather conditions. Over time, fibre coatings or jackets deteriorate, and fibres may break due to significant deformation. In these circumstances, various coatings are beneficial to increase the durability and survivability of the sensor and prevent potential damage or breaking of the optical fibre. However, a portion of the strain is absorbed by the protective coating of the optical fibre. Hence, only a segment of strain may be sensed, i.e., the mechanical properties of the protective coatings employed in conjunction with optical fibres affect the strain transmission capabilities of the sensor (Ansari and Libo 1998). Furthermore, fibre breakage or measurement failure, which is undesirable in testing, might result from interfacial slippage between the fibre core, cladding, and coating (Wang et al. 2019).

Many factors can affect the performance of FO sensors, such as the installation procedure, types of backfill materials, poor choice of adhesive, and insufficient anchorage or bond length of sensors. The protective and adhesive layers are always in the elastic stage during the working period, which may be damaged under large deformation (Schenato 2017). Therefore, the proper selection of the packaging material for protecting sensing fibre and adhesive glue for fixing optical fibre sensors is the most significant.

Another challenge of DFOS in engineering applications is the cost of sensors (Sang et al. 2019). Despite the market's rapid growth, researchers from low-income countries still face numerous economic challenges. Some major optical devices, such as demodulators, are still out of reach, although standard sensing fibres are inexpensive. A distributed FO sensor system can be quite expensive, depending on the applications, the type of cable used, and the operating circumstances. The installation and maintenance cost of these systems makes their deployment problematic. However, compared to other point-based sensors (FBG, electric resistance strain gauges, vibrating wire strain gauges, etc.), DFOS sensing systems significantly decrease costs. For instance, Tang and Cheng (2018) mentioned that the entire cost of the BOTDR monitoring operation in their study was 300,000 yuan; however, if FBG sensors had been employed as alternatives in this scenario due to the high cost of FBG sensors, the cost would have increased to over 600,000 yuan. Although several publications (e.g., Ivanov et al. 2021) highlight the sensor's low cost and robustness, further investigation is still required to encourage broader application in the geohazard sector.

On-site installation issues

DFOS technology must be capable of addressing a variety of harsh realities and challenges. For example, installing optical cables inside boreholes is a time-consuming and complex task. It must be handled carefully to prevent fibre breakage during installation (Bersan et al. 2018; Choi et al. 2021). Furthermore, this task is frequently implemented on steep slopes and hazardous sites, necessitating a sophisticated installation that is minimally invasive to avoid risking the stability of the site. Even though the design of the sensor cables has improved tremendously, improper cable deployment can fail to obtain accurate data. This is mainly because of the lack of standardised cable installation and backfilling techniques.

Wang et al. (2009) highlighted that applying distributed FO monitoring to soil slopes is more challenging than that to concrete structural objects. Iten and Puzrin (2009) reported the failure of road-embedded cables, after which they engrafted metal-protected and polyamide-protected strain cables into the road crossing a potential landslide boundary. Wu et al. (2015) reported the breakage of polyurethane sheath cable (PSC) in a borehole at a depth of 150 m due to low tensile strength and the lack of sheath protection of the fibre cable. Arslan Kelam et al. (2022) documented the breakage of optical cables installed inside a shallow trench to monitor continuously moving shallow landslides. Afterwards, the break was repaired by removing the overburden, which affected the strain measurement data due to the disturbance of the initial configuration. To avoid such problems, Wang et al. (2019) introduced a new type of sensor package (an additional plastic tube) in their study. The strain coefficient of the sensor was 50.5 MHz/0.1%, and the temperature coefficient was 1.13 MHz/°C, which is very close to the theoretical values (49.7 MHz/0.1% and 1.07 MHz/°C). The excellent sensing performance of the proposed sensor was verified.

Even after the cable has been successfully installed up to the bottom of the deep borehole, we cannot map the vertically distributed strains over the entire fibre length. For instance, in a study by Zhang et al. (2018), data measured below a depth of 145.3 m in a 200 m deep borehole were aborted. This is principally attributable to the cable's substantial signal loss. In addition, because of the fluctuation in shallow soil temperature and low CP, aberrant strain values can be detected at a shallow surface (Arslan Kelam et al. 2022; Kogure and Okuda 2018; Zhang et al. 2018). This issue demands an additional temperature sensing cable that is insensitive to strains.

When FO cables are installed in trenches or boreholes, there may be interface slippage between the cable and the soil due to variations in density, MCs, and confining pressure. It is still unclear whether pressures brought on by ground movement transfer to the cable (Zhang et al. 2020). Backfilling using in-situ soil, sand, and gravel causes substantial decoupling problems that make it difficult to quantify actual strain change. Although some researchers have used the cement grouting technique to seal boreholes, high coupling efficiencies still cannot be achieved.

It is crucial to consider factors including temperature variations, moisture influences, chemical attacks on sensor system components, chemical interactions between sensing elements, and the use of specialised sensor materials when building on-site measurement systems. FO demodulators are also required to survive in extremely hostile environments because exposure to radiation, harsh weather, or freezing temperatures may degrade the precision of measurements. Even though water does not impact optical fibres, water entry into the protective barrier due to improper waterproofing bends and cuts off the optical fibre (Choi et al. 2021). Additionally, soil heterogeneity, varied recharge rates, and localised macropores are challenging to account for and can lead to inaccuracies in FO sensing studies (Wu et al. 2021).

