Exploring the Efficacy of Fiber Bragg Grating Sensors in Landslide Monitoring: Current Practices and Future Directions

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Abstract— ***The effectiveness of Fiber Bragg Grating (FBG) sensors in Landslide monitoring is analyzed in this review article, which also highlights some possible future avenues for these sensors. Advanced monitoring methods are required for early detection and risk mitigation since landslides pose serious dangers to human safety and infrastructure. FBG sensors have become important instruments in geotechnical monitoring because of their great sensitivity and capacity to sense displacement, temperature, and strain. The fundamentals of FBG technology are covered in the article, the paper also discusses the difficulties in deploying FBG sensors in various geological settings and highlights the need for more study to improve their performance and incorporation into early warning systems. This work attempts to give insights into the current practices of FBG sensor applications in landslide monitoring by synthesizing existing literature and case studies. It also outlines future research directions to increase the efficacy of FBG sensors in hazard prediction and management.***

Keywords—Fiber bragg grating sensors, Landslide Monitoring, Real-time condition monitoring, Optical Fiber Technology, Real-time Monitoring, Early Warning Systems, Data Acquisition Systems

I. INTRODUCTION

Natural disasters known as landslides are defined by the downhill movement of rock, soil, and debris on slopes. These events are frequently brought on by human activity, earthquakes, volcanic activity, or excessive rainfall. Significant risks to ecosystems, infrastructure, and public safety are posed by landslides. For early detection and risk mitigation, effective landslide monitoring is essential. This allows for prompt measures to avert disastrous outcomes. In order to evaluate changes in the geological environment, such as slope stability and landslide activity, physical measurements such as strain, temperature, displacement, and pore water pressure are essential. Since it is impossible to prevent unanticipated geological threats, effective monitoring of landslide-prone areas is crucial for early detection and risk mitigation. Safety and scientific research both depend on an understanding of these changes. Additionally, this reduces property damage after a crisis and results in cost-effective upkeep[1,2]. Traditional geological assessment systems include individual sensing components, a data collecting system, and a transmission system. Early alert systems for geological hazards use information to predict the magnitude and spread of potential events [2, 3]. Geological monitoring systems typically include discrete sensor devices, data gathering, transmission, and energy sources [4]. The sensing elements of these monitoring systems are geophones[8], inclinometers[5,6,7], and extensometers[2]. To monitor regional threats reliably and consistently, a network of sensors, rather than single-point sensors, is required[35,36]. Given the infinite nature of natural risks, this is imperative. Current landslide monitoring, detection, and early warning systems rely on wireless geophysical sensor networks, laser scanning, also known as LIDAR, Optical fiber technology, high-resolution satellite imaging, and radar satellite interferometry e.t.c. Additionally, Recent advancements in landslide monitoring integrate AI, ML, and IoT[37], enhancing prediction and response capabilities, thereby improving safety and reducing damage from landslides. In that optical fiber technology has emerged as a particularly advantageous choice for landslide monitoring due to its unique features. Furthermore, The most recent technological development is represented by FBG-based optical fiber sensors.

A. Optic Fiber Sensors

Flexible strands of glass or plastic called optical fibers can carry light signals over great distances with little loss. The fiber's core is encircled by a cladding layer with a lower refractive index, which permits light to flow through it via total internal reflection. Optical fibers are perfect for remote areas because they can swiftly and without electromagnetic interference transfer massive amounts of data. Specialized sensors that assess temperature, displacement, strain, and slope stability are used to monitor landslides. Important details regarding landslide conditions are provided by these data points. Optical cables can be buried in the ground or along slopes to create a real-time sensor network.

Because of their broad range and capacity to identify threats such as fault lines and landslides, optical fiber sensors (OFS) are an invaluable instrument for monitoring geological hazards. They are appropriate for monitoring a range of situations because they provide adjustable spatial resolution, which varies based on the technology and application. While precise geographical resolutions are useful for minor changes like gas emissions and pore water pressure, low spatial resolutions are useful for events like landslides. Additionally, OFS may operate in challenging conditions such as underwater and volcanic areas. They provide a thorough grasp of intricate geological processes by measuring several variables at once. Over time, optical fibers provide cost-effective solutions with little effect on the environment.

