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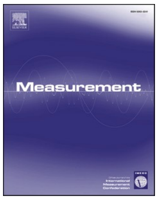

Optical fibre sensors for geohazard monitoring – A review

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ABSTRACT

Geohazards pose significant risks to human life, infrastructure, and the environment, bringing out the necessity of advanced monitoring techniques for early detection and mitigation. This review paper explores the application of optical fibre sensors in geohazard monitoring. Optical fibre sensors have emerged as promising tools due to their inherent advantages. Various types of optical fibre sensors used in geohazard monitoring, categorized as distributed optical fibre sensors and fibre Bragg grating sensors and explains their mechanisms and applications are outlined in the context. Extracting from an ample amount of research and case studies, the successful design and deployment of optical fibre sensors in detecting disaster-causing changes in the environment and providing early warnings for diverse geohazards: landslides, earthquakes, and volcanic activity are brought up in detail. Furthermore, it addresses challenges and limitations in implementing optical fibre sensors for geohazard monitoring while highlighting opportunities for future advancements.

1. Introduction

Geological hazards are complex and often unpredictable natural events that have significant impacts on human societies and the environment. Earthquakes, volcanic eruptions, landslides, tsunamis, and subsidence are some of the most common geological hazards that impact the world. With the rapid growth of population and the infrastructure the effect of a catastrophic event can cause significant damage to human lives and properties. Understanding these geological hazards is crucial to the safety and well-being of communities worldwide.

Geological hazards are unpredictable, so there are rare chances of avoiding them. However, monitoring them is the most basic and important thing to mitigate the effect and have preparedness. Measuring and understanding geological changes is important for science and safety too. It also results in cost-effective maintenance and reduces property damage in the event of a disaster [1,2]. Early warning systems for geological hazards include data that show that an event might occur and forecast its magnitude and propagation [2,3].

Conventional geological condition monitoring systems consist of separate sensing elements, an acquisition system, a transmission system, and a power supply system [4]. These monitoring systems included inclinometers [5,6,7], extensometers [2], and geophones [8] as the sensing elements. While these conventional sensing elements act as single-pointed sensors, geographical hazards need well-spread network sensors to generate repeated and reliable data. This is vital because of the limitlessness of natural hazards.

In the following context, the application of distributed sensing geological parameters is discussed. The most recent developments in optical fibre-based sensing systems are discussed based on geological hazard monitoring. This includes a discussion of the fundamentals of optical fibre sensors based on FBG sensing and distributed sensing followed by the implementation process which is elaborated through the Fig. 1. In the later part, the application of distributed sensing is discussed concerning the most frequent geological hazards. Fig. 1 illustrates the technologies which have used scattered-based fibre optic sensing for geohazard monitoring. Depending on the outcome of the monitored condition the technology involved also changes. However, Fig. 1 does not imply any classification of the distributed sensing technology, but an

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Abbreviations: BOFDR, Brillouin Optical Frequency Domain Reflectometry; BOTDR, Brillouin Optical Time Domain Reflectometry; DAS, Distributed Acoustic Sensing; DOFS, Distributed Optical Fibre Sensing; DTS, Distributed Temperature Sensing; FBG, Fibre Bragg Grating; GIS, Geographic Information System; LVDT, Linear Variable Displacement Transducers; OFDR, Optical Frequency Domain Reflectometry; OTDR, Optical Time Domain Reflectometer; ROFDR, Raman Optical Frequency Domain Reflectometry; ROTDR, Raman Optical Time Domain Reflectometry; SFBG, Sapphire FBG; TDM, Time Division Multiplexing; UWFBG, Ultra-Weak Fibre Bragg Grating Sensing; WDM, Wavelength Division Multiplexing.

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approach of suitable techniques of optical fibre sensing relevant to different subterranean conditions. It reviews the applicability of optical fibre sensors in landslide monitoring, earthquake monitoring and volcanic monitoring depending on the technology. The review concludes with future possibilities and trends for optical fibre-based sensing.

2. Optical fibre sensing

Optical fibre sensors are emerging tools for monitoring geological hazards due to their unique properties. These distributed fibre sensors can span over several kilometres. Due to the same reason, they can be laid up in large areas enabling monitoring over large ground areas. This makes them ideal for identifying hazards like landslides and fault lines. The changeable spatial resolution of OFS is another advantage and it varies with the application and the technology; which is advantageous in monitoring different conditions. Low special resolutions are advantageous in monitoring conditions like landslides which use lengthy fibres. However, in monitoring slight changes like pore water pressure and gas emissions a fine special resolution is advantageous. Together with that, their real-time data collection capabilities are crucial for early warning systems. Optical fibres are immune to electromagnetic interference, making them suitable for noisy environments. Their ability to function in remote and challenging locations, including underwater and volcanic zones, expands monitoring possibilities and capabilities. To fully understand complex geological processes, it's possible to measure several parameters simultaneously with optical fibres. With long-term stability and minimal environmental impact, optical fibres offer cost-effective solutions over time.

OFS can be used to monitor subterranean conditions, such as horizontal and vertical ground displacements, slope stability [6,9,10,11,12,13,14], pore water pressure, and geothermal conditions [15,16,17], by deploying optical fibres along the surface or inside boreholes. Ground displacement can be assessed using DOFS sensors, which provide longitudinal soil structure strain measurements [9]. Simply, the DOFS enables the detection and localization of undesired events that make a change in strain or temperature. Their rapid data transmission enables the development of effective early warning systems, for hazards such as earthquakes, where timely responses are important [2,11,18,19,20].

Simply, optical fibres provide a versatile and powerful platform for enhancing our understanding of geological hazards and improving disaster preparedness and response. Optical fibre sensing measures the changes in the installed environment which is soil or the ground (which may be fully or partially saturated, chemically aggressive, hard with composition or affected by vegetation and underground animals) concerning cases studied in the review that affect the local properties of the optical fibre cable. An OFS system compromises an optical source which sends an optical signal to the OF cable, which is the sensing element. This optical signal might encounter different local properties as it propagates. The change of those local properties causes the scattering of the optical signal.

Changes in temperature and strain affect the fibre's refractive index, which alters light scattering within it. This has a significant impact on Rayleigh scattering since any fluctuations in the refractive index determine the intensity of backscattered light. In a different scenario, when an OF cable is subjected to a change in temperature or strain, its length and diameter also change. As a result, the density of scattering centres also changes, affecting the scattering intensity and pattern [19]. Temperature sometimes can affect fibre attenuation resulting in the strength of both transmitting and scattered signal [21]. In this way, changes in the environment can alter the properties of scattered light, including intensity, phase, wavelength, or polarization The detectors capture modulated light signals, which are processed to determine predetermined measurements like temperature fluctuation or mechanical changes [18,20,22,23].

In the current context, two types of optical fibre sensors are being used: Distributed Optical Fibre Sensors (DOFS) and Fibre Bragg Grating (FBG). FBG provides high-resolution point measurements, while DOFS offers distributed measurements over long distances. The ability of OFS to detect and measure minute changes in the measuring parameter is their resolution which decreases when the measuring range increases. The selection between the two techniques depends on the specific requirements of the sensing application and the installation environment. For fine and sensitive measurements high-resolution configurations are opted when low-resolutions are used for sensors having a larger minimum detectable change in the measuring parameter [24,25] like 1 m over a 10 km length. Both DOFS and FBG sensors are used for measuring temperature and strain, but show a contrast in terms of measurement

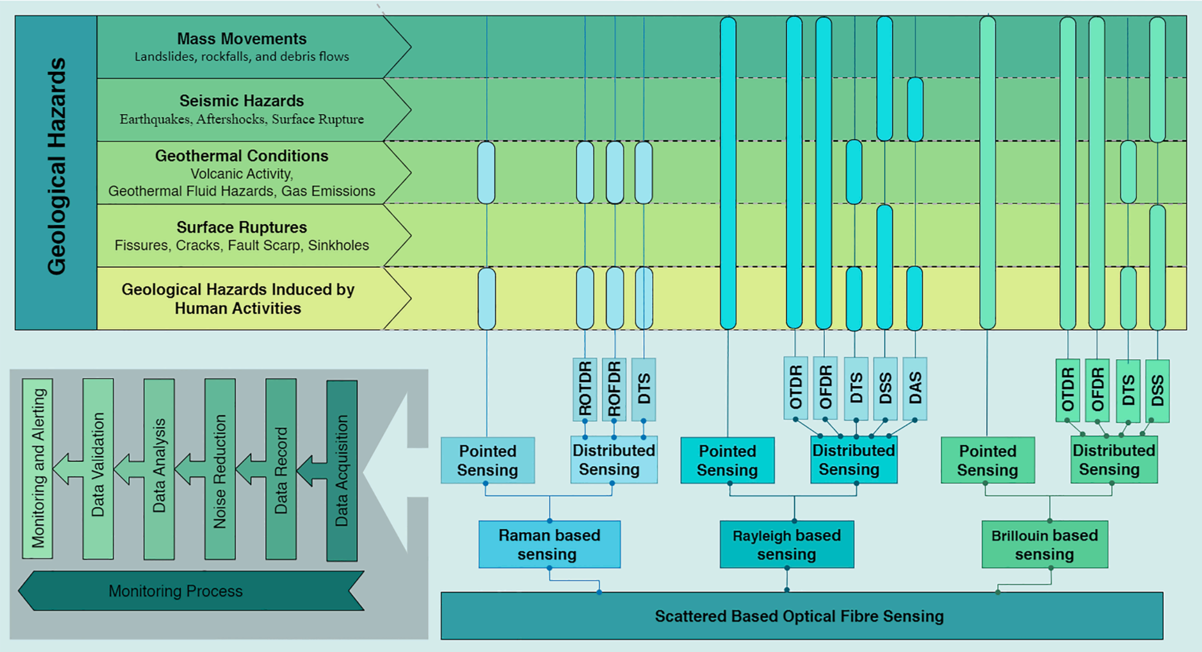

Fig. 1. Overview on optical fibre sensing for geohazard monitoring.

range, accuracy, and nature.

2.1. FBG sensing

FBG sensors include distributed Bragg reflectors that are imposed on the fibre. It is done as the fibre pattern is exposed to intense ultraviolet light which changes the refractive index of the fibre in predetermined intervals. The newly added change in the refractive index creates gratings in the fibre and they refrain from the transmission of certain wavelengths through them but reflect. Fig. 2 (a) illustrated the structure of an FBG with refractive indexes of gratings (n_3) exceeding that of OF cable (n_1) [26,27]. The period of the grating and the refractive index of the fibre defines the wavelength of the reflecting light (the Bragg wavelength) as depicted in Equation (1), when λ_B is fibre Bragg wavelength, n_{eff} is the effective core index of refraction and $\wedge$ is the periodicity of the index modulation (grating period) [28].

$$\lambda_B = 2n_{eff}\wedge \tag{1}$$

In the presence of a temperature or strain change the reflected light wave tends to shift as the reflected wavelength is proportional to those parameters [29].

Consequently, the difference between the central wavelengths due to the change of light path, $\Delta\lambda$ can be expressed in terms of the change in temperature (T (ΔT) and the strain change ($\Delta\varepsilon$) as in Equation (2) [26].

$$\frac{\Delta\lambda}{\lambda} = (1-P_{eff})\Delta\varepsilon + (\alpha+\xi)\Delta T \tag{2}$$

In real-time geotechnical monitoring three types of FBG sensors are adopted; Pointed FBG sensors, Quasi distributed and long gauge FBG sensors. Each of the types has its discrete application where pointed FBG has only one grated section, while the Quasi distributed have FBGs mounted in series. If the sensor array consists of several grated sections for each of the section's different wavelengths (λ_1, λ_2, λ_3…) should be imposed to avoid overlapping the reflected signal, hence the analysis of the received signal may remain accurate.

The detection of a change in the FBG is done by recording the shift in the reflected wave compared to the wavelength as depicted in Fig. 2 (c). That peak shift is identified through an optical source with reflected light interrogating capabilities, and that expands to two basic techniques. One of the methods uses a broadband light source to send light to the fibre and analyses the reflected light using an optical spectrum analyser. The other method uses a narrowband, adjustable laser source where the intensity of the reflected light is detected by a power metre and the wavelength is recorded accurately: numerically with an accuracy of 1 pm [30].

In FBG sensing, Time Division Multiplexing (TDM) and Wavelength Division Multiplexing (WDM) are distinct techniques with unique characteristics and applications [31]. In FBG sensing, WDM is utilized to assign distinct wavelengths of light to individual FBG sensors along the same optical fibre. The unique grating structure of each FBG sensor enables it to reflect light at a specific wavelength. TDM technology can only measure physical parameters at FBG locations and is unable to conduct distributed measurements along the entire cable [32,33].

2.2. Distributed sensing

Distributed sensing overcomes the issue of discrete sensing of FBG and exhibits continuous measuring capabilities by allowing the sensing along the whole cable. However, a limited user-defined number of data points are considered in real applications for the easiness of handling [2]. To analyse external changes using DOFS, optical reflectometry is used [34]. It is that the light propagating in the fibre gets affected by the change of measuring parameter may it be the strain or temperature in the installed environment which is ground or soil regarding this content.