Future directions

Development of early warning systems

LEWS can benefit vulnerable individuals as a nonstructural solution by raising awareness and strengthening preparedness. The LEWS established by earlier researchers relied on rainfall data, crack width, extensometer installation, and a piezometer; however, the FO-based landslide early warning system (FO-LEWS) is still in its infancy.

With the aid of FO monitoring systems, slope disasters can be predicted and provide an early warning. The comprehensive analysis of the literature reveals that most previous DFOS research has only focused on strain profile monitoring. Therefore, future research should concentrate on developing infrastructure and software for EW systems while considering some essential triggering factors and threshold strain values. The research carried out by Wang et al. (2017) and Arslan Kelam et al. (2022) can be considered a landmark for the development of FO-based LEWS, as they have given a clear indication of the potential development of community-based early warning. Fig. 11 shows the integrated system for the FO-LEWS. According to the recorded strain values, threshold values could be selected depending on the landslide's deformation characteristics, velocity, and changes in light intensity. The system could send emails and SMS alerts to residents and authorised individuals when threshold values were exceeded. The monitoring system could be managed through the internet from any desired location, and it is anticipated that early warning stations in hazard-prone areas will use it to reduce casualties and property loss.

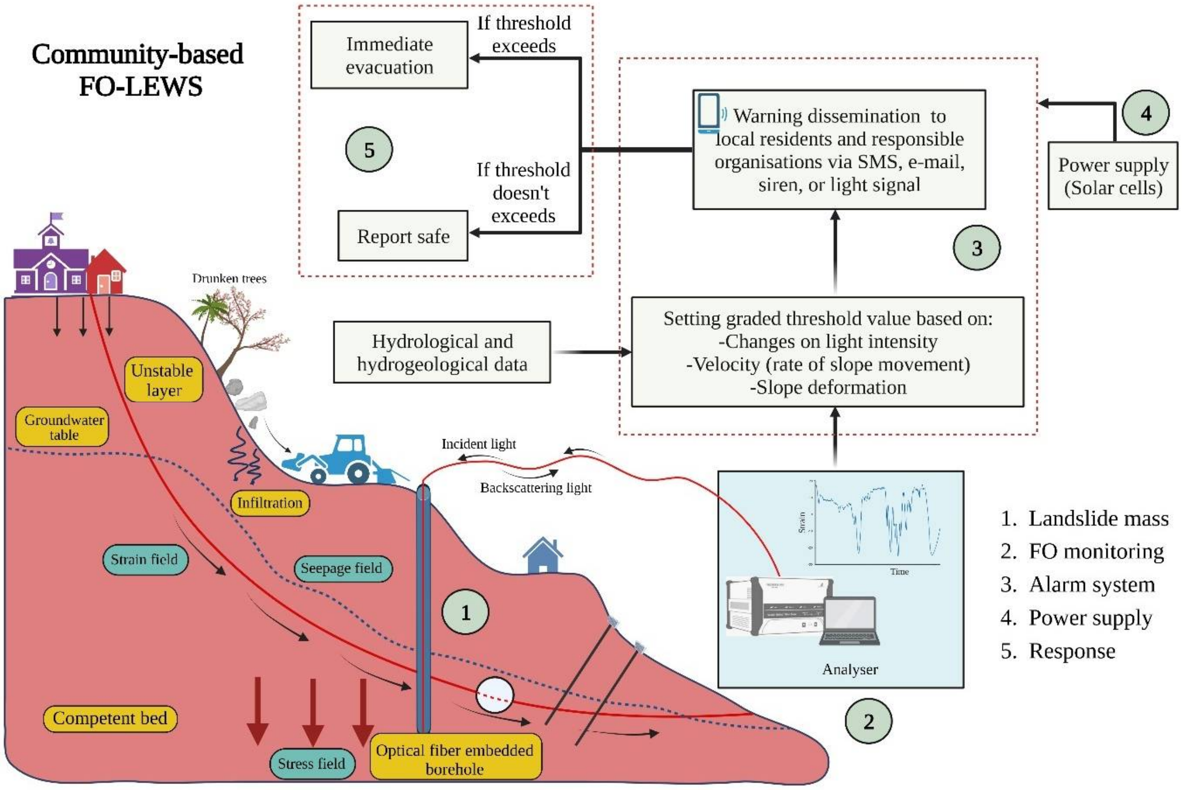


Fig. 11 Integrated module for the FO-LEWS

Other significant insights

Despite significant challenges, DFOS technology is continually evolving since it enables high-precision detection at incredibly long distances. In the last two decades, many difficult-to-solve monitoring problems have been handled using novel FO techniques, replacing the traditionally utilised point-type geotechnical instrumentation technologies and electric sensors. The market is growing due to the increasing demand for distributed FO sensors for monitoring in challenging working environments that humans cannot reach. The distributed FO sensor market is anticipated to develop at an annual rate of 8.5% to reach 1.9 billion USD by 2027 (ReportLinker 2021).