Fiber Bragg Grating (FBG) sensors and Distributed Optical Fiber Sensors (DOFS) are two varieties of optical fiber sensors. Although DOFS offers dispersed measurements across extended distances, High-resolution point measurements are offered by FBG. One important characteristic of optical fiber sensing (OFS) is its capacity to identify and measure even the smallest changes in the parameter being measured; however, this resolution decreases with increasing measurement range. Choosing any one of the methods relies on specific requirements and installation environments. High-resolution configurations are used for sensitive and precise measurements, whereas low-resolution settings suit sensors with larger detectable parameter changes, such as 1 m over a distance of 10 km. While strain and temperature are monitored by both DOFS and FBG sensors, there are significant differences in their characteristics, accuracy, and measuring range.

OFS can be used to investigate subterranean factors including pore water pressure and slope stability by laying optical fibers inside boreholes or along the surface [6,9,10,11,12,13,14], geothermal conditions, as well as vertical and horizontal earth motions [15,16,17]. Ground movement can be evaluated by using longitudinal soil structure strain data from Distributed Optical Fiber Sensing (DOFS) sensors fundamentally [9], DOFS facilitates the identification and localization of unwanted events that result in variations in strain or temperature. Quick data transfer enables effective early warning systems for hazards like earthquakes [2,11,18,19,20].

Optical fibers offer a flexible and efficient basis for advancing disaster preparedness and response as well as our comprehension of geological dangers. Changes in ground conditions and soil saturation, for example, can be detected thanks to their sensing capacities. This technology is essential for danger monitoring, allowing for prompt reactions to possible calamities. During its journey, this optical signal may interact with several local characteristics. When these local properties shift, the optical signal disperses.

The refractive index of the fiber is influenced by temperature and strain variations, which in turn impact how light scatters within it. Since the intensity of backscattered light is determined by variations in the refractive index, this has a substantial effect on Rayleigh scattering. In a different setting, the length and diameter of an optical fiber cable also alter in response to changes in strain or temperature. Hence, density changes of scattering centers affect pattern and intensity [19]. The strength of transmitted and scattered signals can be impacted by temperature, which can also affect fiber attenuation [21]. As a result, variations in the surrounding environment can alter the intensity, phase, wavelength, and polarization of dispersed light. These modulated light signals are detected and processed to determine temperature variations and mechanical changes. [18,20,22,23].

B. Fibre Bragg Grating sensing

In contrast to ordinary optical fiber sensors, the Fiber Bragg Grating (FBG) sensor is a special use of optical fiber technology. Within the core of a single-mode optical fiber, the FBG collects data using spatially-varying UV laser patterns. Stable silicon-oxygen bonds can be broken by short-wavelength UV photons, changing the structure of the fiber and raising its refractive index. As a result, a grating is formed by the periodic changes in refractive index caused by interference from UV light intensity. Light is partially reflected at these variances as it passes through the fiber, creating a grating that serves as a selective mirror for particular wavelengths. However, at most wavelengths, these reflections interfere destructively, allowing the light to continue propagating down the fiber uninterrupted. Nevertheless, light gets reflected back down the fiber due to constructive interference in a specific limited range of wavelengths.

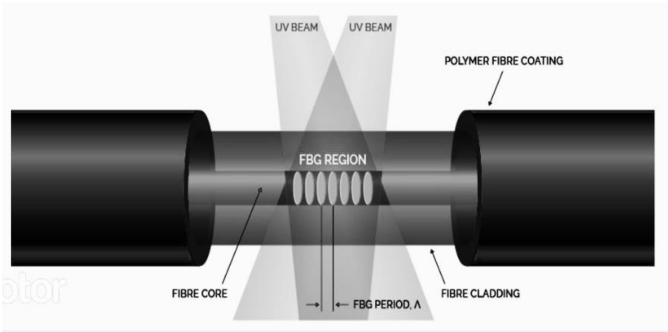

Fig. 1. Fibre bragg grating sensors

The physical characteristics of the FBG are impacted by external factors like strain or temperature changes, which causes alterations in the Bragg wavelength. Due to their high sensitivity, FBG sensors are able to pick up on even the slightest changes in their environment. They can be positioned alongside slopes or infrastructure to monitor landslides and continuously measure strain and temperature. By using these measurements, preventative actions can be taken and early warning indicators of instability can be found. By using a single optical fiber connection to multiplex FBG sensors, less cable is needed, allowing for numerous readings at different locations, simplifying installation, cutting expenses, and enhancing system dependability.

