Groundwater level monitoring using a plastic optical fiber

Esequeil Mesquita a,∗, Tiago Paixão b, Paulo Antunes c, Francisco Coelho d, Pedro Ferreira e, Paulo André f, Humberto Varum a

a CONSTRUCT-LESE, Faculty of Engineering of the University of Porto, Department of Civil Engineering, 4200-465 Porto, Portugal
b Department of Physics, University of Aveiro, Campus of Santiago, 3810-193 Aveiro, Portugal
c Instituto de Telecomunicações and Department of Physics, University of Aveiro, Campus of Santiago, 3810-193 Aveiro, Portugal
d Department of Civil Engineering, Universidade Estadual Vale do Aço, Campus da CIDAO, 62.040-370 Sobral, Brazil
e Department of Civil, Environmental and Geomatic Engineering, University College of London, Lower Street, WC1E 6BT London, United Kingdom
f Instituto de Telecomunicações and Department of Electrical and Computer Engineering, Instituto Superior Técnico, Technical University of Lisbon, 1049-001 Lisbon, Portugal

A R T I C L E   I N F O
Article history:
Received 18 August 2015
Received in revised form 15 January 2016
Accepted 25 January 2016
Available online 28 January 2016

Keywords:
Groundwater level sensor
Plastic optical fiber
Liquid level measurement
Groundwater monitoring

A B S T R A C T
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 groove depth (1/3 and 1/4 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.

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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 special 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
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 et 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], other 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 in 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 grooves spaced at every 0.2 m.

The diameter of the fiber employed was 1 mm (Avago Technologies HFB-RUS100Z) and the grooves 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.

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 fulfil 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
controlled remotely, paired with a computer via a wireless system (module MiWiTM-P2 P from Microchip Technologies), or through a USB cable connection, with the data acquisition and the analysis performed in real time. In this work, the data acquisition was done using the USB connection to collect the optical signal power.

For field monitoring, the system has a battery and the capability of recording data on an SD card. The optical signal is received and processed through a computational management system developed on Labview®.

Initially the two sensors (S025 and S050) were attached along a rebar using adhesive tape (Fig. 2b). The rebar with the sensors was then installed in the center of the test column, leaving the fiber extremities outside, to be connected to the control module; a baseline or an initial reading was taken immediately after installation. Following the installation, the water level was raised in steps of 0.2 m until the final height of 2 m. The reading corresponding to each step was taken once the optical signal was stable, with the stabilization time varying depending on the time test type. After this, the reverse procedure was carried out, in order to check and analyze the changes in the optical signal due to the reduction of the water level. The experimental tests, were performed twice for each situation, namely water increase, water decreasing and groundwater increase (tests A and B), in order to demonstrate the repeatability and accuracy of the results.

The column used in this experiment was made of an external steel frame, holding 3 side panels made of glass and one made of steel with 8 channels for water input. The internal dimensions are 0.40 m × 0.40 m × 2.00 m (Fig. 2a). The aim of this test was to assess the changes in the optical power by varying the water level.

In order to simulate the groundwater variation, the column (Fig. 2c) was filled with sand up to the top. The sand used had an initial moisture content of 1.9% and its grain size distribution is shown in Fig. 3. As in the previous test, once the sensor and soil were in
place, the baseline readings were taken and the water level raised and lowered following the same procedure explained previously.

3. Results

Both sensors (S050 and S025) were initially tested without soil and later with soil. For every step (either raising or lowering the water level by 0.2 m) a measurement of the optical power passing through the fiber was performed, typically after a 15 min stabilization period. After the water was raised to its maximum level a 30 min resting period was used before starting to lower the water level. The test results are shown in Figs. 4 and 5 where the letters A and B at the end of each sensor designation, indicate the test for which the data was acquired, for instance S050A stands for the S050 acquired data during test “A”, the AV designation indicates the average data of A and B tests for the sensor.