The spatial resolution and sensitivity of the optical fibres are significantly impacted by dispersion and nonlinear effects, which ultimately lead to fibre attenuation. This attenuation reduces the sensing range and affects the data quality (Fenta et al. 2021). Therefore, future research should focus on developing new fibres with low loss and dispersion

The strain data obtained from near-surface loose strata are challenging to evaluate precisely; therefore, a more effective design of anchor systems to detect shallow displacements more accurately needs to be investigated. Although microanchored cables have been proven to ensure sufficient ground-cable coupling, the impact of anchorage on ground-cable strain transfer is still unclear. For the borehole embedment methods, the decoupling between optical cable and backfilled materials (in situ soil, sand, and gravel) has proven to be a significant issue in detecting actual strain generated within the ground. Although some investigators used cement grout to seal the borehole, some noise was still recorded due to the decoupling between the cable and ground. Therefore, future research should focus on reducing the noise produced by decoupling.

High-definition fibre optic sensing (HD-FOS), which can detect and measure thousands of distinct points of strain or temperature per metre of fibre length, has proven to be a helpful instrument. Moreover, this technology can be embedded within a part of slope reinforcements and diagnose internal deformations. In geoengineering, the combined digital image correlation (DIC) and DFOS technique have received much interest since they allow the validation of internally measured deformation fields (Mata-Falcón et al. 2020). In summary, DIC is an optical, noninterferometric, noncontact method for measuring the deformation of a structure. In this method, the surface of a tested object is photographed repeatedly before and after the deformation period (Górszczyk et al. 2019). The use of this technology in landslide monitoring will be the subject of research in the coming years. The introduction of fifth-generation dense wavelength-division multiplexing (DWDM) to FO technology enables optical cables to turn light at various wavelengths on and off while transmitting light along the fibre. This makes it possible to record active data in real time via an FO cable. FO sensing based on artificial intelligence has recently been invented for handling massive amounts of data. Because of the ultralong sensing distance and outstanding performance, the use of this technique in the geophysics sector has been rapidly increasing (Fenta et al. 2021). Moreover, combining DFOS with numerical methods is a novel strategy, as different research studies have shown that the two techniques are in good accord.

By modifying the fibre packing material and improving the fibre structure, a variety of durable and damage-resistant optical cables have been developed making it an ideal solution for environmental monitoring (Shi et al. 2021). More convenient packaging and protective technologies will be developed in the future. Several optoelectronic units comprise the FO system, and integrating these parts will be crucial for expanding the industry. Emerging technologies such as silicon- and InP-based photonics will allow the integration of such sensing components at the chip level, decreasing the production cost (Smit et al. 2019). Ground movements are three-dimensional vectors, while optical fibre deployed in a borehole only conveys one-dimensional information along the cable. In response to this, there is currently a need for 3D strain and stress development in intricate geological systems.

Further study is necessary to properly comprehend the long-term sensing capacity of the DFOS system under field experimental conditions (Sun et al. 2010). We have investigated the fact that there are still no accepted standards for laying optical cables. The development of guidelines and specifications for system deployment and administration, as well as technical instructions for the installation team, should be included in future work.

Most significantly, from a technical literature survey, the authors found that almost all previous studies have focused on the long-term monitoring of slow-moving landslides. On the other hand, rapid landslides such as rockfalls and steep channel debris flows can devastate populations and economies because of their high flow velocities, high impact forces and long run-out distances. Future optical fibre research should focus on the early detection of rapidly moving landslides subjected to rainfall, although few studies have recently taken a step in small-scale physical models (Darban et al. 2019; Minardo et al. 2021).

Conclusion

Based on a thorough review of the literature, the following significant conclusions can be drawn:

- DFOS technology has been established as an innovative measurement technology for slope monitoring because it provides remote, real-time, and long-term slope movement monitoring and has achieved good results. Brillouin scattering sensing (BOTDR/A) with spatial resolution from centimetre to a metre is the most experimented sensing method for slope deformation monitoring, followed by coherent optical fibre sensing.
- Lack of standardised installation procedures, sensor breakage due to low tensile strength, safety challenges of optoelectronic components in highly aggressive environments, high cable signal loss, and abnormal strain data due to variations in environmental conditions are some particular in situ monitoring issues.
- The monitored data from the borehole or trench are governed by the degree of rigid ground-anchorage-cable coupling. Although the understanding of the mechanical coupling between the ground, backfill and cable is increasing; however, it is not sufficient. Therefore, one should pay careful attention to crucial factors such as the type of backfill material, cable construction, and overall installation procedures.
- Cement grout backfilling is better than sand, soil, and gravel backfilling to ensure a better coupling effect, although some measurement noise related to cement grouting was documented.
- Most of the previous research has been carried out under controlled laboratory conditions. However, the situation can be completely different in the natural field. In this regard, the present theoretical research and indoor testing must be investigated further.
- Most previous investigations have tested DFOS methods for monitoring slow-moving landslides. In-depth research and analysis of rapid and sudden slope movements need to be carried out in the future. Additionally, it is urgently necessary to build an FO-LEWS considering strain threshold values and an enhanced DFOS system for monitoring rapidly moving landslides.
- There is still a lack of proper cable selection, field installation, or data processing guidelines that demand the validation of the data obtained from the optical interrogator with other techniques (e.g., numerical analysis, extensometers, and inclinometers).
- Due to rapid market growth and continuous research into cost-effective and high-accuracy instrumentation approaches, many more distributed sensor systems are projected to be commercialised and widely used in slope engineering.