Distributed Bragg reflectors are used to the fiber in FBG sensors. This process is brought on by intense UV light exposure to the fiber pattern, which changes the fiber's refractive index at predetermined intervals. Certain wavelengths are reflected instead of transmitted through the fiber due to gratings created by the recently introduced change in the refractive index. According to equation (1), the Bragg wavelength, or wavelength of the reflected light λ_B, is determined by the grating period or periodicity of the index modulation ʌ and the effective refractive index of the fiber n_{eff} [24].

$$\lambda_B = 2n_{eff}\,\Lambda \qquad (1)$$

Therefore, the variation in the center wavelengths brought about by the alteration in the light route Δλ, can be indicated by the temperature change (T) and strain change (Δε), i.e.,

$$\Delta\lambda / \lambda = (1- P_{eff})\,\Delta\varepsilon + (\alpha+\xi)\,\Delta T \qquad (2)$$

Three different FBG sensor types are used in geotechnical monitoring in real time: FBG sensors come in three varieties: long gauge, quasi-distributed, and pointed. Every kind has a particular function; for instance, quasi-distributed sensors contain multiple FBGs connected in series, while pointed FBG sensors have a single grating section. Different wavelengths (λ_1, λ_2, λ_3 etc.) must be allocated to each grating section in the sensor array in order to prevent signal overlap. This guarantees accurate examination of the signals received.

Observing wavelength shifts in reflected waves helps identify changes in the FBG. An optical source that can examine reflected light is used to identify this peak shift, leading to two fundamental processes. One technique involves sending light into the fiber using a broadband light source, and then using an optical spectrum analyzer to look at the reflected light. The alternate method uses a narrowband, tunable laser source to measure the intensity of the reflected light with a power meter and numerically records the wavelength with an accuracy of 1 pm [26,38].

Time Division Multiplexing (TDM) and Wavelength Division Multiplexing (WDM) are FBG sensing techniques with distinct advantages and disadvantages[27]. WDM utilizes unique light wavelengths for each sensor in a single optical cable, while TDM measures specific parameters at designated sites, lacking distributed measurement capability along the cable [28, 29].

II. Landslide monitoring with FBG sensors

A team of experts has been utilizing FBG in the lab to assess the tilt and displacement of geotechnical structures. The horizontal PVC tube had the FBGs positioned on either side of it. The tube functioned like a cantilever when one side was fixed. The vertical displacement was determined using linear variable displacement transducers (LVDTs) and compared to the displacement determined by strain. They discover that FBG installed on an inclinometer can be built to detect soil movements since the LVDT results fit strain-related displacement data with a restricted inaccuracy [30]. Zeng et al. evaluated the displacement readings from a dial indicator and the FBG in order to validate the FBG sensing results. A reasonable linear relationship between the two measurements is shown by an R_2 value greater than 0.99. This might guarantee that FBG is a reliable strain sensor [14]. A modified inclinometer with hinge points at various inclinometer segments was assessed by Pei et al. The researchers achieved a sensitivity of 0.2860/με and a linearity between the angle and strain that was approximately 0.998 and the rotating angle of the inclinometer by measuring the deflection using the linear relationship between the strain and the center wavelength of FBG [5].

The strain from deformation of these bodies, due to ground motion, is the measurement parameter in landslide monitoring.

In real-time applications, FBGs are attached to rigid structures, such as vertically positioned steel rods and PVC pipes.

H. Peng et al. showed that an optical fiber-mounted inclinometer can measure landslide displacement. This technique is especially well-suited for slope monitoring applications since it provides precise displacement calculations when the optical fiber cable is pointed in the direction of the slide [31].

By expanding their experiment to compute horizontal displacement through vertical strain using two lines of fibers along the inclinometer, Hu et al. improved slope monitoring. They also integrated a sensor network to measure axial strain in soil nails. More thorough monitoring of slope behavior and stability is made possible by this method.

A connection was established in the same experiment to determine the horizontal displacement brought on by the sliding condition, the grade of the deformation, and the curve of the casing OF installed. To establish the relationship for displacement computation, two turns of Fiber Bragg Grating (FBG) arrays were installed on opposite sides of the casing. The output parameters are derived from the difference in FBG strain measured at these opposing sides. This method yields accurate displacement calculations when the optical fiber cable is oriented toward the slide, making it particularly suitable for slope monitoring applications. [31].

In a recent investigation, two soft sensors (FBG on plastic bars) and two hard sensors (FBG on reinforced steel rods) were evaluated against landslides that were created artificially. The results demonstrated that there may be landslides in the test region, underscoring the impact of sensor positioning on measurement sensitivity. The sensors were placed 50 cm apart vertically in a 6.93-meter-high pile of stones and sand [32].