Any local change in the fibre is to be identified with the scattering of the light in the fibre in that respective instant and the location. When transmitting the light through the fibre, the light interacts with

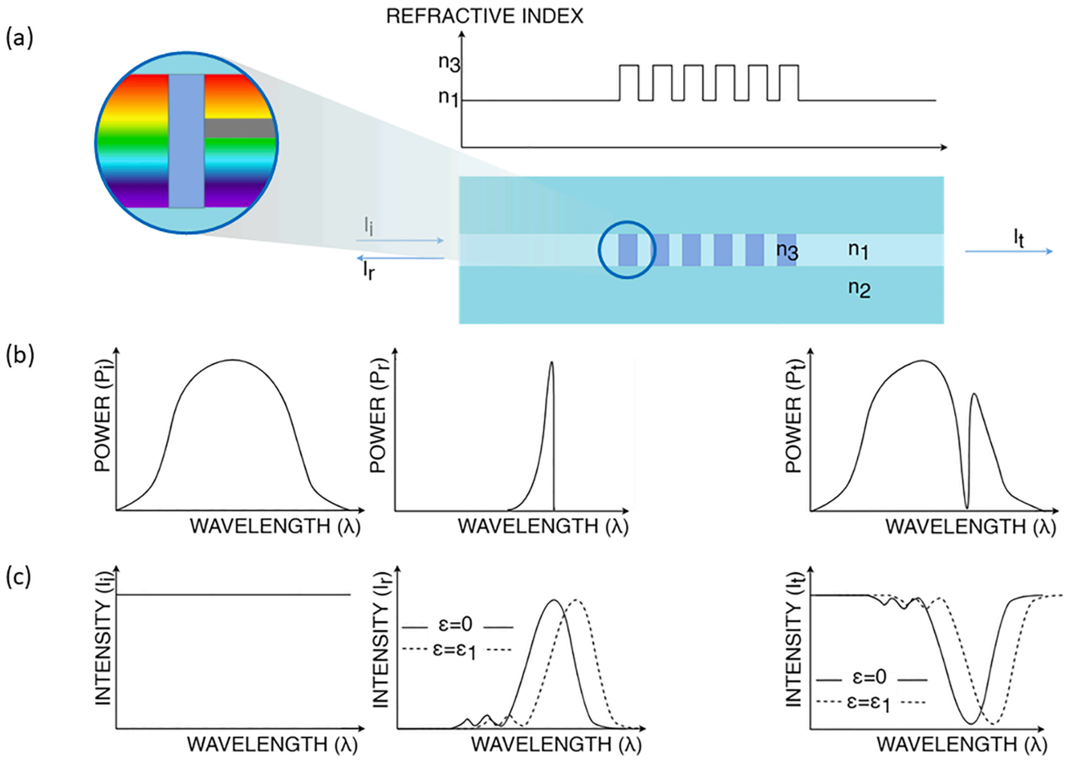

Fig. 2. The structure of an FBG and its spectral response when i, r and t stand for input light, reflected light and transmitted light respectively. n refers to the refractive index. (a) Refractive index profile along the fibre (b) Input spectrum, reflection spectrum with a peak and transmission spectrum with a notch (c) Intensity spectral behaviour of input, reflection and transmitted light wave.

inhomogeneities in the fibre and thus light scatter. The scattered light is received either in the forward direction or backward direction for the analysis. However, in this scenario, no wavelength change happens [19,34,35,36]. Rayleigh, Brillouin, and Raman scattering are the basic optical phenomena that occur and can be utilized for various sensing applications in optical fibres as illustrated in Fig. 3.

The scattering can be analysed to determine changes in the environment around the cable. Table 1 outlines the specific characteristics of each parameter.

While the scattering identifies the local changes, the demodulation schemes: Optical Time Domain Reflectometry (OTDR) and Optical Frequency Domain Reflectometry (OFDR) are used in cooperation to the localization it.

OTDR involves the light intensity of the reflected light and the location of the change encountered. A short pulse of light is transferred through the fibre, and the backscattered light's intensity is measured as a function of time. This light source is typically a laser diode that's driven by an electric pulse modulator. While the backscattered light is detected in the photodiode via a circulator or splitter. After converting the detected backscattered waveform into a digital version, the data acquisition device synchronizes it with the short pulse signal to identify the propagation time of the backscattered waves, which leads to the calculation of the location of change along the fibre [25,26,37]. If the distance along the fibre is denoted by z, Equation (3) denotes the distance along the fibre where the change is encountered by the fibre [25].

$$z = \frac{c}{2n}t = \frac{v_g}{2}t \tag{3}$$

In the given equation 'c' represents the speed of light in the vacuum, 'n' is the refractive index of the medium which is the core of the optical fibre, 'v_g' is the group velocity of light pulses in the fibre, while 't' is the backscattered detection type. Dividing by 2 stands for the round-trip distance of the light pulse.

The analysis conducted by OFDR is based on the frequency shift of light that occurs due to a disturbance to the fibre. OFDR uses a continuous wave and the frequency of that wave sweeps linearly with the time. This frequency sweep is achieved by modulating the laser frequency over time. The swept signal is split into two signals: probe and reference, the probe signal propagates through the fibre. The backscattering probe signal from the fibre combined with the reference signal detects the measurand. As the same light source generates the reference and the probe signal, the backscattering signal is considered a time-delayed reference signal. Both signals interfere at the receiver resulting in an interference signal which includes scattering properties of different segments along the fibre. The Fourier transform analysis on the interference signal transforms the frequency domain function into a spatial domain which gives a profile of the fibre properties along its length [18,25,38,39].

Table 1
Differentiation of scattering in fibre optics.

Parameter	Rayleigh Scattering	Brillouin Scattering	Raman Scattering
Scattering Type	Elastic scattering	Inelastic scattering	Inelastic scattering
Mechanism	Density fluctuations	Acoustic phonons	Molecular vibrations
Energy Transfer	None	Energy transferred to acoustic phonons	Energy transferred to molecular vibrations
Dominance in Optical fibres	Dominant scattering mechanism	Important for distributed temperature and strain sensing	Useful for distributed temperature sensing and signal amplification
Applications	- OTDR for fibre fault location - Signal loss in optical fibres	- Distributed temperature sensing - Distributed strain sensing	- Distributed temperature sensing - Raman amplification
Spatial Resolution	Limited due to dominant scattering	High spatial resolution	High spatial resolution
Temperature Sensing	No direct temperature measurement	Direct temperature measurement	Direct temperature measurement
Strain Sensing	No direct strain measurement	Direct strain measurement	Limited direct strain measurement (secondary effect)

Both OTDR and OFDR techniques can incorporate scattering phenomena to achieve distributed measurements in parameters: strain and temperature, with user-defined spatial resolution [18,40]. Subterranean condition monitoring has specific system requirements with the measurand and the resolution and the range change. Table 2 presents the applicability of each technology in different subterranean condition monitoring depending on their characteristics.

Distributed sensing expands to Distributed Strain Sensing (DSS), Distributed Temperature Sensing (DTS), and Distributed Acoustic Sensing (DAS) as each of the techniques can be extended to geological condition monitoring. Distributed Strain Sensing is a method used to detect strain-induced changes in backscattered light within an optical fibre. This is done by utilizing phenomena such as Brillouin scattering or Rayleigh scattering. Optical Time Domain Reflectometry (OTDR) and Optical Frequency Domain Reflectometry (OFDR) are techniques used to analyse changes in the frequency or phase of the scattered light. These changes indicate the variations in the strain that has occurred in the optical fibre. This technology enables real-time and distributed monitoring of structural health, geotechnical stability, and stress distribution in infrastructure such as bridges, and pipelines.

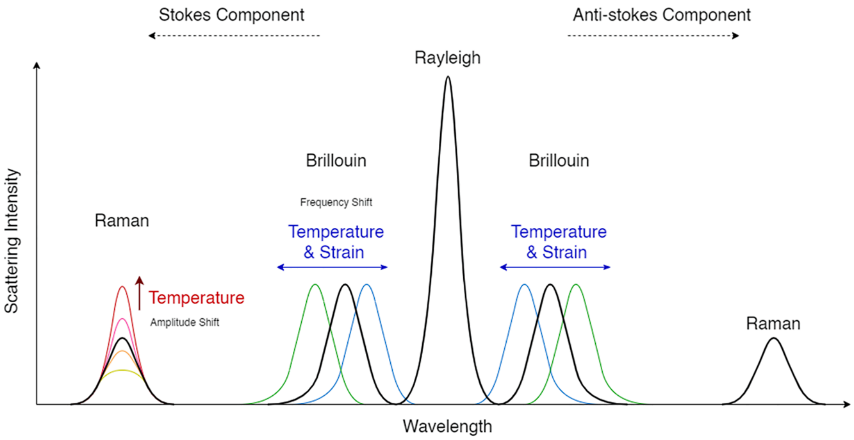

Fig. 3. Rayleigh, Raman and Brillouin scattering intensity in optical fibres.

Table 2
Comparison between technical difference between OTDR and OFDR and their applicability in subterranean condition monitoring.

Factors defining the suitability of the technology.	OTDR		OFDR	
	Characteristic	Applicability in subterranean condition monitoring	Characteristic	Applicability in subterranean condition monitoring
Spatial resolution	Low resolution	More suitable when minute changes are neglected. (landslides, surface ruptures, ground vibrations)	High resolution (a function of optical frequency sweep) [25]	Most suitable for detailed monitoring. (pore water pressure, gas emission, borehole temperature)
Measurement range	Long range more than OFDR	Suitable for monitoring over large areas (ground vibrations and landslides)	Long range, yet limited compared to OTDR [25]	Suitable to monitor geological conditions in limited areas.
Complexity and cost	Comparatively less complex and less expensive		Comparatively more complex and more expensive	More suitable when fine details are required.[38]

Distributed temperature sensing measures temperature variation along the cables while the cable itself is the sensing element. DTS works by directing a laser pulse into a fibre optic cable and detecting the intensity of backscattered photons. Those backscattered photons are generated as a result of Raman scattering which is the temperature dependant. Fig. 4 demonstrates the temperature measurement configuration in a DTS setup. The intensities of the scattered photons vary and those variations of the intensities enable the computation of the respective temperature value. The technique accurately reads the distance of change in real-time by measuring the light velocity within the fibre [1,16,41,42].

The author van de Giesen et al. define the temperature(K) along a fibre by using the ratio of Stokes and anti-Stokes backscattered light [43].

$$T(z,t) = \frac{\gamma}{ln\left(\frac{P_S(z,t)}{P_{aS}(z,t)}\right) + C(t) - \int_0^z \Delta\alpha(z')dz'} \tag{4}$$

Equation (4) gives the temperature, where z is the distance along the cable from the DTS instrument. The ratio PS(z,t) / PaS(z,t) is the measured ratio between the power of the Stokes (S) and anti-Stokes (aS) backscatter that reaches the instrument while $\Delta\alpha$ stands for the differential attenuation between the anti-Stokes and Stokes signal [43,44].

Distributed temperature sensing with Raman scattering has been used in hydrological and geothermal applications. Recently, the technology has been used for geohazard sensing, including earthquake observations, by detecting changes in Brillouin and Rayleigh scattering caused by external strains [45,46,47].

Distributed Acoustic Sensing (DAS) is based upon the Rayleigh backscattering in the optical fibre. When a physical effect acts on the fibre the optical feature of the fibre: frequency, amplitude or phase gets modulated and identified via demodulation. There are two main schemes used for implementing Distributed Acoustic Sensing (DAS) – Φ-OTDR and OFDR [48,49]. To measure perturbation magnitude, advanced methods are needed. Measuring Rayleigh intensity trace directly along the fibre is unreliable due to the nonlinear dependence of Rayleigh scattering intensity on the induced strain [49].

In some scenarios, these techniques might be used together or integrated for advanced and thorough monitoring. Each of the mentioned distributed sensing techniques has its application based on the parameters it measures.

