



Assessment of Soil-Embedded Tapered POF Sensor for Geotechnical Monitoring

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Abstract

Plastic optical fiber (POF) sensors for geotechnical monitoring have gained popularity due to their advantages over traditional methods like inclinometers, strain gauges, and settlement plates, which face issues with installation, accuracy, and long-term efficacy. POF sensors offer distributed sensing, enhanced sensitivity, electromagnetic interference tolerance, and durability under adverse conditions. However, embedding POF sensors in soil presents challenges such as uneven distribution, variable sensing performance due to soil structure and installation methods, and complicated calibration processes. Factors like soil temperature, moisture, and chemical interactions, as well as biological activity, abrasion, and physical disturbances, can affect sensor durability and effectiveness. Research shows that applying pressure to the fiber optic sensor at varied soil depths increases sensitivity. Signal loss increases with tapering length and core diameter, enhancing sensitivity. In sandy soils, sample 'D' (4 cm tapering length, 0.98 mm core diameter) performs best, while samples 'I' and 'F' excel in peat soils and coarse sandy soils, respectively. Further research and development are necessary to improve the reliability and flexibility of POF sensors for geotechnical monitoring, addressing current limitations in sensor distribution, calibration, and long-term performance.

Keywords:

Plastic optical fiber;
Geotechnical monitoring;
Sensor; Tapering;

Article History:

Received: December 16, 2022

Revised: January 23, 2022

Accepted: June 22, 2023

Published: June 22, 2023

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INTRODUCTION

As climate change increases the likelihood of floods and storms and expanding land for developments bring new challenges, therefore monitoring geotechnical projects and infrastructure becomes crucial [1]. Geotechnical projects involve examining and analyzing earth materials to ensure the stability, safety, and durability of structures like buildings, bridges, dams, tunnels, and highways. Geotechnical engineers conduct site investigations, soil testing, analysis, and design recommendations to address construction, infrastructure, and land use planning effectively. Their work helps mitigate geohazards,

optimize construction techniques, and ensure the sustainability of civil engineering projects. Geotechnical monitoring is essential for the development of geotechnical engineering and the security of infrastructure. Various instruments, such as inclinometers, multi-point extensometers, and tiltmeters, measure deformation in geotechnical structures [2]. However, these tools have limitations such as inclinometers may lack precision, multi-point extensometers have limited measurement ranges, and tiltmeters are usually one-dimensional [3].

Plastic optic fibers (POFs) sensors are increasingly used in engineering for applications such as detecting chemical and biological contaminants and monitoring deformation in steel-reinforced concrete structures [4]. POFs are durable, withstand extreme weather, and are suitable for long-term monitoring [2]. They are easy to construct, install in soil or rock without additional sensors, and are cost-effective, making them ideal for many geotechnical projects. For an effective POF-based geotechnical monitoring system, understanding how POFs interact with surrounding soil or rock is crucial. This study uses various Malaysian soil types (40% peat, 20% clay, 40% sand) as independent variables [5]. It evaluates sensor sensitivity using fiber optic core diameters (0.98 mm, 0.96 mm, 0.94 mm) and tapered lengths (2 cm, 4 cm, 6 cm). These parameters help assess soil vibration and conditions to determine the optimal sensor performance for geotechnical monitoring.

SENSOR DEVELOPMENT

Polishing of Fiber Optic Sensor

The high sensitivity of fiber optical sensors relies on the efficient transmission of light through optical fibers. Any pollution or damage to the fiber's end face can cause signal attenuation, reduced sensitivity, and poor precision [6]. Therefore, it is crucial to keep the end face clean and polished. The polishing process removes scratches and dust from the exposed face of the fiber optic connector. To ensure optimal performance, the ends of the fiber sensor must be polished and perpendicular to the fiber axis. A cotton pad dipped in isopropyl alcohol is used to carefully clean the fiber's end face, removing any debris or oils that could interfere with the polishing process [7]. As shown in Figure 1, the fiber optic is firmly held and rubbed on sandpaper in a figure-eight or circular motion. Moderate pressure is applied to achieve a consistent, level finish. After polishing, the fiber optic is cleaned again with a cotton pad and cleaning solution. It is important to record both the pre- and post-polishing values before starting the experiment.



