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Optical Fiber Sensor for Soil Moisture Detection

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Abstract

Soil moisture measurement plays a vital role in various sectors such as agriculture, environmental monitoring, and geotechnical engineering. This research aims to develop and evaluate a fiber optic displacement sensor for soil moisture detection, emphasizing the effects of lateral offset and the sensor's interaction with various soil types. Clay and medium sand soils were examined at moisture contents of 15%, 27%, and 38%, utilizing the evanescent wave effect, where light traveling through the fiber interacts with the surrounding soil, causing detectable changes in optical power. The findings reveal that the sensor is more sensitive to moisture in clay soil, with a higher sensitivity of -0.0135 dBm/% compared to medium sand at -0.0074 dBm/%. Furthermore, the study identifies the lateral offset at which the sensor performs optimally for each soil type. In conclusion, fiber optic sensors prove to be a reliable and efficient tool for soil moisture detection, with significant potential for use in precision agriculture and environmental monitoring, while highlighting the importance of optimizing sensor designs based on soil characteristics.

1. Introduction

Advancements in precision agriculture and geotechnical engineering have underscored the importance of soil moisture monitoring for optimizing water usage, enhancing crop yields, and maintaining structural stability. Optical fiber sensors have emerged as a transformative technology in this domain, offering unparalleled precision, high sensitivity, and immunity to electromagnetic interference. Unlike traditional methods, which are often time-intensive and prone to errors, optical fiber sensors provide reliable, real-time data essential for sustainable water resource management and effective irrigation systems [1, 2].

Optical fiber sensors leverage the principles of light transmission and interaction with the surrounding environment to measure soil moisture with exceptional accuracy. Key attributes, including high sensitivity, compact size, immunity to electromagnetic interference, and remote sensing capabilities, make optical fiber sensors a superior alternative to conventional soil moisture detection methods [3, 4]. The integration of these sensors into soil moisture measurement systems has advanced the development of intelligent, sustainable farming practices and enhanced geotechnical stability assessments.

This study focuses on the design, development, and evaluation of an optical fiber sensor for precise soil moisture measurement. The sensor's operation is based on the interaction between light propagation within the optical fiber and the soil environment. Variations in soil moisture content alter the medium's refractive index and absorption properties, thereby affecting the transmitted light [5]. These changes can be analysed to determine soil moisture content with high precision.

A key innovation explored in this work is the lateral offset technique, which intentionally misaligns the transmitting and receiving optical fibers to enhance sensor sensitivity [6]. This approach enables accurate quantification of soil moisture and displacement, addressing critical requirements in agricultural productivity and geotechnical stability [7].

By bridging the gap between traditional soil monitoring methods and contemporary optical fiber-based technologies, this research aims to advance soil moisture sensing. The findings are expected to contribute to the development of more efficient soil monitoring systems, supporting structural safety, environmental sustainability, and water resource management [8].

2. Materials and Method

2.1 Sample Preparations

Fig. 1 shows two different types of soil, which are medium sand and clay, to prepare soil samples for optical fiber sensor-based soil moisture monitoring utilizing the Fiber Optics Displacement Sensors using Lateral Offset method. These soil types were selected because of their disparate characteristics, which have a big influence on moisture transfer and retention. Larger particle sizes and a reduced water-holding capacity allow medium sand to drain more quickly and is usually less cohesive [9]. Conversely, because of its increased flexibility and compact structure, clay has finer particles, retains more water, and drains more slowly. To preserve their natural composition, soil samples were sourced from nurseries or gardens. 100 grammes of each type of soil will be carefully prepared for each experimental procedure. When comparing the accuracy of sensor performance in detecting moisture levels in various soil settings, this standardised quantity guarantees uniformity between testing.