Abbreviations

BOFDA	Brillouin optical frequency-domain analysis
BOTDA	Brillouin optical time-domain analysis
BOTDR	Brillouin optical time-domain reflectometry
COFDR	Coherent optical frequency-domain reflectometry
COTDR	Coherent optical time-domain reflectometry
CP	Confining pressure
CW	Continuous wave
dB	Decibel

DIC	Digital image correlation
DFOS	Distributed fibre optic sensing
DTS	Distributed temperature sensing
DWDM	Dense wavelength-division multiplexing
EW	Early warning
FBG	Fibre Bragg grating
FO	Fibre optic
FOS	Fibre optic sensing
FO-LEWS	Fibre optic-based landslide early warning system
FUT	Fibre under test
HD-FOS	High-definition fibre optic sensing
IFOST	Integrated fibre optic sensing technology
LEWS	Landslide early warning system
MMF	Multi-mode fibre
OFDR	Optical frequency-domain reflectometry
OTDR	Optical time-domain reflectometry
PD	Photodetector
PET	Polyethylene terephthalate
PPP-BOTDA	Pulse-pre-pump Brillouin optical time-domain analysis
PSC	Polyurethane sheath cable
PVC	Polyvinyl chloride
RI	Refractive index
ROTDR	Raman optical time-domain reflectometry
SBS	Stimulated Brillouin scattering
SMF	Single-mode fibre

Declarations

Conflict of Interests

No conflicts of interest exist in the submission of this manuscript. The contents described have not been published previously and are not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the enclosed manuscript.

References

Addanki S, Amiri IS, Yupapin P (2018) Review of optical fibres-introduction and applications in fibre lasers. Results in Physics 10:743–750. https://doi.org/10.1016/j.rinp.2018.07.028

Amer R, Xue Z, Hashimoto T, Nagata T (2021) Distributed fibre optic strain sensing for geomechanical monitoring: insights from field measurements of ground surface deformation. Geosciences 11(7):285. https://doi.org/10.3390/geosciences11070285

Ansari F, Libo Y (1998) Mechanics of bond and interface shear transfer in optical fibre sensors. Journal of Engineering Mechanics 124(4):385–394. https://doi.org/10.1061/(ASCE)0733-9399(1998)124:4(385)

Arslan Kelam A, Akgün H, Koçkar MK (2022). Application of an optical fibre-based system for mass movement monitoring. Environmental Earth Sciences 81(5):170. https://doi.org/10.1007/s12665-022-10289-w

Aulakh NS, Chhabra JK, Kamar A, Aggarwal AK (2004) Development of a fibre optic based system to monitor landslide activity. IETE Technical Review 21(1):75–81. https://doi.org/10.1080/02564602.2004.11417130

Bado MF, Casas JR (2021) A review of recent distributed optical fibre sensors applications for civil engineering structural health monitoring. Sensors 21(5):1818. https://doi.org/10.3390/s21051818

Bao X, Wang Y (2021) Recent advancements in Rayleigh scattering-based distributed fibre sensors. Advanced Devices and Instrumentation 2021, 1–17 (2021). https://doi.org/10.34133/2021/8696571

Barrias A, Casas J, Villalba S (2016) A review of distributed optical fibre sensors for civil engineering applications. Sensors 16(5):748. https://doi.org/10.3390/s16050748

Berrocal CG, Fernandez I, Rempling R (2021) Crack monitoring in reinforced concrete beams by distributed optical fibre sensors. Structure and Infrastructure Engineering 17(1):124–139. https://doi.org/10.1080/15732479.2020.1731558

Bersan S, Bergamo O, Palmieri L, Schenato L, Simonini P (2018) Distributed strain measurements in a CFA pile using high spatial resolution fibre optic sensors. Engineering Structures 160:554–565. https://doi.org/10.1016/j.engstruct.2018.01.046

Campanella CE, Ai G, Ukil A (2016) Distributed fibre optics techniques for gas network monitoring. 2016 IEEE International Conference on Industrial Technology (ICIT), 646–651. https://doi.org/10.1109/ICIT.2016.7474825

Chai J, Du W, Yuan Q, Zhang D (2019) Analysis of test method for physical model test of mining based on optical fibre sensing technology detection. Optical Fibre Technology 48:84–94. https://doi.org/10.1016/j.yofte.2018.12.026

Chai J, Lei W, Du W, Yuan Q, Zhu L, Zhang D, Li H (2019) Experimental study on distributed optical fibre sensing monitoring for ground surface deformation in extra-thick coal seam mining under ultra-thick conglomerate. Optical Fibre Technology 53:102006. https://doi.org/10.1016/j.yofte.2019.102006

Choi SJ, Park KG, Park C, Lee C (2021) Protection and installation of FBG strain sensor in deep boreholes for subsurface faults behaviour monitoring. Sensors 21(15):5170. https://doi.org/10.3390/s21155170

Dakin JP (1993) Distributed optical fibre sensors. Proc. of SPIE Vol. 10266 (Vol. CR44),102660B. https://doi.org/10.1117/12.145193