Figure 1: Polishing of Fiber Optic Sensor.

Fabrication of Fiber Optic Sensor

Improving the efficiency of light transmission in a fiber optic sensor can be achieved by tapering the middle section of the fiber. This involves gradually reducing the diameter over a specific length, enhancing sensitivity, response time, and overall performance. Tapering increases light intensity as the fiber narrows, improving the sensor's ability to detect subtle changes. A shorter tapering length reduces light propagation time, allowing faster detection and response, essential for real-time monitoring in dynamic applications. To evaluate the effect of tapering length on fiber sensors, specific lengths of 2 cm, 4 cm, and 6 cm are marked. Pressure is applied by stroking the modified region while holding the extremities firmly, as shown in Figure 2. Tapering the core diameter enhances sensitivity, resolution, and flexibility. It allows more efficient interaction with the environment and improves spatial resolution, enabling finer detail detection. During tapering, the fiber's diameter is reduced to a conical shape, with precise measurements taken using a vernier caliper. Measurements such as 0.98 mm, 0.96 mm, and 0.94 mm are achieved through meticulous control of the stroking process.

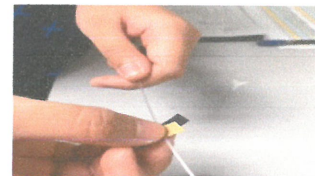


Figure 2: Tapered Fiber Optical Sensor.

Types of Soils

In Malaysia, soil types such as peat, coarse sandy, and sandy soils are categorized into two groups based on moisture content: dry and wet. The masses of these soil samples are 300 grams, 600 grams, and 900 grams, respectively. The sensor's mass correlates with its embedding depth in the soil. This study examines how increased soil mass affects sensor performance, specifically any potential losses in fiber optic sensors. Malaysia's distinct weather patterns such as rainy, sunny, and windy, that indicate climate change, which influences soil moisture conditions. Soil vibrations are used to simulate natural disasters like earthquakes. The goal is to identify the most effective sensor for various environmental conditions in Malaysia. Two settings of soil conditions were set in the study, which is wet and dry conditions as shown in Figure 3.

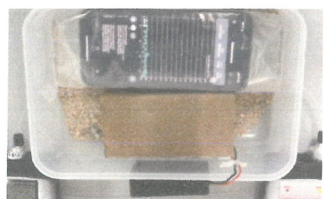


Figure 3: Setting of Dry and Vibrate Soils Condition.

RESULTS AND DISCUSSIONS

Sensitivity and Resolution of Dry Soils and Wet Soils

Based on data obtained, the measurement of different types of soil and mass is recorded for non-vibrate conditions. The formula used to find the sensitivity of the sensor is shown in (1) [8], [9]. Figure 4 and Figure 5 show the graph sensitivity of fiber sensor when embedded in sandy soils, peat soils, and coarse sandy soils with mass of 300g, 600g and 900g. From the graph, we can see that the sensitivity of the fiber is nearly linear among all the soil’s settings and conditions. A fiber sensor with constant sensitivity will consistently respond to input stimuli, enabling precise calibration. By assessing the sensor’s response to known inputs, a calibration curve can be developed to convert sensor readings into accurate measurements. This consistent sensitivity ensures that the sensor’s behavior is predictable, making it easier to forecast its output after calibration. Consequently, measurements become more accurate and repeatable, as long as the sensor’s performance remains stable. This reliability is advantageous for control systems, as it provides dependable and predictable feedback, allowing the system to make necessary adjustments based on the sensor’s output.

$$S = \frac{y}{x} \tag{1}$$

S = Sensitivity of the sensor.
 y = Output signal.
 x = Input parameter if the signal.