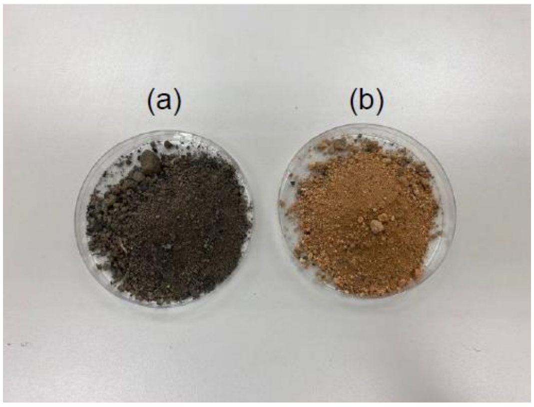


Fig. 1 Clay and medium sand of soil samples a) Clay soil; b) Medium sand

After that, a soil sample is taken, weighed to determine its wet mass, dried in an oven at a constant temperature (typically 105°C) for 24 hours to remove all moisture, and then weighed again to determine the dry mass [10]. This is to ensure that the soil is completely dry without any moisture. This exact, laboratory-based method is known as the gravimetric method of measuring soil moisture. The water content of the soil is represented by the weight difference between before and after drying. To determine the soil moisture content, this water mass is then expressed as a proportion of the dry soil mass. This traditional method is intended as a reference and comparison with the advanced method that will be implemented.

2.2 2.2 Experimental Setup

The experimental setup consisted of a few of the components shown in Fig. 2. It utilized an optical light source, more precisely, with 1550nm working wavelength. A pair of optical fiber were employed to transmit and receive light.

The procedure commenced by connecting the light from the optical light source to the optical power meter via the lateral core offset sensor.

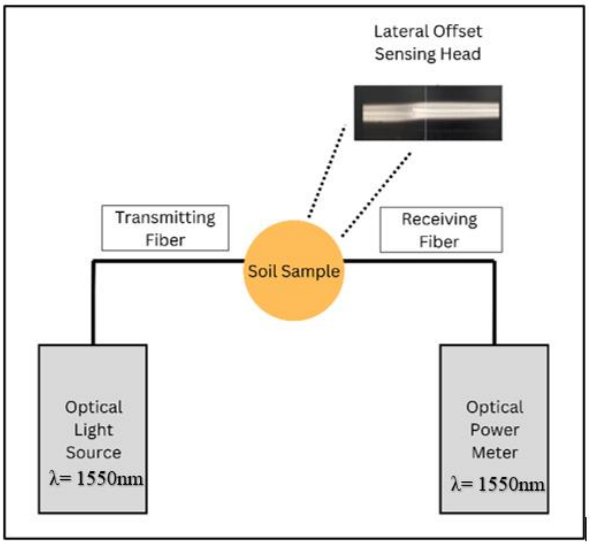


Fig. 2 Schematic diagram for experimental setup

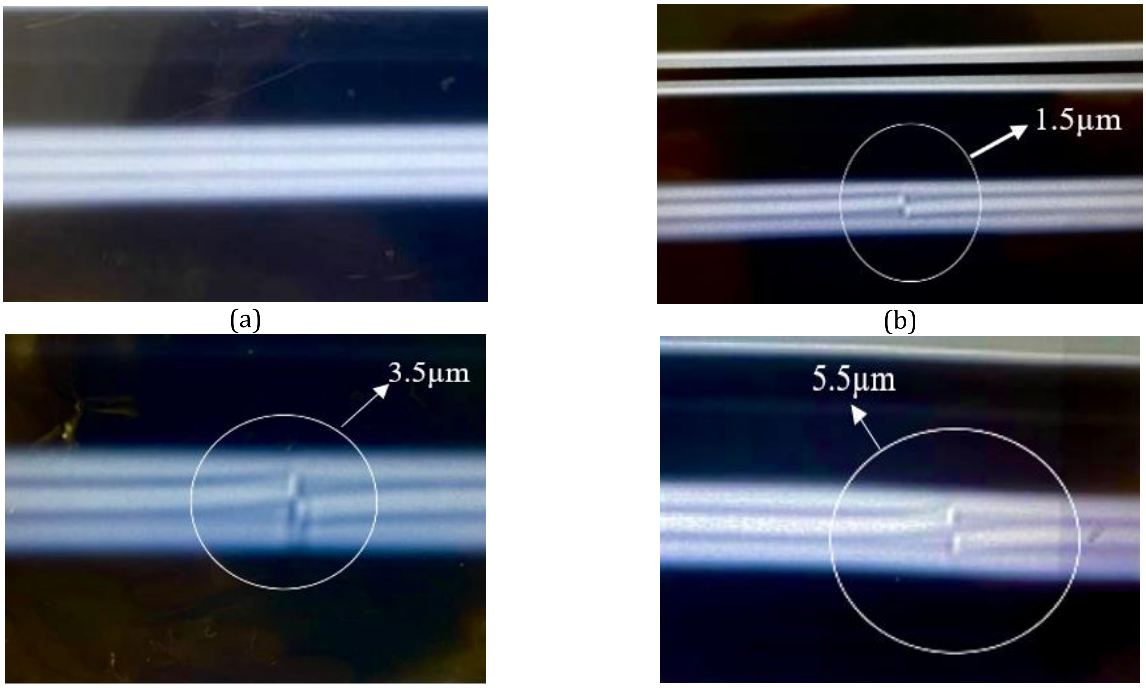
The experimental setup is designed to study the optical transmission characteristics of soil samples using a fiber optic displacement sensor based on a lateral offset approach. The system comprises an optical light source, soil sample, a lateral offset sensing head, and an optical power meter. Because of its suitability for soil moisture monitoring, a laser operating at a wavelength of 1550 nm was selected as the optical light source for this investigation. In order to interact with soil samples, this source creates a steady and uniform beam of light that passes through optical fibers. The infrared wavelength of 1550 nm is perfect because silica optical fibers have very little signal loss, which guarantees effective light transmission. Additionally, it is extremely sensitive to water since water efficiently absorbs infrared light, which makes it appropriate for detecting changes in soil moisture. Furthermore, because it is less likely to pass through the retina, this wavelength is safer for human eyes than shorter ones like 850 nm.

