

Innovative Fiber Optic Inclinometer System for Continuous Deformation and Tilt Monitoring in Geotechnical and Structural Engineering

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ABSTRACT: The early detection of settlements, inclinations, and displacements is essential to ensure the stability and long-term performance of geotechnical structures and civil engineering infrastructure. This contribution presents a novel inclinometer system based on quasi-distributed fiber optic sensing technology, which enables continuous, spatially resolved measurement of longitudinal strains and, consequently, inclination changes with high precision. The sensing technology is based on the integration of optical fibers – containing Fiber Bragg Grating sensors – along flexible rods that can be embedded in soil or mounted on structural components. The system allows for the detection of deformation and tilt phenomena with sub-millimeter accuracy over extended lengths, making it particularly suitable for long-term monitoring of slopes, retaining walls, tunnels, and both concrete and steel structures.

The system has been validated through laboratory and field experiments using conventional measurement methods such as traditional inclinometer systems and digital image correlation (DIC). Results demonstrate strong agreement with reference data, along with advantages in terms of immunity to electromagnetic interference, low maintenance requirements, and real-time capability. Furthermore, the integration into digital monitoring platforms and model-based evaluation frameworks (e.g., digital twins) is discussed. This paper presents the sensor design, calibration methodology, data processing approach, and selected application examples, illustrating the potential of fiber optic inclinometers in advanced structural health monitoring and early-warning systems.

KEYWORDS: Fiber optic sensing, Inclinometer, Structural health monitoring, Geotechnics, Distributed sensing, Rayleigh scattering, Digital twin, Deformation monitoring

1 INTRODUCTION

The continuous monitoring of displacements and inclination changes is a key requirement for ensuring the stability and long-term performance of geotechnical structures and civil engineering infrastructure. Traditional inclinometer systems, while well established, often face limitations in terms of spatial resolution, durability, and integration into modern digital monitoring frameworks. Fiber optic sensing technologies, by contrast, offer significant advantages in precision, robustness, and long-term reliability, making them particularly suitable for applications in challenging environments, such as tunnels, embankments, retaining walls, and deep foundations. This study presents a novel quasi-distributed fiber optic inclinometer system, developed to enable spatially resolved measurement of strain distributions and, consequently, inclination profiles with sub-millimeter accuracy. The system is based on a flexible glass fiber-reinforced polymer (GFRP) rod instrumented with multiple optical fibers, providing continuous, high-resolution monitoring capabilities over extended lengths. The integration of multiple Fiber Bragg Grating (FBG) sensors along each fiber allows for quasi-distributed sensing, capturing fine-grained deformation patterns that are typically undetectable with conventional point sensors. The paper outlines the sensor concept, calibration procedures, and data processing methodology, and demonstrates its performance through laboratory and field validation against conventional reference systems.

The design also emphasizes durability and environmental resilience, with protective coatings and encapsulation strategies ensuring reliable operation under temperature variations, moisture exposure, and mechanical stresses. Furthermore, the system supports real-time data acquisition and remote monitoring, which is crucial for modern digital twin frameworks and predictive maintenance strategies. The

objectives of this study are threefold: (i) to compare the performance of the fiber optic inclinometer with classical inclinometer systems, (ii) to present the applied algorithm for converting strain measurements into inclination profiles, and (iii) to validate the fiber optic inclinometer recordings under laboratory and field conditions. The findings underscore the potential of fiber optic inclinometers as an advanced tool for structural health monitoring, early-warning systems, and risk assessment in geotechnical and structural engineering projects, offering enhanced measurement resolution, long-term stability, and the capability to capture complex deformation patterns that are critical for ensuring safety and optimizing maintenance interventions.

2 FIBER BRAGG GRATING-BASED SENSORIZED GFRP RODS FOR SHM

Bragg Gratings (FBGs) are periodic refractive index modulations inscribed within optical fibers, capable of reflecting a specific wavelength of the injected light while transmitting the remainder. Variations in strain or temperature alter the grating period, inducing a measurable shift in the reflected wavelength. This principle enables highly precise and localized measurements of mechanical and thermal quantities.