Dakin JP, Pratt DJ, Bibby GW, Ross JN (1985) Distributed optical fibre Raman temperature sensor using a semiconductor light source and detector. Electronics Letters 21(13):569. https://doi.org/10.1049/el:19850402

Darban R, Damiano E, Minardo A, Olivares L, Picarelli L, Zeni L (2019) An experimental investigation on the progressive failure of unsaturated granular slopes. Geosciences 9(2):63. https://doi.org/10.3390/geosciences9020063

Di Sante R (2015) Fibre optic sensors for structural health monitoring of aircraft composite structures: recent advances and applications. Sensors 15(8):18666–18713. https://doi.org/10.3390/s150818666

Fenta MC, Potter DK, Szanyi J (2021) Fibre optic methods of prospecting: a comprehensive and modern branch of geophysics. Surveys in Geophysics 42(3):551–584. https://doi.org/10.1007/s10712-021-09634-8

Froude MJ, Petley DN (2018) Global fatal landslide occurrence from 2004 to 2016. Natural Hazards and Earth System Sciences 18(8):2161–2181. https://doi.org/10.5194/nhess-18-2161-2018

Gómez J, Casas JR, Villalba S (2020) Structural health monitoring with distributed optical fibre sensors of tunnel lining affected by nearby construction activity. Automation in Construction 117:103261. https://doi.org/10.1016/j.autcon.2020.103261

Górszczyk J, Malicki K, Zych T (2019) Application of digital image correlation (DIC) method for road material testing. Materials 12(15):2349. https://doi.org/10.3390/ma12152349

Gu K, Shi B, Liu C, Jiang H, Li T, Wu J (2018) Investigation of land subsidence with the combination of distributed fibre optic sensing techniques and microstructure analysis of soils. Engineering Geology 240:34–47. https://doi.org/10.1016/j.enggeo.2018.04.004

Henault JM, Moreau G, Blairon S, Salin J, Courivaud JR, Taillade F, Merliot E, Dubois JP, Bertrand J, Buschaert S, Mayer S, Delepine-Lesoille S (2010) Truly distributed optical fibre sensors for structural health monitoring: from the telecommunication optical fibre drawling tower to water leakage detection in dikes and concrete structure strain monitoring. Advances in Civil Engineering 2010:e930796. https://doi.org/10.1155/2010/930796

Her SC, Huang CY (2011) Effect of coating on the strain transfer of optical fibre sensors. Sensors 11(7):6926–6941. https://doi.org/10.3390/s110706926

Higuchi K, Fujisawa K, Asai K, Pasuto A, Marcato G (2007) Application of new landslide monitoring technique using optical fibre sensor at Takisaka landslide, Japan. 1st North American Landslide Conference, Vail, Colorado, 2007. http://www.cnr.it/prodotto/i/88961.

Hong CY, Yin JH, Zhang YF (2016) Deformation monitoring of long GFRP bar soil nails using distributed optical fibre sensing technology. Smart Materials and Structures 25(8):085044. https://doi.org/10.1088/0964-1726/25/8/085044

Hu T, Hou G, Li Z (2020) The field monitoring experiment of the roof strata movement in coal mining based on DFOS. Sensors 20(5):1318. https://doi.org/10.3390/s20051318

Iten M, Hauswirth D, Puzrin AM (2011) Distributed fibre optic sensor development, testing, and evaluation for geotechnical monitoring applications. In W. Ecke, K. J. Peters, and T. E. Matikas, (Eds.) Proc. SPIE 7982, Smart Sensor Phenomena, Technology, Networks, and Systems 2011 (p. 798207). San Diego, California, United States: SPIE. https://doi.org/10.1117/12.881228

Iten M, Puzrin AM (2009) BOTDA road-embedded strain sensing system for landslide boundary localisation. Proc. SPIE 7293, Smart Sensor Phenomena, Technology, Networks, and Systems 2009, 729316 (7 April 2009). https://doi.org/10.1117/12.815266

Ivanov V, Longoni L, Ferrario M, Brunero M, Arosio D, Papini M (2021) Applicability of an interferometric optical fibre sensor for shallow landslide monitoring – experimental tests. Engineering Geology 288:106128. https://doi.org/10.1016/j.enggeo.2021.106128

Kishida K, Li CH (2006) Pulse pre-pump-BOTDA technology for new generation of distributed strain measuring system. Proc. Struct. Health Monit. Intell. Infrastruct. 1:471-477.