The soil samples, consisting of clay or medium sand, are prepared at three different volume contents (15%, 27%, and 38%) and placed in a secure holder to ensure stability and alignment between the optical components. 15% indicates dry soil, which is typical for plants that require less water or in regions with little rainfall. For normal growing conditions, a soil moisture content of 27% is considered moderate. In farms that receive excessive irrigation or during periods of high precipitation, 38% of the soil is wet or saturated. The sensor's performance can be assessed across a realistic range of soil moisture conditions by testing at these levels.

The study employed SMF, which prevents other modes of light from propagating. In addition, as light travels through the core, the number of reflections decreases, reducing the attenuation and increasing the signal range. The lateral offset distance was varied to ascertain how the misalignment gap affected sensor performance. The position of the receiving fiber can be adjusted laterally to create offsets of 0 µm, 1.5 µm, 3.5 µm, and 5.5 µm, simulating changes in alignment and enabling the study of light behaviour as it interacts with the soil. Smaller lateral offsets, like 0 µm, should result in stronger intensity readings due to better alignment, whereas larger offsets, like 5.5 µm, may lead to weaker readings. The optical power meter (OPM) connected to the receiving fiber, measures the intensity of the transmitted light, providing quantitative data on the amount of light passing through the soil at each offset. Additionally, OPM measures the power loss in optical fiber due to the core lateral offset during splicing process [11].

During the experiment, the soil sample is aligned with the transmitting and receiving fibers, and measurements are taken systematically by increasing the lateral offset while recording the light intensity at each step. This process is repeated for all combinations of soil types and volume contents. The setup ensures precise control of parameters and repeatable measurements, allowing for a detailed analysis of how soil properties, such as particle size, density, and moisture content, influence light scattering and absorption.

3. Results and Discussion



(a) (b)

(c) (d)

Fig. 3 Lateral offset at (a) 0µm; (b) 1.5µm; (c) 3.5µm; (d)5.5µm

In a fiber splice image, the mode fields from the two fibers overlap, resulting in the two bright lines at the top and bottom of the offset core. The light intensity peaks at the borders of the core and cladding when the fibers are not precisely aligned. A misalignment or improper splice, where the light dispersion is not consistent throughout the fibers, is indicated by these brilliant lines. A fiber optic displacement sensor identifies changes in light transmission caused by lateral offset, which refers to the misalignment between the light transmission core and the receiver [12]. In this study, the lateral offsets of 0µm, 1.5µm, 3.5µm, and 5.5µm indicate varying degrees of misalignment or bending of the fiber, which are influenced by different levels of soil moisture as shown in Figure 3. At 0µm lateral offset, the fiber remains perfectly aligned, allowing for optimal light transmission with minimal loss or displacement. However, as the lateral offset increases to 1.5µm, 3.5µm, and 5.5µm, the misalignment grows more significant, causing a corresponding increase in light scattering, reduced intensity, and displacement.