3. Design, fabrication and installation of OFS for measuring subterranean parameters

Optical fibres are made of a transparent centre known as the core, surrounded by a layer called cladding. The core is made of a material with a higher refractive index than the cladding. This structure allows light to travel through the core by a process of total internal reflection, which keeps the light contained within the core even when the fibre bends, allowing for efficient transmission of light over long distances. Silica is the most commonly used material for making optical fibre glass [23]. Optical fibre sensors offer a range of benefits that make them an attractive choice for various applications. These include their small size, lightweight design, ability to withstand high temperatures and pressure, and electromagnetic passivity. These sensors are ideal for harsh environments, such as those with high levels of noise, vibration, heat, moisture, and instability. Low attenuation: less loss of the signal and the high bandwidth are also advantageous features in OFS. They can be easily installed in tight spaces and positioned with flexible fibres [2,11,20,23]. It offers such useful features, but there are some limitations. Since the optical fibre cables are small in size, they have always

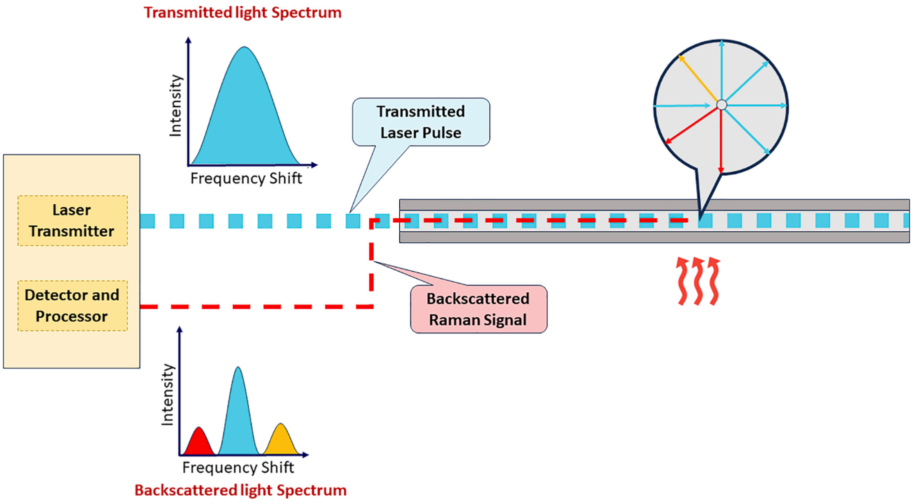

Fig. 4. Temperature sensing setup for distributed temperature sensing.

been fragile. The fragility of fibres and being tiny in size makes them very hard to install and survive in a harsh environment. The underground environment is comprised of rocks, sand, minerals, organisms, and water. It undergoes frequent changes such as water rising, drying, compressions, expansion, and chemical reactions, which can cause significant disturbance. There is a chance that fibres come into contact with underground water over an extended period and this water may contain minerals and chemicals that vary depending on the location. Water can lead to mechanical expansion or contraction of the optical fibre cable due to swelling or shrinking of materials in contact with water generally known as hydrogen darkening. This causes hydrogen to bind to the silica glass compounds. So hydroxyls are formed [50]. This can cause signal attenuation in optical fibres due to absorption and scattering of light [1]. As water penetrates the protective coating, it can absorb and scatter light signals, reducing the signal strength and potentially causing measurement errors [49,51]. To mitigate the effects of water on optical fibre sensors and the effect of fragility, proper environmental sealing and protective coatings are crucial.

The protection is expected to stand for a long time even in harsh conditions. As the literature suggests, there are plenty of methods to protect the fibre. In their experiment, Surre et al. tested an FBG optical fibre sensor called OSC (Optical strain sensor, termed OSC) [52]. The sensor was attached to two large metallic plates using cyanoacrylate adhesive and then fixed to a concrete beam using epoxy resin, as depicted in Fig. 5 (a). A similar type of protection can be extended to geological applications also when they are mounted on underground piles and other structures.

Fig. 5(b) shows a sensor tubed between two anchor plates tested at laboratory conditions. The PVC tube with an external diameter encloses the acrylic ester-coated FBG sensor, while two anchor plates hold the sensor in the soil [53].

In the characterisation of clay weakening using an FBG sensor array, an encapsulation method has been tested successfully. In the sensor built to measure the temperature, an FBG was enclosed in a liquid-free casing and then placed in an external aluminium package as in Fig. 5 (c). In the same experiment, a glass fibre-reinforced polymer (GFRP) material was used to encapsulate the FBG fibre when changing the sensor to a strain sensor [54]. Together with these, there might be protective layers added during the manufacturing of the cable itself [55,56,57,58].

Though this packaging provides a good environment for the fibre to survive it has some drawbacks too. The temperature-sensing optical fibres are greatly affected by the packaging: material type and thickness. Inappropriate packaging causes a delay in temperature reading which is overcome by metal covers. Yet metal packages are hard to handle [55].

Table 3 summarizes a few of the most common types of protection methods on optical fibre cables. However, this represents the general common methods and the protection method must be more specific regarding the application and the sensor design and the discussion is extended in the following subcategories.

Once the fibre is developed to an environmentally compatible form, sensors can be developed to monitor geohazards. The optical fibre sensor design, fabrication method, layout and depend on the specific task they are intended for the hazard to be monitored. To identify geological hazards before the disaster the respective changing parameters are supposed to be identified. Fibre measures strain due to force or temperature. The designing of the sensor is very crucial as that changing factor either should be a strain or a temperature. If not, the parameter must be convertible to strain or temperature. The parameters which define each geological disaster can be summarized as presented in Table 4. As the fifth column indicates those changes are not identified by the OF cables. Yet those changes can be converted to strain or temperature according to the sensor architect. In the summarization non-measurable parameters such as soil type and vegetation, covers are excluded despite their significant impact.

This section discusses the design and fabrication of sensors, which are highly dependent on specific requirements. However, a common overall process for developing optical fibre sensors (OFS) can be represented in Fig. 6. Thought the design of sensors follows the path indicated in the Fig. 6 optical fibre sensors for geotechnical monitoring compromises several architectures that depend on the focused geohazard and geological conditions it is installed in as discussed in section 04.

A well-developed sensor may still face the challenge of installation due to the fragile behaviour of the optical fibre and the harsh conditions of the environment. The installation method varies with its task and the properties. An installation method that shields the fibre cable from environmental effects, protects it for longer life, accounts for soil variations, ensures good contact with the ground, and maintains high strain sensitivity is expected as a must [64]. For more sustainable sensor systems, the optical fibre sensors ought to be installed with a supporting structure or in an already installed structure or a rigid natural support. It is vital for fibre to withstand the changes irrespective of its size and fragile nature. Most essentially, supporting systems must be there to transfer respective local changes to the fibre acting as the transfer medium.

3.1. Design of sensors for ground motion sensing

Many of the geohazards including landslides, cracks, erosions, sinkholes and subsidence are identified through the ground motion. After analysing various measurable parameters, it has been proven that

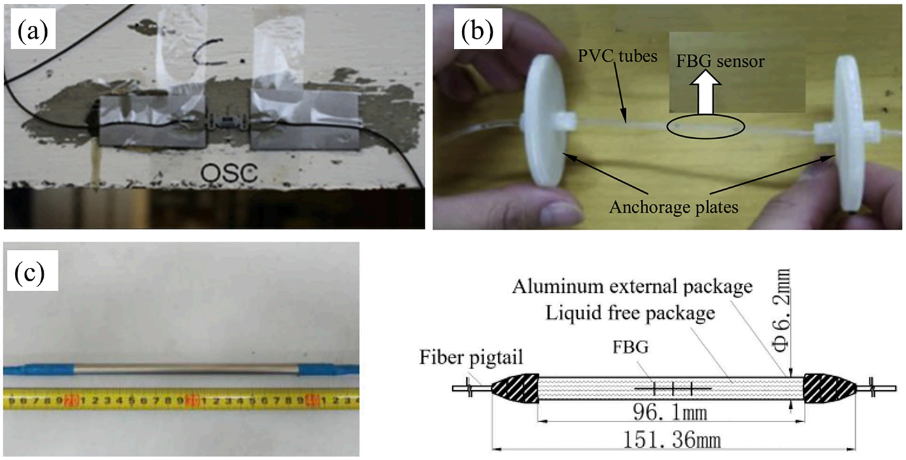

Fig. 5. Protection methods for FBG sensors (a) A sensor mounted on steel straps [52] (b) A sensor protected with a PVC tube and anchored [53](c) A sensor encapsulated with aluminium package [54].

Table 3
Recently used protective methods on optical fibres.

Reference	Optical Fibre	Protective Method	Description
[1]	DTS	Layered protection	It consists of layers of protection from 1. Steel loop tube 2. Stainless strength member 3. TPE outer sheath The layered protection provided 1. High chemical resistance 2. Robust abrasions 3. High flexibility and small bending radii 4. Protection over hydrogen darkening (installed in a chemically aggressive environment with H_2S)
[52]	FBG	Steel straps	Mounting on steel straps provided more contact surface area for the installation, but would not help in identifying the minor cracks as steel won't crack
[53]	FBG	Anchored PVC enclosure	It avoided the direct contact of the OF cable with the soil. As two ends of the fibre are connected to the anchors the, displacement of anchors with soil only enables the monitoring.
[54]	FBG	Enclosures	1. The temperature sensor, was enclosed in a liquid-free package, which is then packaged in an external aluminium package. 2. The strain sensor was packed in glass fibre-reinforced polymer (GFRP) material, which ensured overall strength.
[56]	FBG	Packaging	The adhesion of the sensor to the steel rods was followed by adding layers of protection as, 1. fixing of two fibre gratings onto the rod with adhesive glue. 2. coating the bare fibres with epoxy resin 3. covering by winding of nylon protective cloth after the solidification of the epoxy resin 4. wrapping with adhesive tape is used to ensure the smoothness
[12]	FBG	Outer sheath	Outer sheath of high-strength Medium-Density Polyethylene (MDPE) with embedded metal stiffeners.
[17]	DTS	Packaging	Packaging the tubing encased fibre with two protective bumper wires (flatpack). It can withstand a temperature of 150 °C.
[57]	DOFS	Buffered jackets	Three types of jackets 1. Tight buffered Nylon jacket 2. Tight buffered JPEE jacket 3. Loose buffered nylon jacket

Table 4
The parameters which define each geological disaster [58,59,60,61,62,63].

Disaster	Measurable parameters that allow each geological disaster forecast	Parameters that are directly recognized by optical fibres	Parameters that are not recognized by optical fibres but can be converted into a recognizable parameter
Landslides/Slope instability/ Debris flow/ Rock fall	Ground motion	Strain	–
	Slope angle/tilt	Strain	–
	Moisture content/ water content	Temperature	Water pressure/ Humidity
	Pore water pressure	Pressure	Water Pressure
	Vibration	Vibration	
Earthquakes/ Tsunami	Frequency and the amplitude of the wave tectonic processes	Vibration	Motion
Volcanic eruptions	Temperature gradient	Temperature	–
	Ground deformation	Strain	–
	Gas emission	–	Strain [56], Pressure Vibration
Tsunami	Frequency and the amplitude of the wave	Vibration	–
	Pressure on the sea bottom	–	Deflection of a membrane
Sinkhole/ Ground subsidence	Ground motion	Strain	–
	Propagation of manmade drillings and mines	Strain	–
	Water table fluctuation	–	Deflection of a membrane
Cracks and fissures	Ground deformation (tectonic processes)	Strain	–

ground motion can be effectively monitored through optical fibre strain sensing.

A closely and firmly attached optical fibre enables the monitoring of the following environment. However, an ideal optical fibre cable for the purpose of strain measurements in the soil would behave as if it consisted of the soil itself [50]. The strain identified through the fibre may be a cause of tensile or compressive stresses, material displacements, and changes to the position and shape. In compression density of the fibre material increases and in tension the scattering centre changes resulting an altering of the refractive index. In a bending light tends to scatter at the bend points, which leads to a loss of optical signal and increased scattering.[65,66,67]. When the OF cable experiences high-stress concentration it can experience localized deformation leading to microstructural changes and increased light scattering within that area [68]. Recent studies discuss surface, shallow and deep installation of OF ground motion sensors. The way to monitor changes in a surface is by installing optical fibre cables on the surface [64,69] and sometimes using anchors to hold the fibre as in Fig. 7(a). These cables can detect any changes or deformations happening along the surface, making it an effective method to keep track of its condition.

Sensors buried in the soil, but not deep also been installed to gather data on the ground conditions. However this shallow installation is quite difficult in the natural environment, yet very easy in manmade structures like roads, embankments and dams when the sensors are laid during the construction stages [72]. The shallow installations are done at a maximum of 60 cm below the ground [11] yet can go deeper to the foundation of a construction. For shallow installation, either single fibres or a network of fibres are used. In composites and geosynthetics, optical fibre sensors are embedded to make the network as shown in Fig. 7(b). Geosynthetics are materials used with soil or rock, including geotextile, geogrid, and geocell which are used more than 1.4 billion square meters in one year [73]. This technology involves integrating optical fibres into geotextile materials to enable real-time collection of strain data and analysis in geotechnical and environmental applications [73,74]. Further research has explored the installation of OF sensors at greater depths, allowing for improved performance in deeper conditions. Laying the fibres horizontally in deeper levels is unattainable. For effective monitoring of ground motion caused by soil movement in deeper levels, a vertical installation of sensors is the most optimal solution. Depending on the length and the data resolution the length of the deep sensors can be decided.