The Wencheng landslide in China has been monitored using FBG-mounted inclinometers oriented parallel to the main sliding direction. Inclinometers with many FBGs attached were placed after surface-level fracture indications were found at three different vertical sections of the hill. There is a moving landslide in the monitoring region, as evidenced by the horizontal displacement that has been increasing from the bottom to the surface.

Estimating the size and potential damage of a landslide requires tracking the sliding plane. During a study conducted in Chongquing, researchers found the sliding plane and significant displacements in the Toudu landslide. They produced an internal deformation curve for the fiber sensor array when positioned vertically in the slope [31].

III. Challenges and Emerging Patterns

The requirement for a comprehensive grasp of geological processes and the specific parameters that must be monitored presents the first obstacle in the creation of an OF-based sensor. Notwithstanding the advantages of OF-based sensing, a number of challenges could limit or outright forbid its application. An in-depth knowledge of OFS technology and geology is necessary to determine the sensor configurations. Determining the measuring criteria and linking them to any hazards or geological conditions is another significant challenge.

It is challenging to create a sensor that can withstand collisions, extreme temperatures, wetness, chemical aggression, and physical contact. For precision and dependability in the geological environment, great consideration must be given to mechanical design and material selection. Additionally, optimizing the network topology to maximize coverage and geographic resolution while minimizing complexity and cost is a difficult task. Since these sensors are typically positioned in hazardous, remote locations with limited access, site access is challenging. Because OF cables are small and fragile, they need special care and measures to guard against sensor damage during installation.

This precaution is necessary for both the sensing fiber and the data transmission line [18]. Furthermore, the coverage and resolution of monitoring systems may be limited by restrictions on optical fiber cable length and installation techniques, making it difficult to achieve high spatial resolution across wide areas. It may be possible to expand or fix the sensor by splicing a different OF cable to an already-existing OF cable. Nevertheless, it may result in losses at spliced sites, which attenuate the signal and reduce the sensor's accuracy. There is no set calibration standard or process for utilizing OF to track geological conditions. This prompts the designers to create calibration standards and protocols based on the particular ground condition. Because of the ground's dynamic nature and the calibration may deteriorate over time, the impact of mechanical stresses and high temperatures may need frequent calibration of the sensors.

In order to enhance detection, early warning systems, and data interpretation, optical fiber sensors produce enormous volumes of data that may be assessed using machine learning and artificial intelligence approaches [2,33,39,40]. It's also possible that database, GIS, and DFOS technologies collaborate to make it possible to establish monitoring networks at various levels, which would improve monitoring effectiveness and save expenses [34]. In addition to integrating geological data with other systems, DOFS can be used to build multi-parameter monitoring systems that collect a greater range of environmental and geophysical data.

IV. Conclusion

The use of optical fiber sensors has improved landslide monitoring. This method is accurate, scalable, and economical. After a thorough analysis of a wide range of optical fiber sensor technologies, applications, and case studies, it was concluded that they held significant promise for advancing early detection and mitigation tactics for various geohazards. This paper highlights the benefits of employing optical fibers for geohazard monitoring and makes recommendations for enhancements. Even with their potential advantages, there are still issues that must be resolved before optical fiber sensor networks may be widely used. It is necessary to cover the hydroxyl formation and fragility while sacrificing sensitivity. FBG-mounted inclinometers were used to monitor real-world situations, showing that they could identify horizontal displacement profiles, which would indicate moving landslides. Numerous investigations used FBGs to track displacement; cumulative displacements in various places were reported to range from 3.5 mm to 400 mm. Using optical fiber sensing for landslide monitoring entails precisely placing and orienting sensors within slopes to improve accuracy and consistency. This review highlights the significance of incorporating optical fiber sensor technology into landslide monitoring plans To develop, establish benchmarks, and promote the broad adoption of these sensors, cooperation among researchers, engineers, and industry is essential. Recent studies have suggested ground temperature monitoring with optical fibers for both DTS and FBG, with sapphire FBG temperatures reaching up to 2000 ◦C and 1000 ◦C, respectively. These technologies make it possible to continuously and reliably profile temperatures for environmental monitoring and geological research. With the development of technology, optical fiber sensing is probably going to become more important in identifying and resolving unexplored geological hazards and environmental changes.

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