Kishida K, Yamauchi Y, Guzik A (2014) Study of optical fibres strain-temperature sensitivities using hybrid Brillouin-Rayleigh system. Photonic Sensors 4(1):1–11. https://doi.org/10.1007/s13320-013-0136-1

Kogure T, Okuda Y (2018) Monitoring the vertical distribution of rainfall-induced strain changes in a landslide measured by distributed fibre optic sensing with Rayleigh backscattering. Geophysical Research Letters 45(9):4033–4040. https://doi.org/10.1029/2018GL077607

Li J, Zhang M (2022) Physics and applications of Raman distributed optical fibre sensing. Light: Science and Applications 11(1):128. https://doi.org/10.1038/s41377-022-00811-x

Liu J, Song Z, Lu Y, Bai Y, Qian W, Kanungo DP, Chen Z, Wang Y (2019) Monitoring of vertical deformation response to water draining–recharging conditions using BOFDA-based distributed optical fibre sensors. Environmental Earth Sciences 78(14):406. https://doi.org/10.1007/s12665-019-8409-7

Liu J, Wang Y, Lu Y, Wei J, Kanungo DP (2017) Application of distributed optical fibre sensing technique in monitoring the ground deformation. Journal of Sensors 2017, 1–11. https://doi.org/10.1155/2017/6310197

Lu P, Lalam N, Badar M, Liu B, Chorpening BT, Buric MP, Ohodnicki PR (2019) Distributed optical fibre sensing: Review and perspective. Applied Physics Reviews 6(4):041302. https://doi.org/10.1063/1.5113955

Lu X, Thomas PJ, Hellevang JO (2019) A review of methods for fibre-optic distributed chemical sensing. Sensors 19(13):2876. https://doi.org/10.3390/s19132876

Mata-Falcón J, Haefliger S, Lee M, Galkovski T, Gehri N (2020) Combined application of distributed fibre optical and digital image correlation measurements to structural concrete experiments. Engineering Structures 225:111309. https://doi.org/10.1016/j.engstruct.2020.111309

Mentes G (2015) Investigation of dynamic and kinematic landslide processes by borehole tiltmeters and extensometers. Procedia Earth and Planetary Science 15:421–427. https://doi.org/10.1016/j.proeps.2015.08.025

Minardo A, Damiano E, Olivares L, Picarelli L, Zeni L, Avolio B, Coscetta A (2015) Soil slope monitoring by use of a Brillouin distributed sensor. 2015 Fotonica AEIT Italian Conference on Photonics Technologies 1–4. https://doi.org/10.1049/cp.2015.0156

Minardo A, Picarelli L, Avolio B, Coscetta A, Papa R, Zeni G, Di Maio C, Vassallo R, Zeni L (2014) Fibre optic based inclinometer for remote monitoring of landslides: on site comparison with traditional inclinometers. 2014 IEEE Geoscience and Remote Sensing Symposium 4078–4081. https://doi.org/10.1109/IGARSS.2014.6947382

Minardo A, Zeni L, Coscetta A, Catalano E, Zeni G, Damiano E, De Cristofaro M, Olivares L (2021) Distributed optical fibre sensor applications in geotechnical monitoring. Sensors 21(22):7514. https://doi.org/10.3390/s21227514

Monsberger CM, Lienhart W, Hayden M (2020) Distributed fibre optic sensing along driven ductile piles: Design, sensor installation and monitoring benefits. Journal of Civil Structural Health Monitoring 10(4):627–637. https://doi.org/ghaffori

Nakazawa M (1983) Rayleigh backscattering theory for single-mode optical fibres. Journal of the Optical Society of America 73(9):1175. https://doi.org/10.1364/JOSA.73.001175

Nikles M, Gabioud C, Thévenaz L, Prince R (1995) Highly accurate measurements of temperature and strain-dependence of Brillouin gain in single-mode fibres. Technical Digest of the 1995 Optical Fibre Measurement Conference OFMC'95, Liege Belgium, Paper VII.2, CBO-BCO

Nikles M, Thévenaz L, Prince R (1996) Simple distributed fibre sensor based on Brillouin gain spectrum analysis. Optics Letters 21:758-769(1996). https://doi.org/10.1364/OL.21.000758

Nyarko-Boateng O, Xedagbui FEB, Adekoya AF, Weyori BA (2020) Fibre optic deployment challenges and their management in a developing country: a tutorial and case study in Ghana. Engineering Reports 2(2):e12121. https://doi.org/10.1002/eng2.12121

Olivares L, Damiano E, Greco R, Zeni L, Picarelli L, Minardo A, Guida A, Bernini R (2009) An instrumented flume to investigate the mechanics of rainfall-induced landslides in unsaturated granular soils. Geotechnical Testing Journal 32-2. https://doi.org/10.1520/GTJ101366

Peng H, Chen B, Dong P, Chen S, Liao Y, Guo Q (2020) Application of FBG Sensing technology to internal deformation monitoring of landslide. Advances in Civil Engineering 2020:e1328945. https://doi.org/10.1155/2020/1328945

Personick S (1983) Review of fundamentals of optical fibre systems. IEEE Journal on Selected Areas in Communications 1(3):373–380. https://doi.org/10.1109/JSAC.1983.1145958

Piciullo L, Calvello M, Cepeda JM (2018) Territorial early warning systems for rainfall-induced landslides. Earth-Science Reviews 179:228–247. https://doi.org/10.1016/j.earscirev.2018.02.013

Puzrin AM, Iten M, Fischli F (2020) Monitoring of ground displacements using borehole-embedded distributed fibre optic sensors. Quarterly Journal of Engineering Geology and Hydrogeology 53(1):31–38. https://doi.org/10.1144/qjegh2018-166

ReportLinker (2021, August 31) Global distributed fibre optic sensor market by technology, by application, by end user, by regional outlook, industry analysis report and forecast, 2021—2027. GlobeNewswire News Room. Retrieved from: https://www.globenewswire.com/news-release/2021/08/31/2288991/0/en/Global-Distributed-Fibre-Optic-Sensor-Market-By-Technology-By-Application-By-End-User-By-Regional-Outlook-Industry-Analysis-Report-and-Forecast-2021-2027.html