Laying fibres in the ground conditions needs exceptional conditions (firm attachment between soil and the fibre, strain transfer ability) to transmit the strain without or with minimal loss. Recently, the industry has been manufacturing several types of buffered cables with

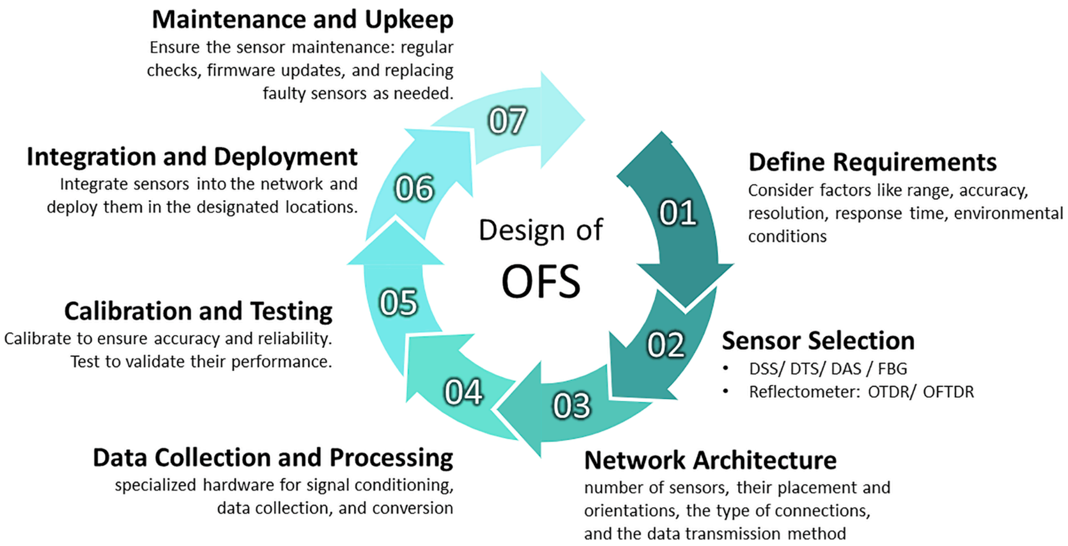

Fig. 6. OFS design procedure.

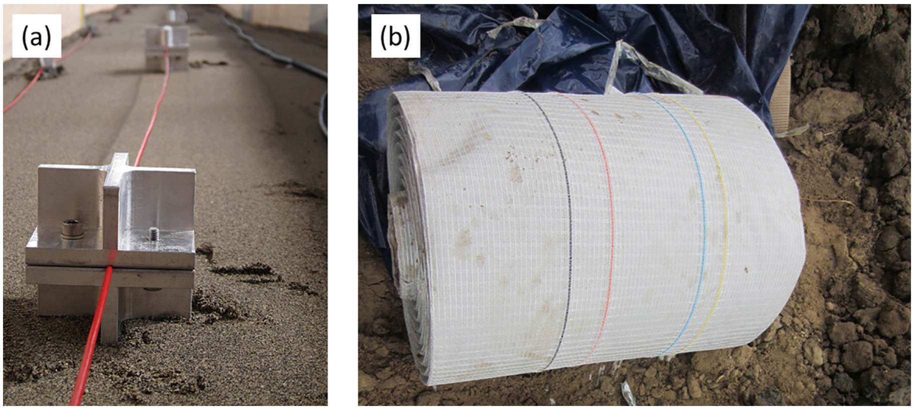

Fig. 7. Surface installation of optical fibre sensors (a) Surface installation of the fibres [70] (b) Optical fibres embedded in geotextile for shallow installation [71].

interlocking layers which can include steel armouring and polymer coatings (V3,V4, V9-type strain sensing cables) as shown in Fig. 8 [50,75]. The interlocking multilayer buffer guarantees that the strain is always transferred to the sensitive glass core. Customisation of the outer protection layers based on the type of cable enables the adjusting of the sensor cable selection to suit different monitoring object [75].

The protective layers of the cable affected both its strain sensitivity and its elastoplastic behaviour. As to A. Piccolo et al. the strain sensitivity of a V9 type strain sensing cable varied by up to 12 % when comparing the bare fibre to the complete cable with protective layers. The cable was found to be more plasticised than the fibre, likely because of the presence of the steel tube, which is more ductile than glass [76,77]. When multiple layers of protective coating materials are used, the strain on the structure is not fully transferred to the fibre core. This is because some of the strain is absorbed by the protective coating and bonding materials, leading to a loss in strain transfer [36].

3.2. *Design of sensors for temperature sensing*

The temperature changes affects the scattering properties of light in optical fibres in various mechanisms, as mentioned in Table 5. Brillouin Scattering and Raman Scattering are used in most sensing applications.

Deciding the distributed temperature sensor cable depends on the temperature range, the type of coating, and the number of fibres. Same as strain sensing cables either multimode fibre (MMF), single-mode fibres (SMF), and photonic crystal fibres (PCF) can sense temperature along the cables. Each fibre type has a different temperature sensing range, which depends on the sensing mechanism used. MMF has a

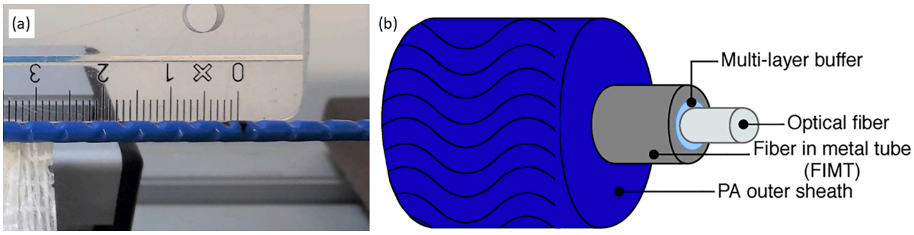

Fig. 8. V9-type strain detection cable (a) V9 cable used to test the strain sensitivity [76](b) Schematic of the V9 cable [77].

Table 5
Effects of temperature changes on optical fibres.

Phenomenon	Effect	Impact on Optical Fiber
Thermal Expansion and Contraction	Change of microstructure	Affect the scattering properties, and propagation characteristics of light [78]
Changes in Refractive Index (silica-based fibres,)	Refractive index reduces as temperature increases due to the thermo-optic effect	Change of polarity of light [68]
Thermal Stress	Variations in refractive index due to stress	Induces birefringence in the fibre [79]
Brillouin Scattering	Varies the speed of the sound signal in the fibre	Frequency shift of Brillouin scattered light is directly proportional to temperature [80]
Raman Scattering	Shifts in the Raman spectrum	Induces changes in the scattering properties of the fibre [81]

temperature sensing range between −40 °C and 300 °C, while SMF has a temperature sensing range between −200 °C and 1000 °C. PCF is a new type of optical fibre with a temperature sensing range of −50 °C to 1000 °C [82,83].

To ensure optimal performance, it's important to use sensing fibres with the appropriate coating for the temperature range they will be operating in and must transfer the heat properly. For standard temperatures, acrylate coating is recommended, while polyimide coating is more suitable for higher temperature ranges or cryogenic environments [84].

Distributed Temperature Sensing (DTS) units provide temperature data that is not processed. This data is derived from default assumptions such as loss of connection and differences in attenuation of external fibres. Due to spatial and temporal changes, this data can cause failures in environmental detection applications. Thereby the design-specified calibrations are expected for DTS for proper operation.

The gas and oil industry uses DTS effectively in monitoring their pipelines and leaks along those pipes as shown in Fig. 9. Hence the temperature of gas, oil and LNG are significantly lower any drop of temperature detected by the OFS along the pipe indicates a leakage of those products. The distributed temperature sensor detects underwater temperature changes with high sensitivity, even subtle ones caused by fluid release [37,85]. The same theory can be advanced to monitor leakages in structures like dams, seasonal changes and melting of ice or snow.

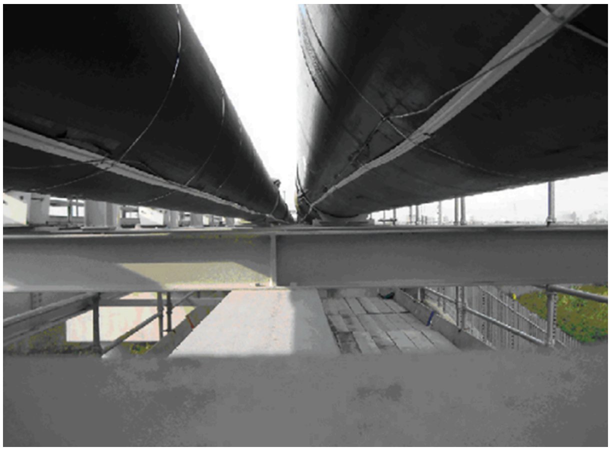

Fig. 9. Fibre optic monitoring cable on the LNG pipelines [85].

3.3. *Design of sensors for ground-vibration sensing*

A distributed optical fibre vibration sensor enables the reading of vibration data along the cable and so any external vibration also can be located accurately. In an application of external vibration, the light properties are modulated thus the vibration is identified. These light properties include phase, polarization, intensity and frequency [86]. As García, Y.R. et al. classify three types of sensor architectures have been identified: intensity-based sensors, FBG sensors and Fabry-Pérot interferometer sensors [87]. Fig. 10 indicates 2 sensor designs developed for vibration sensing.

As depicted in Fig. 10 a, the fibre-optic sensor is designed in the form of an air-backed mandrel structure. An elastic–plastic tube encloses the fibre, which is suspended by a metal wire at the centre of a polyethene (PE) casing. When exposed to a sound field, the pressure alters the diameter of the mandrel. The relationship between radial strain and pressure is determined by a set of equations, which are used to calculate the radial pressure the fibres receive [88]. A cantilever-based FBG acceleration sensor is used to measure vibration signals, as shown in Fig. 10 b. At the end of the cantilever, a mass is installed, and two FBGs are attached to the surface of the cantilever. The two Bragg gratings are situated on the upper and lower surfaces of the equal-strength beam and are in series in the shell. One of the gratings can compensate for the other's wavelength measurement, ensuring accurate results [89].

These sensors monitor local vibrations caused by vehicle and machine operations. Due to the reason that these sensors do not cover a vast area which is very advantageous in disaster monitoring a sensor network will be more effective. Such elongated and extended sensor networks will have the capability of monitoring ground vibration: may it from earthquakes or mass movement over a large span and in a range of frequencies. Such advanced sensor architectures are discussed in section 4.

3.4. *Design of sensors for pore water pressure sensing*

Even though pore water is not a hazard the existence of the natural water table is a significant factor that can lead to geohazards like landslides, debris flow and subsidence [90]. The increment of the pore water pressure causes a decrease in the effective stress and shear strength in the soil which leads to a lubrification of the sliding surfaces in the case of landslide [90,91]. Real-time pore pressure monitoring is critical for disaster forecasting as well as during construction, drilling and mining. In the context of optical fibre sensing, the intrinsic optical fibres have low sensitivity to hydrostatic pressure with around about $-2.2 \times 10-6$/MPa for uncoated glass fibres [8] and $-2.05 \times 10-6$/MPa for FBG [92,93]. In increasing the pressure sensitivity different options have been tried in recent experiments. In those experiments, the pressure has been transferred to a longitudinal strain component [94].

Aime et al. in their experiment brought up a sensor with a circular diaphragm membrane an FBG surface mounted on it, that deflects in the presence of pressure as in Fig. 11a. The strain induced on it later calibrated in to pressure values enables the pressure sensing. As the paper concludes the OF obtained data for the pressure tallies with the applied pressure values [93].

Meanwhile Qin et al. presented a three-layered diaphragm with fibres embedded in it to measure the water pressure. The sensor was designed with three layers to measure earth pressure, water pressure, and effective stress [95]. Another test has been conducted to identify the leaks in pipes with the mean of pressure difference. In that setup, a flexible PVC was used with of mounted inside it. When the pressure deviates outside the tube the curvature of the pipe gets affected thus the strain of the fibre [96]. A new optical fibre sensor has been designed to measure hydrostatic pressure and temperature in soil for riverbank monitoring purposes. The sensor compromises a dual-chamber system. A polymer cylinder in one chamber converts pressure into strain on the embedded fibre when an empty chamber simultaneously measures

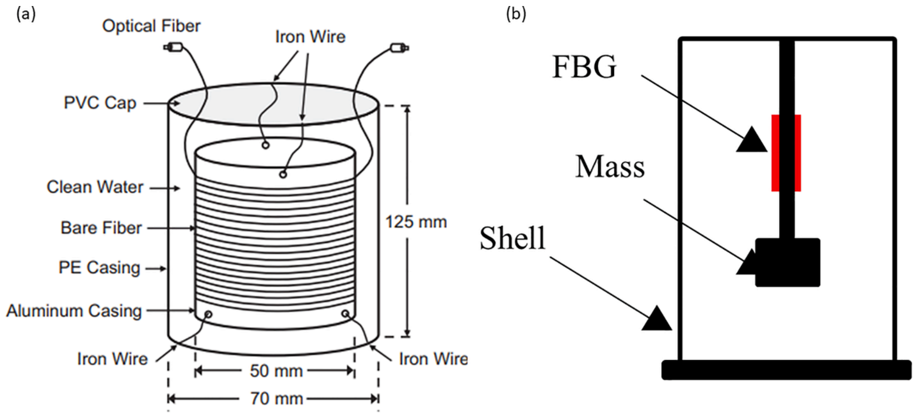

Fig. 10. (a) Interferometer-based vibration sensor architecture [88] (b) FBG-based vibration sensor architecture [89].