FBG technology has been widely adopted across multiple engineering domains. In civil engineering, it facilitates structural health monitoring of concrete elements, steel frameworks, tunnels, and bridges. In the energy sector, fiber optic sensing is employed for monitoring strain and temperature in high-voltage cables, wind turbines, and conventional turbines. Aerospace applications include load monitoring in wings and fuselage structures, while the oil and gas industry relies on FBGs for pipeline surveillance, encompassing deformation detection, leak monitoring, and thermal management. Medical applications exploit FBGs in minimally

invasive catheters for integrated pressure and temperature measurements, demonstrating the technology's versatility.

Compared to conventional electrical sensors, fiber optic systems present several advantages. They are inherently immune to electromagnetic interference, capable of covering extensive measurement ranges exceeding 100 km in distributed sensing configurations, and exhibit high resilience to extreme temperatures and aggressive chemical environments. Moreover, FBGs enable wavelength-division multiplexing, allowing multiple sensors to be interrogated along a single fiber, which significantly enhances measurement density, system flexibility, and installation efficiency, particularly for large-scale infrastructure monitoring.

Due to their intrinsic spectral selectivity, FBGs allow quasi-distributed strain measurements along optical fibers over distances ranging from centimeters to hundreds of meters. The small fiber diameter ($\approx 200 \mu\text{m}$) facilitates integration within GFRP rods, yielding flexible sensorized elements with multi-point monitoring capabilities across both the rod's cross-section and longitudinal axis. Such embedded sensors permit direct assessment of internal stresses and environmental effects within structural materials, which are often inaccessible to surface-mounted instrumentation.

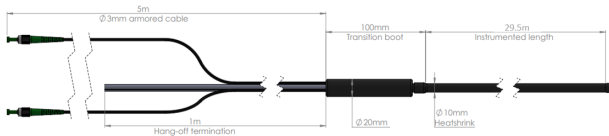


Figure 1. „HBK FOS system architecture“.

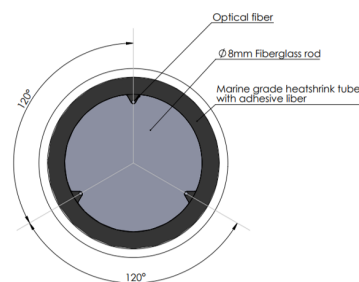


Figure 2. „Working principle of the HBK FOS inclinometer“.

In this study, a cylindrical GFRP rod assembly with an 8 mm diameter is proposed, incorporating three optical fibers positioned equidistantly from the neutral axis at 120° intervals (Fig. 1). Each fiber is equipped with 15 FBG sensors, spaced at 2.0 m center-to-center intervals over an 18 m length. The sensors' central wavelengths are uniformly distributed between 1510 nm and 1580 nm, ensuring unambiguous sensor identification. The rod assembly is encapsulated within a marine-grade heat-shrink tubing to prevent water ingress, thereby enhancing durability under harsh environmental conditions.

Fig. 2 illustrates the wavelength distribution of the FBG sensors along each fiber and their placement within the rod. This configuration is particularly suitable for applications in offshore structures, underground tunnels, and other critical infrastructures requiring continuous, high-fidelity monitoring over extended periods. The combination of multi-point sensing along the rod and robust environmental protection ensures reliable long-term operation, even in challenging conditions.

3 COMBINED INCLINOMETER AND FIBER-OPTIC MONITORING FOR LANDSLIDE INVESTIGATION

The investigation of the landslide at Grimmenstein is conducted using both traditional inclinometers and modern fiber-optic systems. The study area is characterized by a complex geological environment, which significantly affects the stability of the slope. The subsurface is predominantly composed of mica schists, with subordinate occurrences of gneiss and quartzite. The entire area is characterized by intense tectonic stress, resulting in a highly fractured and faulted rock mass. The heterogeneous lithological composition leads to spatial variability in hydraulic conductivity and shear strength parameters, which in turn causes localized differences in slope deformation behavior. The terrain surface is steep, with several smaller benches and incisions that promote water accumulation and erosion processes. In the past, repeated slope movements and minor landslides have been observed, particularly following prolonged rainfall or rapid snowmelt. Therefore, drainage wells have already been installed along the slope to manage groundwater and reduce hydrostatic pressure. These observations highlight the necessity for continuous monitoring to detect early warning signs of larger slope failures.