Rogers A (1999) Distributed optical-fibre sensing. Measurement Science and Technology 10(8):R75–R99. https://doi.org/10.1088/0957-0233/10/8/201

Rui Y, Kechavarzi C, O'Leary F, Barker C, Nicholson D, Soga K (2017) Integrity testing of pile cover using distributed fibre optic sensing. Sensors 17(12):2949. https://doi.org/10.3390/s17122949

Sang H, Zhang D, Gao Y, Zhang L, Wang G, Shi B, Zheng B, Liu Y (2019) Strain distribution based geometric models for characterising the deformation of a sliding zone. Engineering Geology 263:105300. https://doi.org/10.1016/j.enggeo.2019.105300

Schenato L (2017) A review of distributed fibre optic sensors for geo-hydrological applications. Applied Sciences 7(9):896. https://doi.org/10.3390/app7090896

Schenato L, Palmieri L, Camporese M, Bersan S, Cola S, Pasuto A, Galtarossa A, Salandin P, Simonini P (2017) Distributed optical fibre sensing for early detection of shallow landslides triggering. Scientific Reports 7(1):14686. https://doi.org/10.1038/s41598-017-12610-1

Segalini A, Carri A, Valletta A, Martino M (2019) Innovative monitoring tools and early warning systems for risk management: a case study. Geosciences 9(2):62. https://doi.org/10.3390/geosciences9020062

Šegina E, Peternel T, Urbančič T, Realini E, Zupan M, Jež J, Caldera S, Gatti A, Tagliaferro G, Consoli A, González JR, Auflič MJ (2020) Monitoring surface displacement of a deep-seated landslide by a low-cost and near real-time GNSS system. Remote Sensing 12(20):3375. https://doi.org/10.3390/rs12203375

Shi B, Zhang D, Zhu H, Zhang C, Gu K, Sang H, Han H, Sun M, Liu J (2021) DFOS applications to geoengineering monitoring. Photonic Sensors 11(2):158–186. https://doi.org/10.1007/s13320-021-0620-y

Smit M, Williams K, Van der Tol J (2019) Past, present, and future of InP-based photonic integration. APL Photonics 4(5):050901. https://doi.org/10.1063/1.5087862

Soga K, Luo L (2018) Distributed fibre optics sensors for civil engineering infrastructure sensing. Journal of Structural Integrity and Maintenance 3(1):1–21. https://doi.org/10.1080/24705314.2018.1426138

Song Z, Shi B, Juang H, Shen M, Zhu H (2017) Soil strain-field and stability analysis of cut slope based on optical fibre measurement. Bulletin of Engineering Geology and the Environment 76(3):937–946. https://doi.org/10.1007/s10064-016-0904-4

Sun M, Staszewski WJ, Swamy RN (2010) Smart sensing technologies for structural health monitoring of civil engineering structures. Advances in Civil Engineering 2010 1–13(2010). https://doi.org/10.1155/2010/724962

Sun Y, Cao S, Xu H, Zhou X (2020) Application of distributed fibre optic sensing technique to monitor stability of a geogrid-reinforced model slope. International Journal of Geosynthetics and Ground Engineering 6(2):29. https://doi.org/10.1007/s40891-020-00209-y

Sun Y, Liu J, Xue Z, Li Q, Fan C, Zhang X (2021) A critical review of distributed fibre optic sensing for real-time monitoring geologic CO_2 sequestration. Journal of Natural Gas Science and Engineering 88:103751. https://doi.org/10.1016/j.jngse.2020.103751

Sun Y, Shi B, Zhang D, Tong H, Wei G, Xu H (2016) Internal deformation monitoring of slope based on BOTDR. Journal of Sensors 2016 1–8(2018). https://doi.org/10.1155/2016/9496285

Tang B, Cheng H (2018) Application of distributed optical fibre sensing technology in surrounding rock deformation control of TBM-excavated coal mine roadway. Journal of Sensors 2018 1–10(2018). https://doi.org/10.1155/2018/8010746

Wang B, Li K, Shi B, Wei G (2009) Test on application of distributed fibre optic sensing technique into soil slope monitoring. Landslides 6(1):61–68. https://doi.org/10.1007/s10346-008-0139-y

Wang H, Xiang P, Jiang L (2019) Strain transfer theory of industrialised optical fibre-based sensors in civil engineering: a review on measurement accuracy, design and calibration. Sensors and Actuators A: Physical 285:414–426. https://doi.org/10.1016/j.sna.2018.11.019

Wang T, Shi B, Zhu Y (2019) Structural monitoring and performance assessment of shield tunnels during the operation period based on distributed optical-fibre sensors. Symmetry 11(7)-940. https://doi.org/10.3390/sym11070940

Wang X, Shi B, Wei G, Chen S (2017) An energy demodulation based fibre optic sensing system for landslide early-warning. Applied Sciences 7(7):699. https://doi.org/10.3390/app7070699