Table 1 Soil samples after undergoing oven drying process

Soil samples	Before (g)	After (g)	Moisture content (%)
Clay	100	77.6957	28.85
Medium Sand	100	91.2537	9.59

Table 1 illustrates that the difference in weight before and after drying becomes more pronounced as the water content increases. This implies that there was more water in the soil at first, but that water was eliminated when it dried. The observed weight reduction correlates with the initial water content.

In comparison to sandy soils, clay soils in particular typically retain more water. The samples' varied water contents, which represented the soil's moisture levels, are in line with the experiment's conclusions. As is common for soils that retain more moisture, weight decreased more after drying the greater the water content in the sample [13].

The findings are consistent with the usual behaviour of medium sand, which has a big particle size and coarse texture, which results in a relatively low water-holding capacity. The coarser particles in medium sand produce bigger pores, which facilitate rapid water drainage and lessen the material's capacity to hold moisture. Because of this feature, medium sand is less likely to waterlog, but it is also not appropriate for long-term water storage.

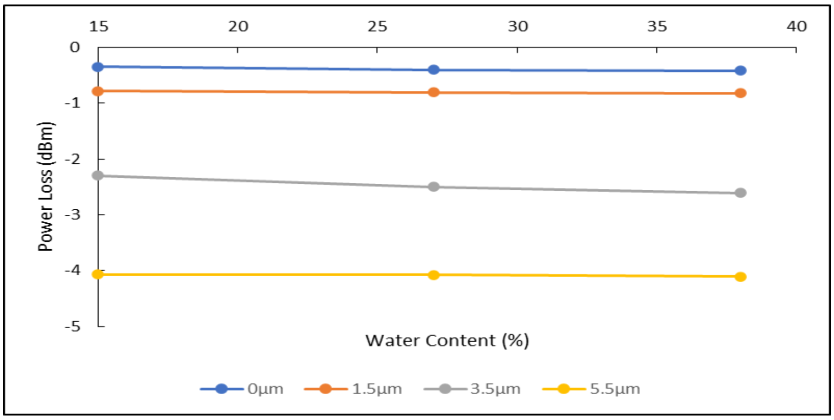


Fig. 4 Relationship power loss and water content for clay soil

Fig. 4 illustrated the power loss rises more pronouncedly with increasing water content in clay soil over all lateral offsets. When the water content increases, the power loss at 1.5 µm lingers around -1 dBm, while at 0 µm, it barely changes and stays close to -0.5 dBm. When the offset is bigger, such as 3.5 µm and 5.5 µm, the power loss is more noticeable and drops to about -2.5 dBm and -4.5 dBm, respectively. The pattern suggests that clay's high-water retention and fine texture have a considerable effect on signal attenuation since water raises the medium's conductivity and dielectric constant. Furthermore, because the signal interacts with the clay soil more when lateral offsets are larger, power loss increases.