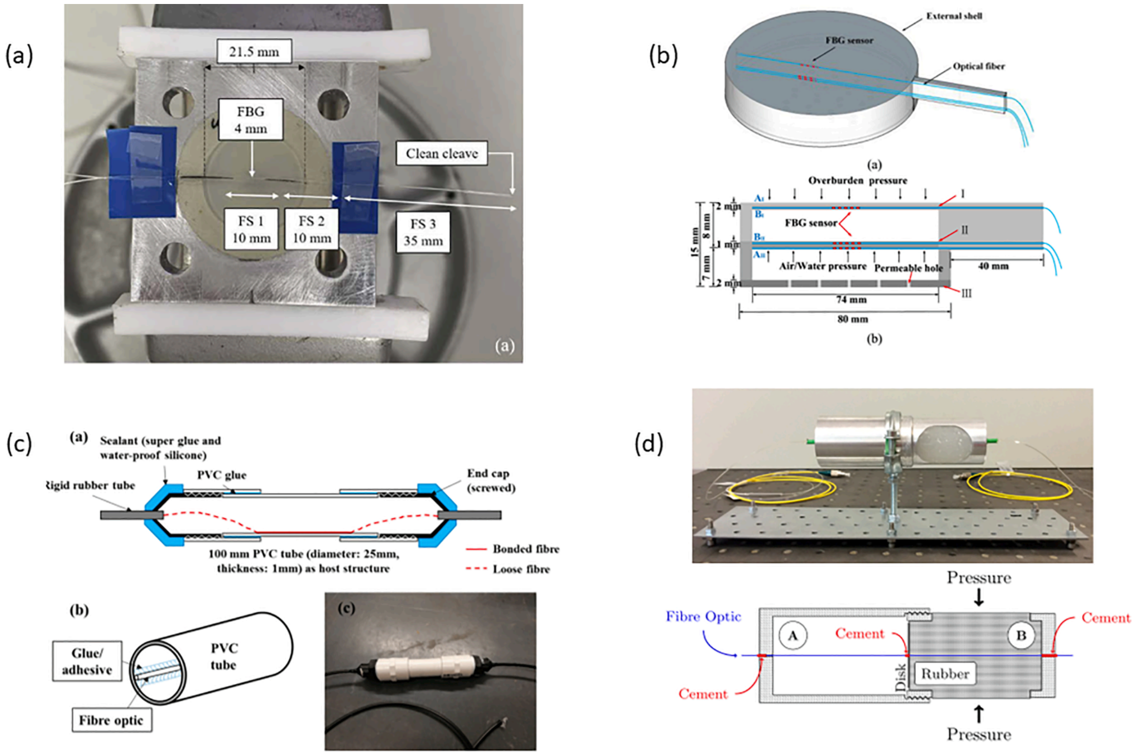

Fig. 11. OFS-based pressure sensors (a) OF cable mounted on glass fibre reinforced polymer membrane [93] (b) Three layered diaphragm with OF in the middle layer [95] (c) OF mounted inside of a flexible PVC tube [96] (d) Silicone rubber membrane with OF cable mounted on it [92].

temperature. A working prototype was built and tested to validate the sensor's performance as in the Fig. 11 d [92].

However, those pressure sensors need to be modified and enhanced properties to be implemented in ground conditions. The diaphragm material and its properties must withstand the composition of the soil and a considerable range of pressure.

4. Optical fibre-based geohazard monitoring

Both optical fibre-based sensors and conventional sensors have their advantages and limitations in monitoring geohazards. The choice between them depends on factors such as the desired spatial coverage, sensitivity, environmental conditions, and budget constraints. Table 6 gives an insight into the pros of choosing an OF-based sensor in subterranean condition monitoring over a conventional sensor designed for the same purpose.

4.1. Landslide monitoring

Landslides are one of the most common natural disasters in the world, causing phenomenal damage to people and property. There may be numerous deformable landslides around the world, particularly in water-prone locations. A landslide is reluctant to occur when the critical limit of deformation is exceeded. The displacement rate of the landslide can change considerably when the landslide switches from stable creep to accelerated deformation [12]. The conventional methods of slope monitoring include the use of inclinometers, extensometers, geodetic photogrammetry methods and tiltmeters. In addition to that, once the FBGs are mounted along slope reinforcements such as geosynthetics [2,3], soil nails [99] and retaining walls, the respective axial force, distribution, shear force and bending moment can be obtained [30]. With these techniques, both surface and sub-surface deformation have been investigated. When monitoring landslides, it is important to consider two main factors: the location of the potential landslide and the

Table 6
Comparison of OF-based sensors and alternative sensors in monitoring landslides, earthquakes and thermal conditions.

Geological condition monitoring sensors			Evaluated parameters		
			Range	Sensitivity	Limits
Landslide monitoring sensors	OF-based sensors	Optical inclinometers	Several kilometres	accuracy of ± 10 microstrain (με)[97]	Mechanical Fragility, interference or crosstalk between sensors (strain affected by the temperature) [98]
	Alternative sensors	MEMS (Micro-Electro-Mechanical Systems) Inclinometers and Mechanical Inclinometers	Limited by the length of the borehole or the structure being monitored	10 μm over a range of 100 mm [99]	Affected by electromagnetic interference [98]
Thermal condition monitoring sensors	OF- based thermal condition monitoring sensors	sapphire FBG based sensors	up to 2000 °C [100]	–	High temperatures can affect Bragg gratings' stability.[101]
		DTS based sensors	up to 800 °C [1,16]	0.01 °C [1,16]	Mechanical stresses can affect the temperature reading
		FBG based sensors	below 1000 °C [100]	–	
	Alternative thermal condition monitoring sensors	Thermocouple	−200 – 1250 °C (based in the type)[102]	7.4 (±0.3) μVK^{-1} [103] varies by type; E has the highest, followed by J, K, and T, while R and S have lower sensitivity [104]	1. Prone to corrosion 2. Limited Accuracy: generally limited to accuracies of about 1 °C
		Resistance Temperature Detectors (RTDs)	−200° to 850 °C [105]	–	1. Expensive 2. Sensitive to mechanical stress
		Thermistor	−55° to + 150 °C [105]	Depend on the material	Drift and de-calibration
		Bimetallic Sensors	−70° to + 600 °C	Depends on the metals used and their coefficients of thermal expansion [106,107]	1. Slow response time 2. Less precision [107]
		Infrared Sensors	Up to 120 °C [108]	Depends on the spectral range they can detect, (typically from 780 nm to 50 μm)	Affected by environmental conditions like fog, dust, and rain
Earthquake monitoring sensors	OF–based earthquake monitoring systems	DAS systems	High sensitivity depending on the architecture	Tested up to 535 km [8]	Limitations in detecting very low-frequency seismic waves [109,110]
	Alternative earthquake monitoring systems	seismometer	High sensitivity depending on the architecture	typically installed at specific locations	Electromagnetic interference, corrosion caused by exposure to seawater, and damage due to the high pressure found in deep-sea environments

estimated time until it collapses. Recent studies have employed both FBG and DOFS in monitoring landslide and slope stability.

4.1.1. *Landslide monitoring with FBG sensors*

In the laboratory stage, a group of researchers have been testing FBG to measure the tilt and displacement of geotechnical structures. The horizontally placed PVC tube consisted of FBGs mounted on opposite sides. One side of the tube being fixed the tube behaved as a cantilever. Linear variable displacement transducers (LVDTs) were used to identify the vertical displacement that was later compared to the displacement measured by the strain. As the LVDTs results fit strain-related displacement data with a limited error they find that FBG mounted on an inclinometer can be developed to detect soil movements [99]. To validate the outcomes of the FBG sensing, the FBG displacement readings have been compared by Zeng et al. with the displacement readings of a dial indicator. The two readings show a fair linear relationship with

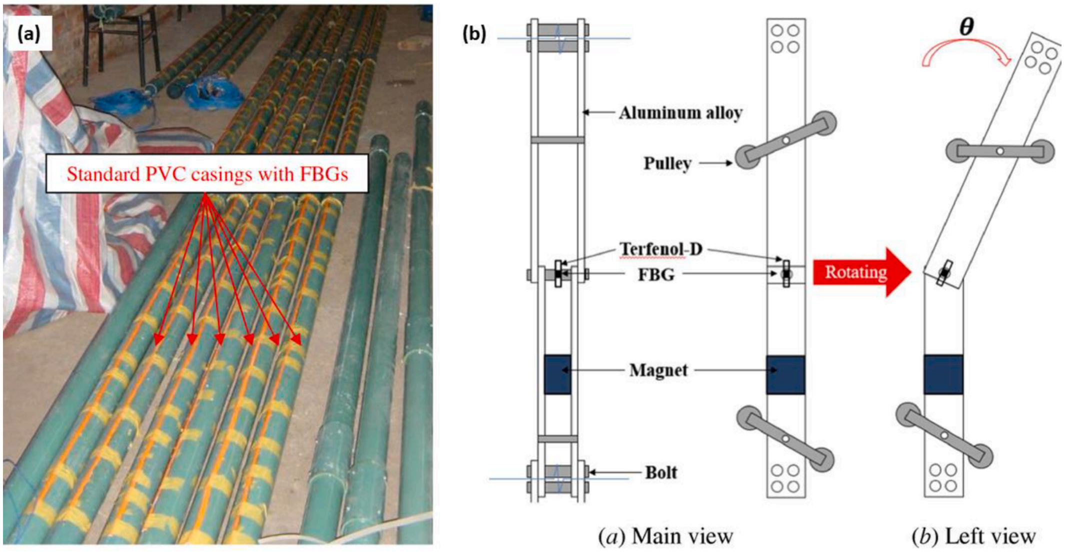

Fig. 12. (a) FBG sensors Mounted on inclinometers [99] (b) Schematic diagram of the modified inclinometer [5].

R^2 over 0.99. This could ensure the validity of FBG as a strain sensor [14]. Meanwhile, Pei et al. have tested a modified inclinometer which has hinge points at different segments of the inclinometer. The group used the linear relationship between the centre wavelength of FBG and the rotating angle of the inclinometer to measure the deflection and could achieve a sensitivity of $0.286^0/\mu\varepsilon$ with a linearity between the angle and the strain reaching 0.998 [5].

In real-time application the FBGs are mounted on rigid bodies be it PVC pipes, inclinometers and steel rods as illustrated in Fig. 12(a) and (b) and they are placed vertically in the monitored area. So, it is expected to transfer the motion of the ground to that certain rigid body. The strain induced in the FBG as a result of the deformation of that body is considered the measuring parameter in landslide monitoring.

As H. Peng et al. prove through their experiment the displacement made by landslides can be measured using an optical fibre-mounted inclinometer. The displacement of the measured point during a slide can be expressed in terms of the number of fibre gratings from the bottom of the sensor array, slope (magnitude of the slope angle), strain of a grating point and the initial distance between each grating. However, that calculation is based on that sensor arrangement and cannot be reused in a different arrangement [111].

Extending the capabilities of slope monitoring Hu et al extended their experiment to calculate the horizontal displacement via vertical strain having two runs of fibres along the inclinometer. They also integrated the sensor network to soil nails to investigate the axial strain. Their sensor architecture and the installation is depicted in Fig. 13.

In the same experiment, a relationship was developed to obtain the curvature of the casing OF mounted, the gradient of the deformation, and the horizontal displacement that occurred due to the sliding condition. This relationship was obtained by mounting two turns of FBG arrays on opposite sides of the casing. As to the calculation the output parameters are obtained through the difference of the strain of FBGs at opposite sides of the casing. This calculation of the displacement is valid when the OF cable is attached in the direction of the slide, much more suitable for a slope [111].

A recent study tested two soft sensors (FBG mounted on plastic bars) and two hard sensors (FBG mounted on reinforced steel rods) against artificially induced landslides. Each sensor with two sensors 50 cm apart from each other was placed vertically in a 6.93 m high hillock of stones and, sands. The results of the experiment show the possibility of detecting landslides near the implemented area. Through the test, he emphasizes that the optimization of the sensor location affects the measurement sensitivity [56].

The Wencheng landslide in China has been monitored using FBG-mounted inclinometers which were placed parallel to the main sliding direction. Upon identification of signs of fractures at the surface level inclinometers with several FBGs mounted on them were placed in the slope at three different vertical sections as depicted in the Fig. 14(a) [6].

As implied through Fig. 14 (c) the horizontal displacement has been developing from the bottom to the surface, which indicates a moving landslide in the monitoring area.

In a landslide, the monitoring, and the identification of the sliding plane are vital since to understanding the magnitude and the possible damage. In the Toudu landslide, Chongquing being the tested area, a group of researchers have determined the sliding plane while deep displacements also have been identified. They have developed the internal deformation curve for the fibre when the sensor array is placed vertically in the slope [111].

