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Groundwater level monitoring using a plastic optical fiber

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ABSTRACT

The present work describes the testing and application of a low cost plastic optical fiber sensor on the monitoring of groundwater levels. Two sensors with different grove depth (½ and ¼ of the core thickness) and a resolution of 20 cm along 2 m of the optical fiber were produced and tested. The sensors were tested under two experimental setups: water level variation (increasing and decreasing of the water level) and groundwater increase simulation, in a soil column. The analysis of the optical signal's amplitude and its variations due to the increasing or decreasing of water level showed that both tested sensors presented an appropriate performance and adequate sensibility to groundwater level variation and, therefore, can be used for in situ applications of monitoring.

1. Introduction

Especially after the turn of the millennium, a high number of sensors for monitoring applications were developed worldwide, as sensors for monitoring of strains, accelerations, temperatures, displacements crack evolutions and corrosion process [1]. Also, a high number of application cases, where different kind of sensors were employed for structural assessment in real structures, are reported in the literature [2]. Usually these monitoring case studies mention applications in bridges, highways, pipelines, turbines and offshore platforms [3]. However, monitoring advances focused to application on foundations elements are careless reported, especially if optical technologies were considered.

Comparative studies between electrical sensors and fiber optical sensors, for structural monitoring, performed on different types of civil engineering structures (adobe wall, steel footbridge and a reinforced concrete water reservoir), showed that the optical sensors has similar performance in dynamic and static tests to his electric counterpart [4]. According to André et al. [5], during the construction of a reinforced concrete building, optical fiber sensors based in fiber Bragg grating (FBG) were employed for structural monitoring of the concrete strain evolution and the concrete temperature, and the results presented high confidence and accuracy, nonetheless the authors observed that the adoption of especial protection is necessary to improve the performance of the sensors and to protect it from mechanical impacts or fiber wear provoked by concrete pH. In complementary way, the work developed by Li et al. [6] also employed optical sensors for structural monitoring, but the results collected by these authors showed that temperature changes and strain data might be used for the understanding of the structural behavior in the real time and also for the structural risk prediction.

It is important to highlight that the optical fiber sensors were introduced in SHM due to their advantages when compared with other measurement devices, such as: no interference from external electromagnetic fields, electric isolation (passive operation with no electrical power needed at the measuring point), possibility to use a high number of sensors in the same fiber (multiplexing), and reduction of the implementation and maintenance costs, and, due to these advantages, a large number of the structural monitoring applications, using optical fibers have already been described, as reported by Kostecki et al. [7], Laing et al. [8], Antunes et al. [9], and in the references therein.

Beyond the application in structural assessment, the optical fibers have been used to evaluate material performance, as well

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as to monitor the concrete curing process [5]. However, in order to provide high sensor systems durability and to ensure good performance, it is recommendable that the sensors are designed to resist aggressive environmental conditions [6], for example the presence of salts and water pressure.

Considering the development and application of optical sensors on foundation elements monitoring, the water level monitoring is an important topic for SHM in civil engineering applications and geotechnical studies, due to the variety of applications, such as measurement of the water reservoir level and groundwater level monitoring.

Especially in reinforced concrete structures, the foundation elements are exposed to the humidity effect, and this might accelerate the occurrence of damage like corrosion. Other than the durability aspect, the water level monitoring is important in the observation of soil characteristics with direct impact on the engineering project, and this can be done during the design phase, before any works have begun. Moreover, natural hazards like typhoons and floods can make increase the water level in the soil mass, reducing the soil strength and influencing the stability of slopes and structures; for these cases, special maintenance procedures are needed to preserve a safe condition.

Traditionally, water level measurements in real time are implemented using pressure transducers inside sealed piezometric tubes, however, recent developments in the sensors' technology have enabled the use of optical fibers for water level measurement. One recent example of the application of optical sensors based on FBG for sea level prediction is the monitoring system presented by Ferreira et al. [10] based on measures changes in the optical spectral properties. Another recent application is the prediction of a liquid level through of a distributed sensing system based in temperature measurements, as mentioned by Peng at al. [11]. In Ref. [12] a group of plastic optical fiber (POF) segments, aligned and equally spaced was proposed as a low-cost water level sensor, taking into account the different transmission coefficients between water and air. In fact, POF presents a higher optical loss than silica fiber, nonetheless, such sensing systems are designed for the interrogation unit to be a few meters away from the sensor head, not for remote monitoring at bigger distances. For example for short-distance applications [13], others fiber properties also should be taken in account, as can be cited the low-cost, high flexibility, large diameter and easy manipulation [14], and this characteristics have motivated the employment of POF for sensors development, as can be noted in Refs. [12,15,16].