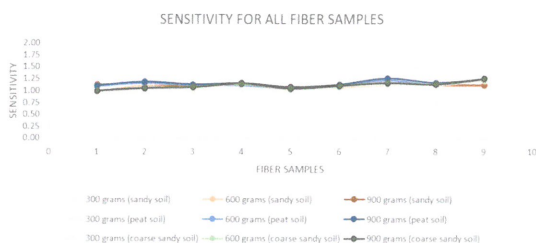


Figure 4: Sensitivity for Dry and Non-Vibrating Soil Setting for All Fibers Optic Sensor.

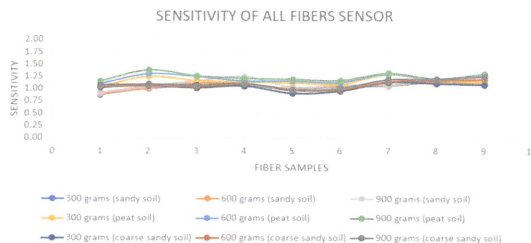


Figure 5: Sensitivity for Wet and Non-Vibrating Soil Setting for All Fibers Optic Sensor.

Figure 6 depicts the resolution of a fiber sensor when implanted in vibrating sandy soils, peat soils, and coarse sandy soils with masses of 300g, 600g, and 900g from same data obtained to find the sensitivity. Upon observing Figure 7, it becomes apparent that the sensitivity of all the soils remains relatively consistent, which exhibits the highest sensitivity. On the other hand, the resolution as obtained by (2) of all tested samples across different soil types remains constant throughout the experimentation process.

$$R_s = \frac{x}{S} \tag{2}$$

R_s = Resolution of the sensor.
 x = Sensor measurement.
 S = Sensitivity of the sensor.

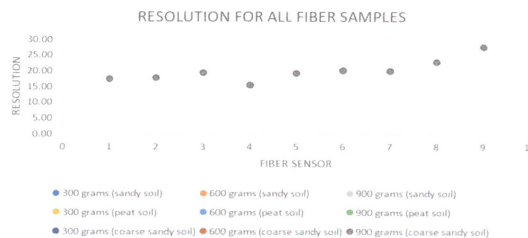


Figure 6: Resolution for Dry and Non-Vibrating Soil Setting for All Fiber Optic Sensors.

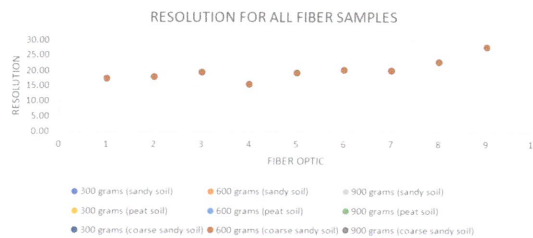


Figure 7: Resolution for Wet and Non-Vibrating Soil Setting for All Fiber Optic Sensors.

The resolution of non-vibrate and vibrate is same for all the samples. When the resolution of a fiber

optic remains constant, it implies that the sensor can consistently differentiate between two points even when they are separated by the smallest discernible distance. The resolution of an optical imaging system is essentially the minimum distance at which two distinct points can be distinguished. Hence, if the resolution of a fiber optic remains unchanged, it signifies that the sensor possesses the ability to discern between two points that are a specific distance apart, irrespective of other influencing factors. Nonetheless, it is important to note that the linearity of the fiber optic sensor might be influenced by various factors, including the refractive index of the core and cladding materials, as well as the numerical aperture of the fiber. These factors can potentially affect the performance and accuracy of the fiber optic sensor beyond the resolution alone.