Previous studies suggest that inclinometer-based sensors are the most suitable to identify the sliding direction and Table 7 summerises some instances where thse inclinometrs have been used in real monitring environments. However, when geogrids are used as reinforcement their purpose can be extended to condition monitoring too. As Sun et al. indicates in their study, geogrids are installed to reinforce the slope and the geogrid is embedded with FBG to monitor the slope condition as in Fig. 15. As the calculated strain and the measured strain tally during the slope failure, they suggest that FBGs can be used for stability evaluation of geogrid reinforced slopes [114].

4.1.2. *Landslide monitoring with DOFS*

When it comes to DOFS it reduces the discrete nature of the reading than FBGs and thus a dense collection of readings can be obtained. This is quite advantageous due to the vast scope of a landslide.

The large physical model with a slope of 32° was developed by Schenato et al. to identify artificially triggered and rainfall-induced shallow landslides when the optical fibre cables are laid parallel to the ground surface. As Fig. 16 indicated strain field variation of each cable of four cables has been plotted against the length and it clearly indicates the deviation of strain from its linearity as the slide develops [11].

In real situations, the landslides are monitored at surface and subsurface levels. In their experiment, Shi et al. used a combination of surface and subsurface level monitoring with the embedded installation of DOFS to anchors and inclinometers which were buried later to monitor slope stability. Due to the reason that the anchors were capable of bearing the deformation of the slope during the monitored period no significant damage was identified through the monitoring system, though an increment of strain was identified at the top of the anchors [115]. In the context of surface-level monitoring of slope conditions, Takisaka landslide monitoring consisted of optical fibres laid above the surface level with stakes connected to the soil such that it works as same as the extensometer as depicted in Fig. 17. Through this method, a direct reading for the strain can be obtained without calibration but it is expected that the topmost stake to be an anchor and skip the sliding surface [116]. With the over the surface level installation of fibres does not allow the identification of the sliding hence the degree of the damage is unpredictable.

Furthermore, surface level monitoring with DOFS the slopes have been monitored at the surface level too. The most recent work that uses DOFS is the monitoring of the Majiagou landslide based on BOTDR. Concerning Fig. 18, Sun et al. develop an expression to the lateral

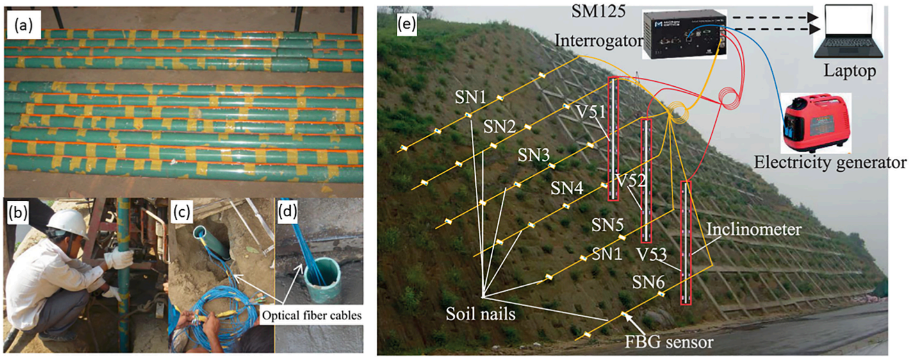

Fig. 13. (a)FBGs mounted on inclinometer (b)(c) Installation of sensors (d) Installed sensors (e)Installed sensor network;(SN-Soil Nail, V-inclinometer) [112].

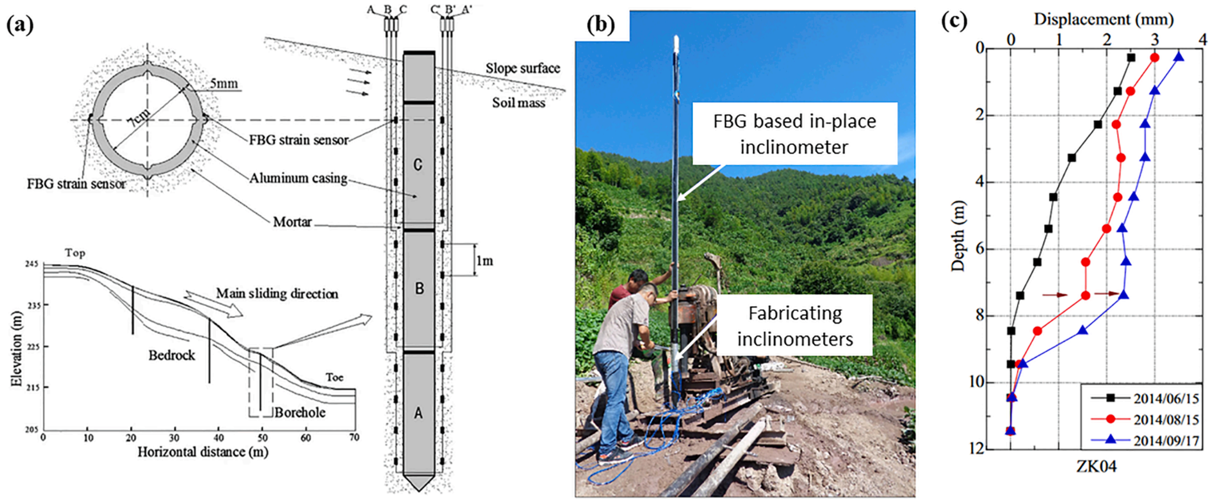

Fig. 14. Schematic for the sensor and the installation environment (b) Placement of FBG in the inclinometer and inclinometer placement in the slope (c) Displacement profiles measured by FBGs at 1 of 3 boreholes at same vertical section [6].

Table 7
FBG mounted on inclinometer to monitor ground stability.

Reference	Parameter	Wavelength	Interrogating technique	Location	Cumulative displacement (mm)	Stability status
[56]	Strain	1525 nm and 1520 nm	SMF-28C and SM125 interrogator	–	–	–
[6]	Strain	1550 nm	–	Wencheng Landslide	3.5	Stable
[111]	Strain	1531 nm, 1543 nm, and 1555 nm	–	–	–	–
[12]	Strain and temperature	1528 nm ~ 1568 nm	UWFBG- Ultra-weak Fibre Bragg Grating sensing	Majiagou landslide – China	–	–
[112]	Strain and temperature	1510 nm –1590 nm	SM 125 interrogator	expressway slope along the highway from Panzhihua to Tianfang in Sichuan Province	5.06	–
[113]	Strain	–	–	Diao shui yan slope	70	Stable
[13]	Strain	–	–	Xinpu landslide	400	Stable
[7]	Strain	–	Optical fibre grating demodulator	Chongqing city-China	–	Stable

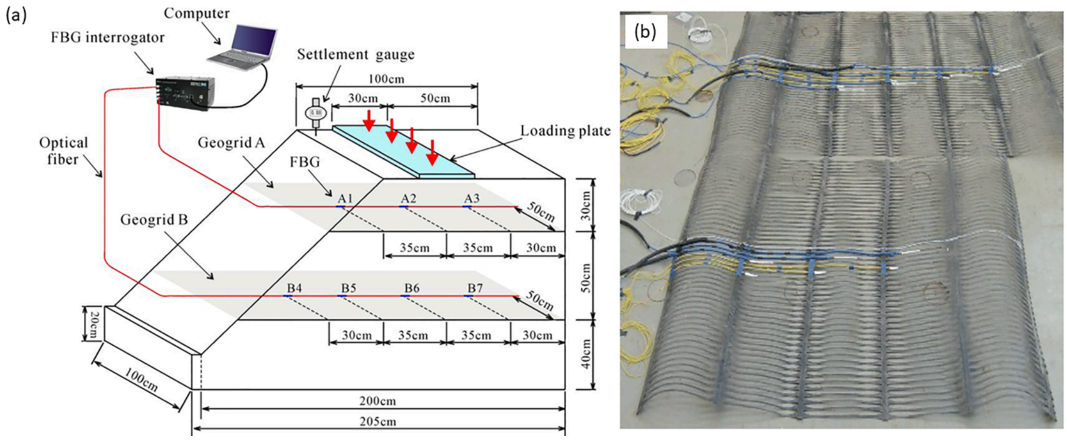

Fig. 15. Geogrid-based condition monitoring for slope stability (a) Arrangement of sensors in the sand slope laboratory setup (b) Sensor installed geogrid [114].

displacement of the inclinometer using the classic Eulers beam theory [117].

In the installation when the upper surface and lower surface strain values are obtained through the OF cable bending displacement and rotation angle at the respective location is achievable through calculation [117]. During the same laboratory tests, it was discovered that the measurement error is primarily determined by the inclinometer length, the precision of the BOTDR instrument, and the diameter of the tube. In the field experiment, six inclinometers were placed in boreholes to determine the internal behaviour of the slope [117].

The subsurface landslide monitoring with DOFS mounted on an inclinometer is the most frequent method and Table 8 presents monitoring scenarios. Other than that Wang et al. brings out a method based on BOTDR for subsurface level monitoring with either fibres planted directly on the soil or bonded to short-needled fabric geotextile and glass fibre geogrid as in Fig. 19 [57].

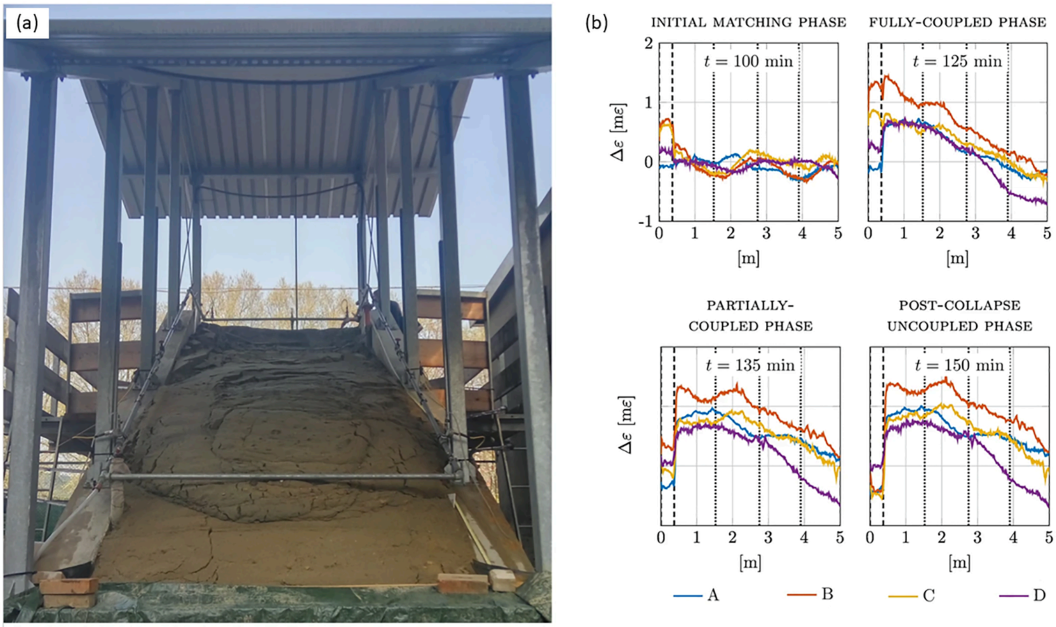

Fig. 16. Stability of an artificial landslide tested with DOFS. (a)Physical model for the artificial landslide (b)Strain field variation of four different cables named A, B, C, and D corresponding to different stages of the slope stability change [11].

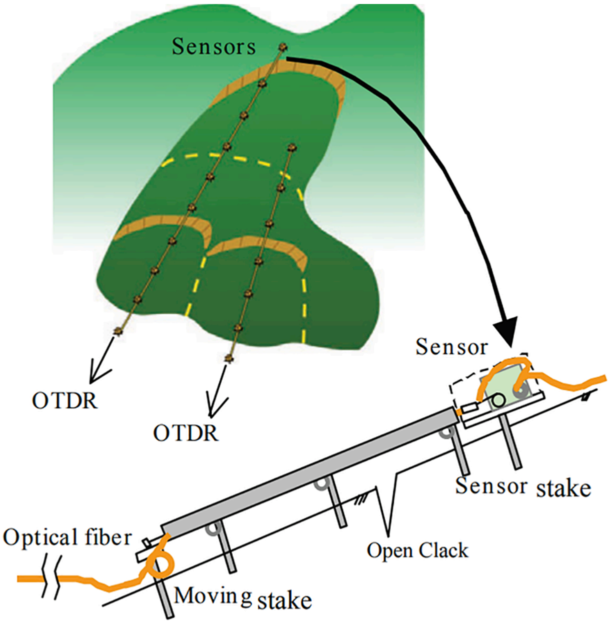

Fig. 17. Optical fibre installation orientation in Takisaka landslide monitoring [91].

FBGs are characterized such that their wavelength is affected by both temperature and strain. The temperature compensation is a critical task in geological monitoring since the underground temperature could change with the depth [7,14,111]. While monitoring the Toudu landslide, Chongquing the researchers have used separate FBG sensors to compensate for the effect of the temperature in strain readings. While strain sensors are attached to the PVC pipe (which is used as the conversion medium of ground motion) the sensor for temperature is placed inside the PVC unattached as in Fig. 20; thus, no deformation is expected [111]. However, while monitoring Majiagou landslide in China the researchers found that the geothermal effect on the strain readings taken through UWFBG is very small when the depth is more than 3 m [12].