In the literature, some others optical sensors for water level monitoring had been described beyond the above mentioned works, as can be seen in Refs. [14,15,17]. However, these sensors need a complex monitoring system for work and also the sensor's configurations do not allow the application on aggressive environments. Thus, the main goal of the present work is the proposal of a simplified optical monitoring system focused on water and groundwater level monitoring that can be submitted to work under aggressive environments without sensibility losses, with easy application and low cost of production and implementation.

2. Sensor, setup and experimental program

The implemented sensors, here assigned as S025 and S050, have a total length of 5 m of optical plastic fiber, essentially composed by polymethylmethacrylate. The sensing portion starts on one end of the fiber and has 2 m in length, with groves spaced at every 0.2 m. The diameter of the fiber employed was 1 mm (Avago Technologies HFBR-RUS100Z) and the groves had a depth of 0.25 mm in sensor S025 and 0.5 mm in sensor S050. The opposite extremity of the fiber (without grooves) was connected to the data acquisition system.

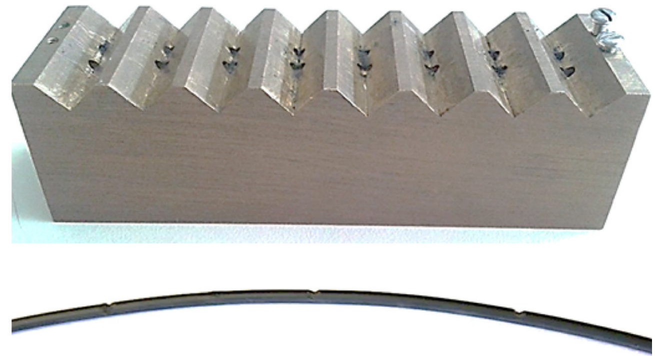

Fig. 1. Brass mold used to create the grooves in the POF, and a detail of the POF with the grooves is shown below the mold photograph.

The decision about the sensor design was based in the main idea of to provide a most simplified sensing system for water level monitoring. This same direction has been defended by others works, as can be cited [18,19].

A standard plastic optical fiber is composed of three concentric layers, named: the protective layer, the cladding layer and the core. The protective layer and the cladding layer provide physical and chemical isolation of the core fiber from the environmental action, while the core of the fiber is responsible for signal passage. When grooves are introduced, along the fiber and the core is exposed, each groove is responsible for provoking a signal loss, due to the local change in refractive index between the fiber core and the environment. If the grooves are filed by a material that presents a refractive index similar to the fiber core, like water, the signal losses will decrease according to the number of grooves being progressively filled or vice-versa.

The principle applied in this experimental work is based on the fact that the contact between the water and the fiber grooves promotes a decrease in signal dissipation when compared with air. A similar application of this principle was used on a case of concrete curing monitoring [5].

The grooves were made manually, with a sharp knife and a brass mold, that allow the grooves to be made with a minimum spacing of 1 cm and depths of half and/or one quarter of the diameter of the fiber (Fig. 1). The presence of a groove in an optical fiber disturbs the propagation of the optical signal to the external region, interacting with the surrounding environment and inducing an additional optical signal attenuation. When the space on the groove is filled with a substance with a refractive index closer to the refractive index of the fiber core, the amount of light propagated increases, therefore the optical signal measured will increase.

Considering the sensor disposition in the soil test column and the simulation of the water level increase, the liquid fulfilling the grooves refractive index is different from the POF core index, changing the propagation of the optical power. Therefore, the optical signal power transmitted depends on the refractive index of the fluid. If the fluid's refractive index does not change during the acquisition, for each fulfilled groove, the transmitted optical power increases. A plastic fiber with several grooves, placed perpendicularly to the liquid surface, can act as a sensor. When the liquid rises it will sequentially fulfill each groove, increasing the transmitted optical power.

The data acquisition system used is composed of four identical channels, each one with a LEDs emitting at 670 nm (IF-E96, Industrial Fiber Optics Inc., USA) and four photodetectors channels (FB120-ND, Industrial Fiber Optics Inc., USA). The control module comprises of a 16-bit microcontroller (model PIC24FJ256DA206 from Microchip Technologies) with a 16-bit ADC, operating within a 2.5 V range and resulting in a resolution of 38.15 μV. It can be