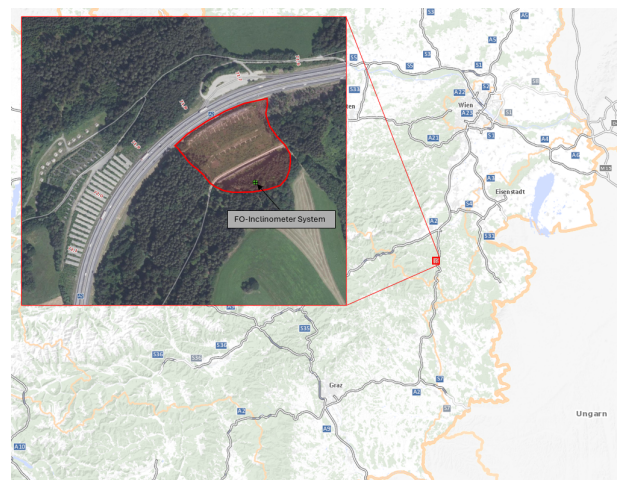


Figure 3. Overview of the Grimmenstein Slope and Monitoring Setup.

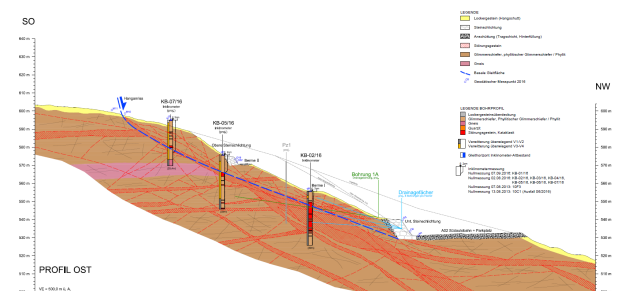


Figure 4. Geological Profile of the Grimmenstein Slope [1].

Traditional inclinometers provide point measurements within boreholes, allowing the tracking of soil inclination and displacement over depth. While they deliver reliable data on local soil behavior, their spatial coverage is limited and they require regular maintenance and access to measurement points. Moreover, the installation of multiple inclinometers can be labor-intensive and costly, particularly in steep or inaccessible terrain. Nevertheless, they remain essential for validating the results obtained from distributed systems and for providing high-resolution vertical profiles of subsurface movement.

In contrast, fiber-optic systems allow continuous monitoring of deformations along the entire length of the fiber. By using Fiber Bragg Gratings (FBGs) or distributed measurement methods such as Rayleigh or Brillouin scattering, even very small movements over long distances can be detected without the need for numerous separate measurement points. These systems offer high spatial resolution and the ability to capture temporal variations in slope behavior, which is critical for detecting precursory movements prior to significant landslides. Additionally, fiber-optic sensors are robust against environmental influences, including moisture, temperature fluctuations, and electromagnetic interference, making them suitable for long-term deployment in challenging field conditions.

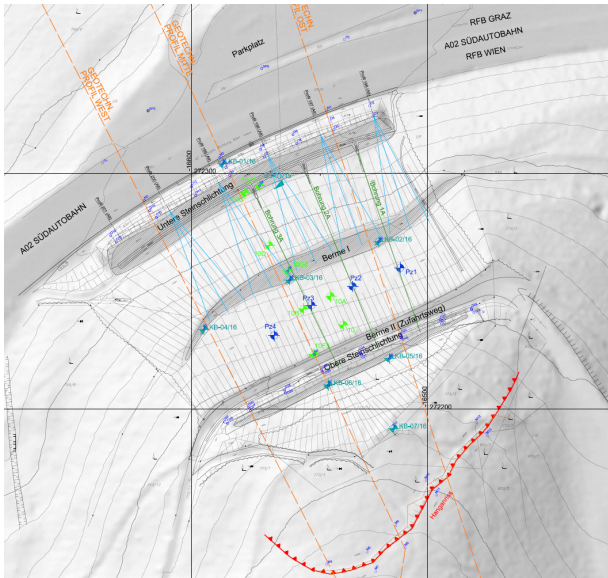


Figure 5. Layout of Monitoring Instruments at the Grimmenstein Site [1].

Experience from the Grimmenstein site shows that combining both methods—traditional inclinometers for detailed depth profiles and fiber-optic systems for continuous, distributed monitoring—offers a comprehensive understanding of slope stability. The integrated approach enables more accurate geotechnical modeling, enhances the detection of localized deformation zones, and improves the assessment of slope failure mechanisms. This combined monitoring strategy supports geotechnical risk analysis, informs the planning of protective measures such as retaining walls or drainage systems, and allows better prediction of future movements. Furthermore, it provides critical data for early-warning systems, contributing to improved safety for nearby infrastructure and communities exposed to landslide hazards.