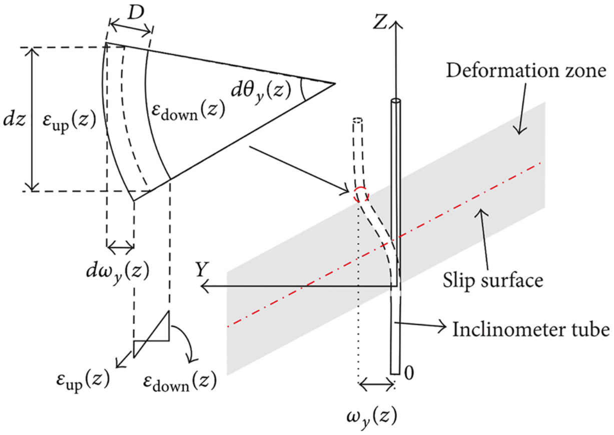

Fig. 18. Schematic diagram for the deformed BOTDR-based inclinometer with fibre mounted on it [117].

Landslide monitoring with optical fibre sensing is focused on sensor placement optimization which can be elaborated through the optimal depth of sensor installation, orientation and the distribution of the fibre within the slope. Furthermore, integrating the technology with weather stations and other types of geotechnical sensors can enhance the predictability and the preciseness of landslides.

Overall, landslide monitoring with optical fibre sensing is focused on enhancing the understanding, detection, and prediction of landslides with the use of distributed sensing capabilities of optical fibres. It is directed to more reliable and efficient monitoring systems that can mitigate the risks associated with landslides and enhance the safety of slope-prone areas.

4.2. *Earthquake monitoring*

Earthquakes are a result of natural geological change but are destructive; the damage can extend immensely. The movement of the tectonic plates or the earth’s crust is the most proximate reason and thus it releases a sudden energy followed by the generation of seismic waves

Table 8
DOFS mounted on inclinometer to monitor ground stability.

reference	Parameter	Span	Spatial resolution	Interrogating technique	Location	Stability status
[11]	Strain		10 mm	Optical Frequency Domain Reflectometer OBR 4600 from Luna Innovation	Laboratory setup	Collapsed
[117]	Strain			N8511 BOTDR produced by ADVANTEST Co. Ltd. of Japan	Majiagou landslide	stable
[118]	Strain			Using Brillouin scattering	Lab scale	
[119]	Strain	60 km	1 m 1 m	BOTDA interrogator-Omnisens DITEST	South western Peru Swiss mountain resort of St. Moritz	Stable

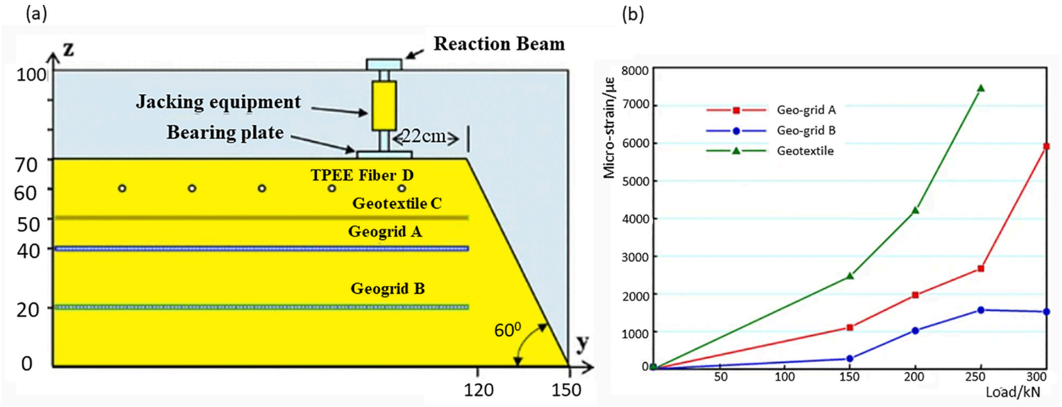

Fig. 19. Installation of geo textile and geo grids in ground motion monitoring (a) layout of the geogrid and geotextile sensors in the slope model (b) propagating strain in each sensor network [57].

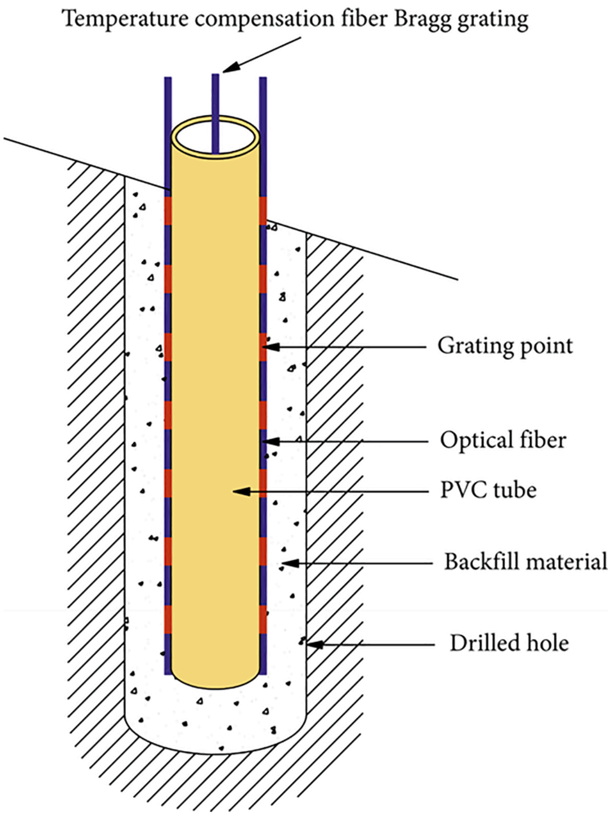

Fig. 20. Schematic diagram of the sensor array used to monitor the landslides with temperature compensation fibre [111].

[109]. Even though the mechanism of an earthquake is identified it is quite hard to predict an earthquake with the correct time and location. In such a background, an early warning system for earthquakes can provide valuable seconds to minutes of warning to people in affected regions. An earthquake releases two waves whereas the non-destructive P wave travels faster than the followed- destructive S wave that has a speed of 60 % of the P wave. If P waves are detected, an alert can be issued within seconds to tens of seconds before the more intense shaking occurs, horizontal fibres are more sensitive to S waves than P waves [120]. This provides individuals and systems with ample time to take protective measures. The detection of the P wave makes it possible to identify the upcoming earthquake yet it is hard with the low frequency which lies between 1 and 3 Hz [109,110].

Out of the three most used technologies DOF, FBG and DAS (distributed acoustic sensing), the seismic recording has been using DAS technology. DAS uses optical fibre for acoustic sensing, whereas the backscattering light pattern in the fibre is used to identify the acoustic disturbance along the fibre. But Optical fibres are sensitive to seismic waves as well as environmental acoustics, and mechanical disturbances [121]. DAS systems offer several advantages such as high resolution, distributed reading capability, and durability, despite being typically less sensitive than available geophones by 1–2 orders of magnitude [49].

DAS uses Rayleigh scattering of optical fibres to identify seismic activities. As Daley et al. state, every meter up to 10 km of the fibre can be interrogated by sending light pulses every 100 microseconds and continuously processing the returning optical signal at 10 kHz. Through this, any vibroacoustic disturbance along an optical fibre can be detected through changes in reflective characteristics, allowing for near-accurate monitoring of local changes in space and time [49,122,123]. When a seismic event, such as ground motion or vibrations, occurs near the optical fibre, it generates acoustic waves that interact with the fibre. The seismic wave propagates through the medium, causing elastic deformation and producing a time-dependent strain rate signal. This signal is measured at intervals along the fibre to identify seismic waves. As the strain waves propagate along the fibre, they modulate the phase of the backscattered light in a predictable manner [124].

DAS is better than transmission analysis because it only needs access to one end of the seafloor cable and provides a dense spatial sampling of the wavefield. This allows for using array techniques to identify and track seismo-acoustic signal sources [123,125,126]. Calibration is essential for accurate magnitude estimation using DAS. This process includes a comparison between DAS-derived measurements and ground-truth data from nearby seismometers to establish a relationship between DAS data and traditional seismic measurements [120].

Icequakes are also happening in the polar regions. DAS is not as good as geophones for detecting icequakes, but it is good for analysing their frequency and physics. However, while monitoring the Rutford Ice Stream, Antarctica for icequakes the researchers were not able to identify the P wave but the S wave. It is stated that the fibre can only identify the horizontal strain component, thus the P wave went unidentified as shown in Fig. 21 [124].

There have been some instances where seismic activities have been affecting the volcanic activities too. In that scenario identification of seismic activities around the volcanic active area enables the forecasting of volcanic activity. For this, both DAS [127] and FBG [128]have been used. It has been found that the magma masses migration-related events can be detected in the frequency range of 0.001–0.01 Hz and yet this is very hard to identify with traditional detectors [128]. Moreover, DAS has been successfully operated on the sea floor while the monitoring has been extended to the land. With that seismic related to ocean dynamics have been monitored [129,130].

Usually in monitoring the seismic actions, the fibres are laid on and in sublayers of the ground. Anyway, depending on the factor that the optical fibres do not have broadband sensitivity (the ability to detect particle motion in all directions) DAS system shows a low sensitivity in detecting orthogonally oriented waves. Thus the above-discussed orientations of the fibres limit the possibility of detecting a seismic action [120,124,131]. P-waves that travel nearly vertically during near-surface seismic surveys can be poorly detected with horizontally deployed straight fibres [131]. Upon the recent development in DAS already laid telecommunication cables are proposed to be re-purposed against seismic activity monitoring. That provides a dense sensor network all around the world without new installation effort and cost [49].

Depending on the factors: the distance from the epicentre and the speed of seismic waves the effectiveness of the early warning system is decided. Early warning systems work best for earthquakes with moderate to large magnitudes and when the distances from the epicentre to populated areas are more than 10 miles from the epicentre [132]. However laying DAS in earthquake and volcano active areas is challenging as installation of fibres need the support of a structure [127].

When it comes to monitoring seismic activity, DAS has been found to generate more random noise from the interrogating unit compared to other sources. This can pose a challenge in detecting weaker signals, particularly in microseismical applications [133].

The limited sensing range of DAS below 100 km seems to be too short for continuous monitoring of large areas [59]. To overcome that frequency metrology technique (a laser signal is injected to the fibre and the output is analysed) [8] and the light polarization changes analysis of ocean floor telecommunication channels [124] are suggested in the most recent experiments. Marra et al. combined injected and returned optical signals, measuring their phase difference to detect seismically induced, phase changes caused by local and remote earthquakes. So identified earthquake is presented in Fig. 22 with optical phase change and the displacement of the same earthquake simultaneously identified with optical fibre and the seismometer [8].

DAS systems offer several advantages such as high resolution, distributed reading capability, and durability, despite being typically less sensitive than available geophones by 1–2 orders of magnitude [49]. Table 9 presents applications of optical fibre based seismic activity monitoring.

4.3. Volcanic activities monitoring

The excessive underground heat can originate from various sources, including geothermal activity, solar radiation, and heat generated by natural processes such as radioactive decay. Geothermal monitoring is a valuable tool for predicting volcanic eruptions and assessing the potential of geothermal energy in geothermal areas. Optical fibre sensing is the optimal choice for operation in high temperatures and harsh environments [1,15,16]. Distributed temperature sensing is the technology basically used here. This technology is very helpful for measuring continuous temperature profiles in the subsurface to aid in geothermal exploration [134].

With the high resistivity of optical fibres, a sensor can be developed which can sense up to 800 °C. The temperature rating is close to the temperature of magma and exceeds the supercritical temperature of a

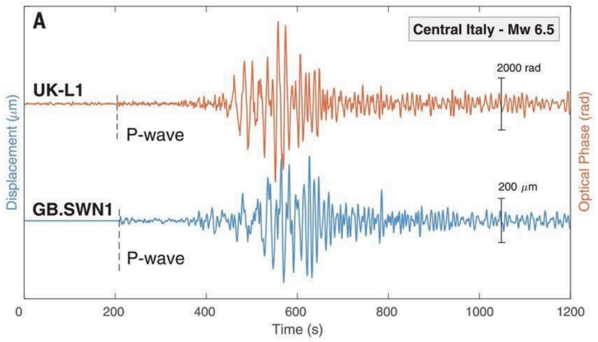

Fig. 22. Seismically induced optical phase changes detected on the optical fibre (UK-L1) link and the signal from a seismometer in Swindon (GB.SWN1) in the event of central Italy earthquake on 30 October 2016 [8].