Comparison Between the Soil’s Settings

By comparing the conditions of the soil when it is dry or wet, we can see that the sensitivity of the dry soil is nearly linear compared to wet soils. But for all conditions, regardless of the soils setting, the resolution of the sensor remained constant throughout the experiment. This shows that the sensor resolution is good and can be used as a initial study to monitor the landslide. Table 1, 2 and 3 below show the summary of the fiber sensor with highest sensitivity for all types of soils conditions. High sensitivity shows the perfect fiber optic that can be used as sensor for geotechnical monitoring for each type of soil.

Table 1. Summary of Dry and Non-Vibrate Settings for Different Soils and Mass.

SOILS TYPE	DETAIL	LOSSES
Sandy Soil	900g	D (1.16) & G (1.16)
Peat Soil	900g	G (1.26)
Coarse Sandy Soil	900g	I (1.26)

MASS	DETAIL	LOSSES
300 g	Peat soil	I (1.22)
600 g	Peat and Coarse Sandy Soil	I (1.23)
900 g	Peat and Coarse Sandy Soil	GI (1.26)

Table 2: Summary of Dry and Vibrate Settings for Different Soils and Mass.

SOILS TYPE	DETAIL	LOSSES
Sandy Soil	900g	D (1.22)
Peat Soil	900g	I (1.29)
Coarse Sandy Soil	900g	F (1.58)

MASS	DETAIL	LOSSES
300 g	Peat soil	I (1.23)
600 g	Coarse Sandy Soil	F (1.26)
900 g	Coarse Sandy Soil	F (1.58)

Table 3: Summary of Wet and Non-Vibrate Settings for Different Soils and Mass

SOILS TYPE	DETAIL	LOSSES
Sandy Soil	900g	D (1.25)
Peat Soil	900g	F (1.38)
Coarse Sandy Soil	900g	I (1.26)

MASS	DETAIL	LOSSES
300 g	Peat soil	G (1.30)
600 g	Peat Soil	G (1.31)
900 g	Peat Soil	F (1.38)

Factors Affecting the Sensor Outputs

Fiber optic sensors, known for their sensitivity, are designed with smaller core diameters and longer tapering lengths. This design minimizes light reflection back into the core by eliminating cladding, though it also increases signal loss as the core thickness decreases. The length of the tapering area further affects this loss, with longer tapers resulting in greater signal attenuation. To maintain accuracy, careful design of the tapering section and optimization of mode matching with system components are essential. These sensors are particularly effective in distinguishing between dry and wet soils due to their sensitivity to changes in the refractive index. Dry soil typically results in higher signal loss because air has a lower refractive index than water. Therefore, in dry conditions, the sensor’s readings are more precise compared to wet soil.

CONCLUSION

As climate-related disasters become more frequent, monitoring geotechnical structures and infrastructure is essential. Advanced techniques like Fiber Bragg Grating, Brillouin Scattering, and Optical Time Domain Reflectometry are used, but the challenge lies in processing the vast amounts

of data they generate. To address this, engineers are developing an affordable and precise plastic optical fiber sensor for geotechnical monitoring. The sensor's sensitivity and resolution are evaluated using a power meter and plastic optical fiber. Soil characteristics, such as density, tapering length, core width, condition, and diversity, are considered. The results show that these sensors perform well under various conditions. Soil particles influence fiber losses during vibration and compression due to moisture.

In the experiment, the highest sensitivity was found in group sample 'F' with a value of 1.58 in dry and vibrating soil conditions. All fiber optic sensors demonstrated consistent resolution across different soil types and conditions, indicating their potential for geotechnical applications. Sample 'F', with a 4 cm tapering length and a 0.94 mm core width, showed the best performance. For both dry and wet soil settings, group sample 'F' exhibited higher sensitivity, making it an effective sensor for detecting soil movement. High sensitivity is crucial for efficient sensing. Consistent resolution in fiber sensors means they can reliably differentiate between two points, even at the smallest distances. This consistency is influenced by factors like the refractive index of the core and cladding materials and the fiber's numerical aperture. Overall, plastic optical fibers show promise as sensors for geotechnical monitoring.

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