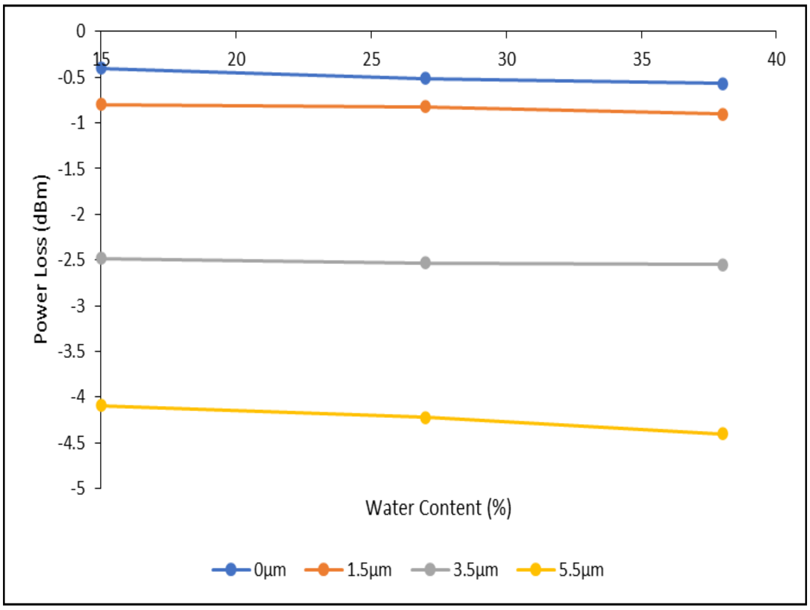


Fig. 5 Relationship between power loss and water content for medium sand

On the other hand, Fig. 5 shows that medium sand exhibits a comparatively constant power loss as the water content rises. The power has a very minor decrease trend at 0 µm and stays about -0.5 dBm. Likewise, power loss at 1.5 µm is constant at -1 dBm. As water content rises, power loss for 3.5 µm and 5.5 µm remains relatively constant at about -2.5 dBm and -4.5 dBm, respectively. The coarse texture and reduced water retention of medium sand, which lead to weaker interactions between water molecules and electromagnetic signals, are responsible for this stability. Since signal attenuation is constant across places, lateral offsets have less of an effect on power loss in sand than in clay.

Table 2 illustrated the sensitivity and linearity for each sample. The performance analysis of the fiber optic displacement sensor for clay soil and medium sand shows distinct differences in sensitivity and accuracy depending on the lateral offset. For clay soil, the optimal performance occurred at a lateral offset of 3.5 µm, where the sensor recorded its highest sensitivity of -0.0135 dBm/% and strong linearity with an R^2 value of 0.9803. This result indicates that the sensor was most effective at detecting changes in water content at this offset. In contrast, lower offsets, such as 0 µm and 1.5 µm, yielded reduced sensitivity values of -0.0031 dBm/% and -0.0018 dBm/%, respectively, showing a diminished response to water content variations.

Table 2 Sensitivity and linearity for each sample

Lateral Offset (µm)	Clay Soil		Medium Sand	
	Sensitivity (dBm/%)	Linearity (R^2)	Sensitivity (dBm/%)	Linearity (R^2)
0	-0.0031	0.9534	-0.0074	0.9797
1.5	-0.0018	0.9359	-0.0043	0.8768
3.5	-0.0135	0.9803	-0.0031	0.9534
5.5	-0.0017	0.9093	-0.0134	0.9862

For medium sand, the sensor performed best at a lateral offset of 5.5 µm, achieving a sensitivity of -0.0134 dBm/% with an impressive linearity of $R^2 = 0.9862$. This suggests the sensor was highly accurate and responsive to water content changes at this offset. At a lower offset of 0 µm, the sensitivity was -0.0074 dBm/%, which still demonstrated good linearity ($R^2 = 0.9797$) but did not match the performance at 5.5 µm. These results reveal that clay soil, with its finer particles and greater water retention, performs optimally at a mid-range offset of 3.5 µm, whereas medium sand, characterized by larger particles and lower water retention, requires a higher offset of 5.5 µm for peak performance.

4. Conclusion

The results confirm that the sensor can detect minor changes in moisture content, supporting future optimization of the lateral offset range to improve its performance. While the current findings do not claim superiority over other sensors, they validate the sensor's potential and functionality for detecting subtle moisture variations. After thorough calibration and testing, the sensor demonstrated high sensitivity and consistent performance, making it a reliable tool for accurate soil moisture measurement. This conclusion is supported by data showing strong linearity across various conditions. The study also aimed to characterize how lateral offsets (0 µm, 1.5 µm, 3.5 µm, and 5.5 µm) affect sensor sensitivity and linearity in different soil types. Results revealed that offsets significantly influence sensor performance, with medium sand optimal at a 5.5 µm offset and clay at 3.5 µm. Finally, the sensor's effectiveness was evaluated at various water content levels, performing well in medium sand ($R^2 = 0.9862$) and clay ($R^2 = 0.9803$) based on specific offsets.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Nuralia Zulkapli;* ***solve the governing equation:*** *Nuralia Zulkapli, Nurul Nadia Adnan;* ***data collection:*** *Nuralia Zulkapli;* ***analysis and interpretation of results:*** *Nuralia Zulkapli, Nurul Nadia Adnan;* ***draft manuscript preparation:*** *Nuralia Zulkapli, Nurul Nadia Adnan. All authors reviewed the results and approved the final version of the manuscript.*

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