4 MEASUREMENT PRINCIPLES AND VALIDATION OF FIBER-OPTIC INCLINOMETERS

Inclinometers are geotechnical instruments used to measure lateral movements and deformations in soil or structures. Their operating principle is based on recording inclinations along a defined axis, typically by means of a probe inside a casing or a sensor integrated into the structure. From the measured inclination values, displacement profiles can be obtained through integration over depth, providing insights into ground or structural stability. Additionally, the derivative of the inclination profile yields curvature, which, when multiplied by the bending stiffness (EI), allows the determination of bending moments.

Conventional inclinometer systems are costly due to the precision required in sensor technology and mechanics. As a result, they are usually read only at larger time intervals. Within this research project, however, novel fiber-optic inclinometers (FOS inclinometers) have been developed that are available at approximately one quarter of the cost of traditional systems. The FOS inclinometer consists of a carrier rod, for example a circular fiberglass rod, in which three optical fibers with integrated Bragg gratings are evenly distributed in the cross-section. Along the entire length of the rod, these Bragg grating packages are arranged at regular intervals. This configuration enables precise measurement of cross-sectional strains, from which the local curvatures can be derived. The curvature data are available at each measurement plane along the FOS rod and can be assembled into a continuous curvature profile over the full length. Based on these curvature profiles, classical mechanics can be applied to reconstruct inclination profiles and bending moments. In a further step, lateral displacements normal to the rod axis can also be determined.

In addition to their mechanical clarity and well-defined measurement principle, FOS inclinometers offer significant advantages: they are substantially cheaper to manufacture and install, and they allow continuous monitoring. This enables real-time, uninterrupted observation of processes such as landslides. Furthermore, threshold values for excessive movements can be implemented, providing immediate alarm functions. Despite these clear advantages, three independent validation processes were conducted within this project. These were designed to thoroughly evaluate the precision and performance of the FOS inclinometer system, and the validation approaches and results are outlined in the following sections.

4.1 Validation Process – Laboratory Investigations

The first validation process consisted of detailed laboratory analyses of the relationship between Bragg grating strain measurements and the corresponding curvatures. For this purpose, a dedicated test setup was constructed, comprising an 18 m long FOS inclinometer with 12 Bragg grating cross-sections. As shown in Fig. 6, surface strains were additionally measured using a Digital Image Correlation (DIC) system, allowing a direct comparison with the Bragg-derived strain data. In parallel, tensile tests were carried out to determine the elastic modulus and to validate the mechanical relationships between applied load, strain, and curvature. The test setup allowed the application of predefined deformation patterns with approximately 12 modes along the rod. The strain data obtained from the Bragg gratings were then compared with the predefined curvature and displacement profiles, enabling a systematic error analysis. Furthermore, DIC measurements provided additional surface strain information, which was again compared with the Bragg data. This comprehensive validation approach allowed for an extensive error analysis, with deviations consistently below 2%.

The laboratory experiments also formed the basis for transferring the local curvatures derived from Bragg strains into the global reference system of the rod, thereby reconstructing the overall deformation line, as illustrated in Fig. 7. In addition, a digital twin in the form of a finite element model was created using SOFiStiK software to validate the functional relationships and confirm the consistency of the experimental results.

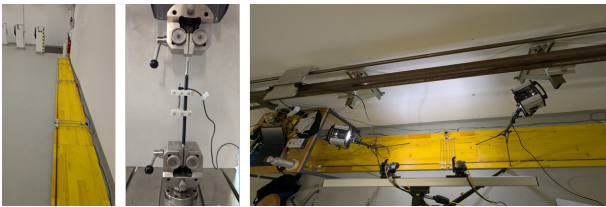


Figure 6. Overview of the laboratory test setup and material testing procedures, including the comparison of surface strains measured via Digital Image Correlation (DIC) with the Bragg grating strain measurements in the cross-section.

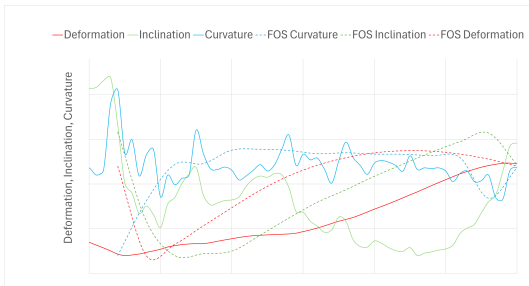


Figure 7. Experimentally validated relationships between curvature profiles, inclination profiles, displacement profiles, and bending moment diagrams derived from Bragg grating strain measurements, including error analysis.