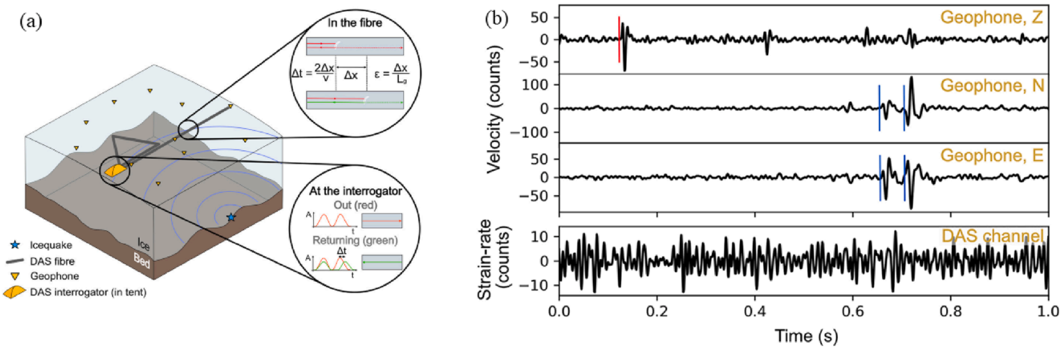

Fig. 21. (a) schematic diagram of the experiment to identify icequakes with optical fibres laid in surface level and geophones (b) icequake arriving at a geophone coincident with the fibre and a single Distributed Acoustic Sensing channel 950 m along the fibre [124].

Table 9
Application of optical fibre based seismic activity monitoring.

Ref	Technique	Expand	Specifications	Location	Results
[126]	DAS	41.5 km		Toulon, France	1. Detection of a M1.9 regional earthquake 2. Detection of Ocean surface gravity wave in the coastal environment.
[123]	DAS	50 km		Sarinku, northeastern Japan	1. Recorded small earthquakes with a magnitude of 1.8 2. Observed the arrivals of P- and S-waves of an earthquake with a magnitude of 3 observed a teleseismic event with an epicentral distance of approximately 2,300 km and a magnitude of 6.6
[124]	DAS	1 km		Rutford Ice Stream, Antarctica	1. Detected 449 events of 1321 icequake events 2. Detected 139 events of 1270 icequake events
[120]	DAS	1 km		dry lake in the Irpinia, Italy	Detected 3 earthquake related events with each having a magnitude 2.3,08 and 1.0 at distances of 19.6 km, 8.1 km and 6.6 kms
[127]	DAS	1.3 km	gauge length- 10 m spatial sampling- 2 m	Etna volcano, Italy	1. Quantified hidden subsurface structural features 2. Accurately detected and located volcanic events 3. Detected a reflective layer beneath the scoria layer and determined its direction.
[8]	Submarine optical fibre cables	79 km	Sampling rate 100 samples per second	Teddington (1400 km form the epicentre)	Detected an earthquake of magnitude of 6 in central Italy followed by 2 more events of magnitude of 5.9 and 6.5
		75 km		Southeast England	Detected teleseismic events with magnitudes of 5.9 to 7.9 with epicentres in New Zealand, Japan, and Mexico.
		535 km		Fibre laid between Turin and Medicina	Detected a magnitude 7.3 earthquake on the Iran-Iraq border
		96.4 km		Fibre laid between Malta and Sicily	Detected a magnitude 3.4 earthquake, with an epicenter 89 km away in the Malta Sea

volcanic substructure, which falls between 400 and 500 °C with temperature down as low as 0.01 °C [1,16].

R. Somma *et al.* deployed an optical fibre cable in a deep well (500 m) to monitor the temperature profile in the respective volcanic are and extracted the temperature profile as in the image Fig. 23 during the monitoring time. The results are presented after calibration and the results validate the successful implementation in aggressive environments [1].

Other than DTS FBG have shown their potential to be used in geothermal monitoring with their high-temperature tolerance and sensitivity to temperature variations. FBGs made in silica-based fibres can result in stable spectral responses at high temperatures below 1000 °C and Femtosecond laser inscribed sapphire FBGs (SFBG) can go up to 2000 °C [100]. Both DTS and FBG are located within geothermal wells or boreholes as presented in Table 10.

Table 10
Optical fibre based geothermal conditions monitoring.

Reference	Technique	Location	Results
[134]	DTS	UC Berkeley campus	Observed the seasonal changes in the ground temperature as a function of depth.
[17]	DTS	Upper Jurassic reservoir of the Bavarian Molasse Basin in Southern Germany	Achieved dynamic monitoring of the thermal distribution in a geothermal production well.
[1]	DTS	Naples, Campi Flegrei volcanic area	Continuously measured the temperature profile in a bore hole in the volcanic area.

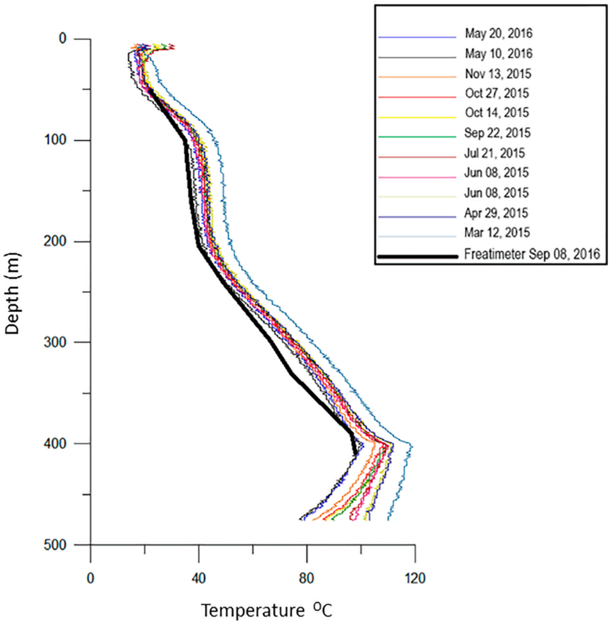

Fig. 23. Temperature variation at different depths along the monitoring time, in the borehole for monitoring volcanic activities in Naples [1].

According to recent studies in the soil and hydrological environment, three types of DTS systems have been tested. The first type is active-DTS which uses a heated fibre optic cable to monitor the thermal response during the temperature change. In another method referred as passive DTS collect temperature data along the cable without the aid of external heat. The third method is a combined active and passive DTS [135].

5. Challenges and future trends

As a novel and advanced approach distributed sensing has unique advantages in monitoring over multiple subterranean parameters may it be with a higher range and accuracy. Despite the advantages of OF-based sensing, several challenges may limit or prevent the application of this technology. The initial challenge of OF-based sensor design is the need for a comprehensive understanding of geological processes and the specific parameters to be monitored. An expert knowledge of OFS technology and geology is vital to deciding the sensor configurations. Identification of the measuring parameter and relating them to the potential hazards or a geological condition is a principal challenge too.

In the designing stage, it is quite challenging to develop a sensor which could withstand extreme temperatures, moisture, chemical aggressiveness and physical contacts and impacts. When integrating sensors into the geological environment, accuracy and reliability require careful consideration of material selection and mechanical design. In addition, Optimizing the network layout to maximize spatial resolution and coverage while minimizing cost and complexity is a complex task. Usually, these sensors are installed in remote and hazardous locations with limited access making the approach to the site difficult. Due to their fragility and small size, OF cables require extra attention and precautions during installation to prevent damage to the sensor. This precaution is well required to the data transmission line also as well as the sensing fibre [18]. Along with that achieving high spatial resolution over large areas can be challenging due to limitations in optical fibre cable length and installation methods, which can restrict the coverage and resolution of monitoring systems. There is a potential to connect a separate OF cable to an existing OF cable through splicing to extend it or to repair the sensor. However, it can cause losses at spliced locations causing a signal attenuation which affects the accuracy of the sensor. When using OF to monitor geological conditions, there is no defined calibration standard or procedure. That drives the designers to the development of standards and procedures for calibration depending on the specific ground condition. Due to the dynamic nature of the ground, mechanical stresses and high temperatures affecting the sensors, it may need regular calibration as the calibration may drift with time.

DFOS systems generate large volumes of data. Managing, storing, and analysing this data can be a logistical challenge, requiring appropriate infrastructure and dedicated software and hardware tools. Due to this big volume of data, much data is kept unexplored, and so important geoscience discoveries are not highlighted [130]. Proper data analysis and interpretation of these collected data require expertise in geotechnical engineering and sensor technology. Maintaining optical fibre networks and DOFS equipment in remote or inaccessible geological locations can be a challenging task. Regular inspection, maintenance, and hardly repair or replacement of sensors and optical fibres are required for continuous operation. To minimize downtime and ensure system performance, it's essential to develop system-specific maintenance procedures. Challenges related to OF-based sensing emerge in almost every stage from design to execution. The overall scenario of OF-based sensing challenges is presented in Fig. 24. For uninterrupted and reliable condition monitoring of subterranean conditions, these challenges should be addressed.

Optical fibre sensors generate vast amounts of data, which can be processed using machine learning and artificial intelligence techniques to improve detection, early warning systems, and data interpretation [2,136]. Another possibility is that the integration of DFOS, GIS, and database technology allows for the creation of monitoring networks at different levels, enhancing monitoring efficiency and reducing costs [137]. While geological data is combined with other systems developing multi-parameter monitoring systems to capture a broader range of geophysical and environmental data also can be achieved with DOFS.

6. Conclusion

Geohazard monitoring has advanced with the integration of optical fibre sensors. This approach is precise, scalable, and cost-effective. Various optical fibre sensor technologies, applications, and case studies have been reviewed, and they have shown great potential in advancing early detection and mitigation strategies for different geohazards. This paper emphasizes the importance of optical fibre-based f geohazard monitoring and how it can be improved. Despite their potential benefits, there are still challenges that need to be addressed to implement optical fibre sensor networks on a larger scale. Covering the fragility and the hydroxyl formation has to be done while compromising the sensitivity. Real-world scenarios were monitored using FBG-mounted inclinometers, demonstrating the ability to detect horizontal displacement profiles, indicating moving landslides. Various studies monitored displacement using FBGs, with reported cumulative displacements ranging from 3.5 mm to 400 mm in different locations. Researchers have implemented DOFS in both surface and subsurface monitoring. This includes combining surface and subsurface level monitoring with embedded DOFS to anchors and inclinometers, providing insights into strain increments and slope stability. Landslide monitoring with optical fibre sensing includes precise sensor placement (depth, and orientation), and distribution within slopes to enhance precision and predictability. In earthquake monitoring, P-wave detection warns of earthquakes yet P-wave detection is challenging due to low frequency below 3 Hz. DAS has been applied to monitor seismic activities related to earthquakes, icequakes in polar regions, and volcanic activities, depending on the fibre orientation. However, it is less sensitive than geophones but offers dense spatial sampling and durability. Recent researches suggest ground temperature monitoring with optical fibres both DTS and FBG with their temperatures ranging up to 1000 °C and up to 2000 °C in sapphire FBGs. These technologies enable continuous, reliable temperature profiling for geological exploration and environmental monitoring. As technology continues to advance, optical fibre sensing is expected to play a larger role in understanding and addressing geological risks and environmental changes which are not explored yet. This review highlights the importance of using optical fibre sensor technologies in geohazard monitoring strategies. Collaboration between researchers, engineers, and industry is crucial to drive progress, establish standards, and promote global adoption of these sensors.

CRediT authorship contribution statement

Kusumi Anjana: Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Madhubhashitha Herath:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Jayantha Epaarachchi:** Writing – review & editing, Visualization, Supervision, Investigation.

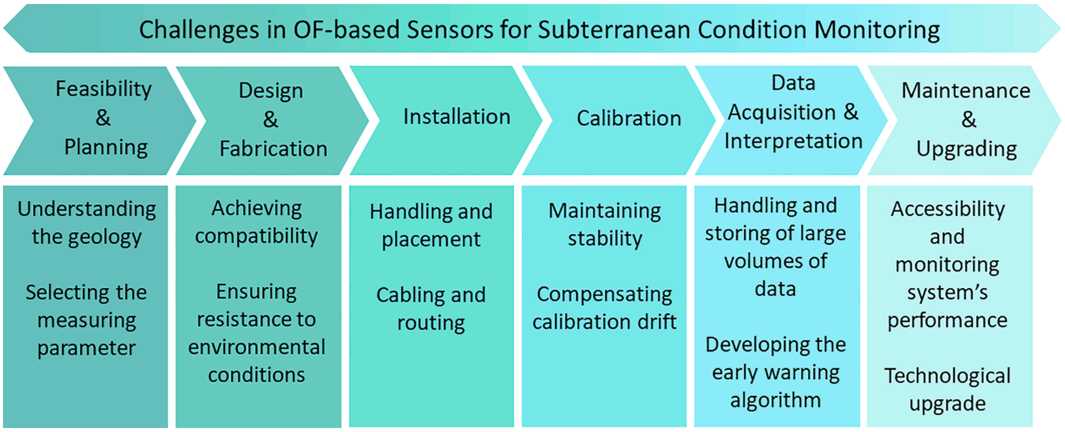

Fig. 24. Challenges in OF-based subterranean condition monitoring.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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