Weber S, Faillettaz J, Meyer M, Beutel J, Vieli A (2018) Acoustic and microseismic characterisation in steep bedrock permafrost on Matterhorn (CH). Journal of Geophysical Research: Earth Surface 123(6):1363–1385. https://doi.org/10.1029/2018JF004615

Wijaya H, Rajeev P, Gad E (2021) Distributed optical fibre sensor for infrastructure monitoring: field applications. Optical Fibre Technology 64:102577. https://doi.org/10.1016/j.yofte.2021.102577

Wu J, Jiang H, Su J, Shi B, Jiang Y, Gu K (2015) Application of distributed fibre optic sensing technique in land subsidence monitoring. Journal of Civil Structural Health Monitoring 5(5):587–597. https://doi.org/10.1007/s13349-015-0133-8

Wu R, Lamontagne-Hallé P, McKenzie JM (2021) Uncertainties in measuring soil moisture content with actively heated fibre-optic distributed temperature sensing. Sensors 21(11):3723. https://doi.org/10.3390/s21113723

Ye XW, Su YH, Han JP (2014) Structural health monitoring of civil infrastructure using optical fibre sensing technology: a comprehensive review. The Scientific World Journal 2014 1-11(2014). https://doi.org/10.1155/2014/652329

Ye X, Zhu HH, Wang J, Zhang Q, Shi B, Schenato L, Pasuto A (2022) Subsurface multi-physical monitoring of a reservoir landslide with the fibre-optic nerve system. Geophysical Research Letters 49(11):e2022GL098211. https://doi.org/10.1029/2022GL098211

Zhang CC, Shi B, Gu K, Liu SP, Wu JH, Zhang S, Zhang L, Jiang HT, Wei GQ (2018) Vertically distributed sensing of deformation using fibre optic sensing. Geophysical Research Letters 45(21):11732-11741. https://doi.org/10.1029/2018GL080428

Zhang CC, Shi B, Zhang S, Gu K, Liu SP, Gong XL, Wei GQ (2021) Microanchored borehole fibre optics allows strain profiling of the shallow subsurface. Scientific Reports 11(1):9173. https://doi.org/10.1038/s41598-021-88526-8

Zhang CC, Shi B, Zhu HH, Wang BJ, Wei GQ (2020) Toward distributed fibre-optic sensing of subsurface deformation: a theoretical quantification of ground-borehole-cable interaction. Journal of Geophysical Research: Solid Earth 125(3):e2019JB018878. https://doi.org/10.1029/2019JB018878

Zhang CC, Zhu HH, Liu SP, Shi B, Zhang D (2018) A kinematic method for calculating shear displacements of landslides using distributed fibre optic strain measurements. Engineering Geology 234:83–96. https://doi.org/10.1016/j.enggeo.2018.01.002

Zhang CC, Zhu HH, She JK, Zhang D, Shi B (2015) Quantitative evaluation of optical fibre/soil interfacial behavior and its implications for sensing fibre selection. IEEE Sensors Journal 15(5):3059–3067. https://doi.org/10.1109/JSEN.2014.2386881

Zhang CC, Zhu HH, Shi B (2016) Role of the interface between distributed fibre optic strain sensor and soil in ground deformation measurement. Scientific Reports 6(1):36469. https://doi.org/10.1038/srep36469

Zhang CC, Zhu HH, Shi B, She JK (2014) Interfacial characterisation of soil-embedded optical fibre for ground deformation measurement. Smart Materials and Structures 23(9):095022. https://doi.org/10.1088/0964-1726/23/9/095022

Zhang D, Du W, Chai J, Lei W (2021) Strain test performance of Brillouin optical time domain analysis and fibre Bragg grating based on calibration test. Sensors and Materials 33(4):1387. https://doi.org/10.18494/SAM.2021.3255

Zhang D, Shi B, Sun Y, Tong H, Wang G (2015) Bank slope monitoring with integrated fibre optical sensing technology in Three Gorges Reservoir area. Engineering Geology for Society and Territory-Volume 2 (pp. 135–138). Springer https://doi.org/10.1007/978-3-319-09057-3_13

Zhang L, Cheng G, Wu J, Minardo A, Song Z (2021) Study on slope failure evolution under surcharge loading and toe cutting with BOTDA technology. Optical Fibre Technology 66:102644. https://doi.org/10.1016/j.yofte.2021.102644

Zhao M, Yi X, Zhang J, Lin C (2021) PPP-BOTDA distributed optical fibre sensing technology and its application to the Baishuihe landslide. Frontiers in Earth Science 9:660918. https://doi.org/10.3389/feart.2021.660918

Zhu HH, She JK, Zhang CC, Shi B (2015) Experimental study on pullout performance of sensing optical fibres in compacted sand. Measurement 73:284–294. https://doi.org/10.1016/j.measurement.2015.05.027

Zhu HH, Shi B, Zhang J, Yan JF, Zhang CC (2014) Distributed fibre optic monitoring and stability analysis of a model slope under surcharge loading. Journal of Mountain Science 11(4):979–989. https://doi.org/10.1007/s11629-013-2816-0

Zhu ZW, Liu B, Liu P, Zhao B, Feng ZY (2017) Model experimental study of landslides based on combined optical fibre transducer and different types of boreholes. CATENA 155:30–40. https://doi.org/10.1016/j.catena.2017.03.003