4.2 Digital Twin and AI-Based Validation of the FOS Inclinometer

In addition to the experimental test setup, the FOS inclinometer from both the laboratory and the field trial in Grimmenstein was represented as a digital twin using SOFiSTiK software. This enabled, in addition to benchmark studies on the test setup, more extensive and advanced simulations of the deformation curves in combination with the Bragg strains. In this way, the previously described mechanical relationships could be validated, particularly regarding the spacing between the Bragg cross-sections along the FOS rod. Furthermore, the digital twin, combined with AI technologies, allowed the creation of training datasets that supported the integration of the Bragg readout data with the deformation profiles of the entire FOS inclinometer. By simulating several thousand deformation states, theoretical Bragg measurements could be characterized and their behavior under different load conditions analyzed. As a result, both the AI-generated training sets and the mechanical relationships of the theoretical concept are applied directly on the FOS inclinometer test setup to assure the robustness and accuracy of the method.

4.3 Third Validation Process – Field Trial at a Landslide

In the third validation process, the FOS inclinometer was directly tested at a landslide site in Grimmenstein (see Section 2). A 33 m long FOS inclinometer system was installed alongside a conventional inclinometer, which was read at periodic, discrete time intervals. The objective was to identify deformation horizons and to compare the measured displacements with those obtained from the conventional system. The field trial also enabled the assessment of additional influencing factors, such as temperature variations and soil settlement, on the performance of the FOS inclinometer. As introduced earlier, the FOS inclinometer allows continuous readout of Bragg strain measurements, enabling the detection of temporal deformation processes across multiple time scales, from short-term daily variations to weekly, monthly, and even annual trends. This capability provides detailed deformation information and also allows for the extraction of environmental

influences, such as surface temperature fluctuations or temperature variations within water-bearing horizons.

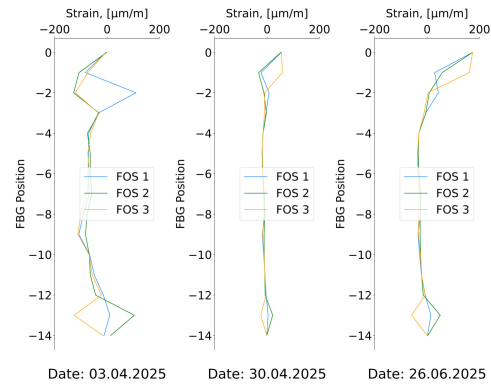


Figure 8. FOS inclinometer: Bragg strain profiles of the three fibers rotated by 120° in the cross-section. The blue curve represents the principal movement direction, shown for three selectively chosen time points relative to a reference in April.

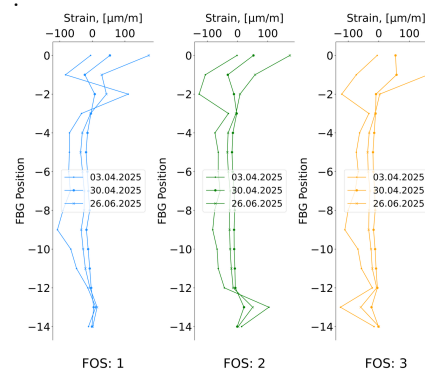


Figure 9. FOS inclinometer: Bragg strain profiles of the three fibers (blue, yellow, and green) rotated by 120° in the cross-section, shown over the time series.

Figure 8 presents strain measurements from the Bragg gratings at three selected time points, along with the corresponding strain profiles along the FOS inclinometer. The profiles indicate movements in both the upper and lower soil horizons. The three fibers are color-coded: blue aligns with the main slope movement direction, yellow is rotated 120° relative to blue within the circular cross-section, and green is rotated 120° relative to both blue and yellow. This arrangement allows identification of both the primary slope movement and perpendicular movements, enabling full three-dimensional characterization of the deformation. As shown in Figure 8, deformations occur throughout the soil horizons. A clearer view is obtained by examining the time series of each fiber individually, as shown in Figure 9 for the primary direction (blue) and the two rotated fibers (yellow and green). These data indicate an active zone in the upper horizon at approximately 4 m depth. Additionally, all three fiber groups exhibit similarly sized negative strains over an extended middle section, which may be attributed to uniform settlement or to temperature effects.

Detailed Measurements: Figure 8 compares the evolution of axial strain in three FBG fibers (FOS 1–3) at three measurement times, referenced to an April baseline. The abscissa shows strain in $\mu\text{m/m}$, and the ordinate lists FBG measurement points from top to bottom (increasing depth downward). In the upper and lower ranges of the FBG measurement points, the fiber profiles are nearly straight but uniformly shifted relative to the zero line, with only small depth gradients. This pattern indicates predominantly horizontal

movement (rigid-body translation) of the end regions rather than bending or axial extension. In the central range, the curves for all three fibers converge toward negative strain and exhibit larger depth gradients and local sign changes, which is characteristic of vertical shortening (compression) concentrated in the middle section. Across the three measurement dates, this kinematic partition is maintained: the end regions exhibit lateral displacement, while the mid-depth zone accommodates the primary compressive response.

Overall, the profiles separate into end zones and a mid-depth zone. At the uppermost and lowermost FBG points, the curves show small but systematic deviations from zero with gentle depth gradients and local sign changes, consistent with moderate bending of the end segments. In the central range, the curves reach their largest negative values and remain predominantly below zero, indicating a compression-dominated zone at mid-depth. Temporal comparison shows that the difference between the second and third measurements (30.04.2025 → 26.06.2025) is small, whereas changes from the first measurement (03.04.2025) to the later two dates are clearly larger, both in amplitude and in the extent of the compressed region. This pattern is consistently captured by all three fibers, confirming that it reflects the underlying deformation field rather than sensor orientation.

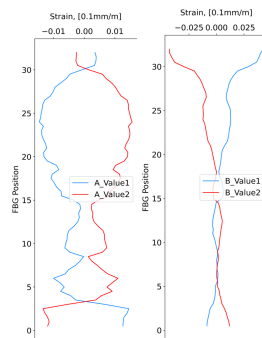


Figure 10. Comparison of displacement profiles derived from FOS inclinometer Bragg strain measurements (Figures 8 and 9) with a conventional inclinometer. The blue lines indicate the principal slope movement direction, showing excellent agreement between both systems.

Validation of the FOS Inclinometer with a Conventional Inclinometer: In the final step, the strains obtained from Figures 8 and 9 were converted into displacement profiles using the previously described methodology, applying the mechanical relationships and the SOFiSTiK digital twin, as shown in Figure 10. These displacement profiles were then compared with the measurements from a conventional inclinometer system, also presented in Figure 10. The analysis shows that the blue line from the conventional inclinometer aligns very well with the blue line from the FOS inclinometer, corresponding to the principal slope movement direction. Minor deviations observed at certain depths are likely attributable to local heterogeneities in the soil or rock mass, as well as small differences in sensor positioning. Overall, the strong agreement between the two systems confirms that the FOS inclinometer provides accurate and reliable measurements of lateral displacements. This successful validation demonstrates the potential of the FOS inclinometer for continuous, high-resolution monitoring of slope stability, offering a cost-effective alternative to traditional systems while enabling detailed spatial and temporal analysis of deformation patterns.

5 CONCLUSIONS

The comprehensive validation of the FOS inclinometer system, encompassing laboratory tests, digital twin simulations, and field trials, demonstrates its high accuracy, reliability, and robustness. Laboratory experiments confirmed the precise relationship between Bragg strain measurements and curvature, inclination, and displacement profiles, with error levels consistently below 2%. Digital twin and AI-assisted simulations further validated the mechanical relationships and allowed the generation of extensive datasets for system calibration and robustness testing. Field deployment at a landslide site showed that the FOS inclinometer accurately captures deformation patterns across multiple temporal scales and reliably reproduces the principal slope movements observed with conventional inclinometer systems. In addition, the system proved resilient under variable environmental conditions, including temperature fluctuations, moisture exposure, and minor mechanical disturbances. The ability to obtain continuous, high-resolution measurements along extended lengths provides unprecedented insight into localized deformations that may be overlooked by traditional sensors. Overall, the FOS inclinometer provides a cost-effective, continuously readable, and mechanically well-understood solution for monitoring soil and structural deformations, offering significant advantages over traditional systems and enabling improved early-warning capabilities, risk assessment, and informed decision-making in geotechnical and structural engineering projects.

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