As expected, an increase of the optical signal power occurred with the rise of the water level and the opposite occurred when the water level decreased. In fact, changes in the optical power presented a proportional relationship with the water level increase or decrease. Essentially, this phenomenon occurs due to the fact that the water refraction index is higher than the air refraction index and, as the grooves are submerged and the air is expelled from the grooves by the water, the local refraction index change and more optical power is required. However, the optical power measurements in the two sensors also can be affected by several factors, as the characteristics of the LED emission, photodetector accuracy, POF length, the number and deep of the grooves carved along of the optical fiber and by sand grain size distribution. The particles size of the sand can influence the amplitude of signal variation and the time of signal stabilization, especially considering that the fiber grooves can be filled by some sand grains. Essentially, this situation can occur if the soil be composite by silts or clayey (particles diameters < 0.05 mm). An alternative for the case in that the soil grain particles are really fine (particles diameters < grooves diameters), when the possibility of fiber grooves be fill by sand grains are high, is to involve the optical fiber with a filter layer.

Temperature changes can also influence the measurements. This way, compensation measures should be adopted, one possibility is to place a similar POF fiber, without grooves, close to the one acting as a sensor. Such fiber with serve as a reference, and the signal changes on that fiber will be due to temperature effects (or other, such as emission LED optical power fluctuation) and can be compensated on the sensing fiber.

The average optical power change per groove observed during the water level increase was of 0.0717 u.a. for S050 and 0.0306 u.a. for S025.
for S025. Now, in relation to the water level decrease, the average changes in the optical power presented values in order of 0.0385 u.a. and 0.0380 u.a. for S050 and S025 respectively.

It was also noted that, during the water level increase, the optical power presented the highest variability in values when compared to the values collected during the water level decrease. If the values of the optical power measurements of S050 and S025 were compared between them, the average variation per groove will be of 0.0407 u.a. for the water increase simulation and 0.005 u.a. for the water level decrease test.

Considering that when the decreasing water level test was done, after the water level increase test, and based in the linear variation of the optical power measured, it is correct to say that the stabilization time has an influence on the optical signal calibration. During the experiments it was observed that sensor S050 required around 20 min less time for the stabilization of the optical signal than sensor S025, while the water level was being raised. It is the authors believe that this is related to the difficulty offered by the grooves to the penetration of the water (e.g., the bigger the size of the grooves), the easier it is for the water to occupy this space, requiring, therefore, a lower stabilization time; another important consideration is how the surface tension influences the flow of the water in and out of the grooves. However, considering that the contact between water and soil can provoke the emergence of points of different pressures, and resulting in water capillarity ascension, the time of 20 min can be considered ideal for avoid measure mistakes.

Additionally, the results showed that the optical power readings of sensor S025 are more sensible to water variation than the
readings from sensor S025. This is also due to the greater depth of the grooves, which allow a higher amount of optical radiation to be lost to the outside of the fiber. The optical power changes, observed during the water level increase simulation, in the column test, showed variations of the order of 0.1461 u.a. for sensor S050 and of 0.0675 u.a. for sensor S025. The level of confidence of the linear fit applied to the results obtained for the water increase test, is of 95% for sensor S050 and 96% for sensor S025.

The second part of this experimental program was dedicated to simulate the groundwater level in the soil. During the test in a soil column, the optical power presented a similar linear behavior like the one observed in the tests without soil. The time needed for signal stabilization was around 1 h for each measured point. The results from this experimental setup are presented in Fig. 6.

Measurements with sensor S050 presented a smaller change between the water level points due to the biggest groove depth. This can be explained by the influence of the initial moisture content of the sand on the measurements of the optical signal. The size of the grooves on S025 present a higher resistance to the penetration of water due to its smaller size, therefore, given its area, it is easier for water entering into the sensor S050 groves. Also, the sand humidity should be considered because it can affect the signal amplitude variation, as observed in the results water rising in the soil column test (Fig. 6).

Initially, the sand humidity did not promote any changes in the optical signal transmitted by S025, but during the experiment, when the water rises on the optical fiber, fulfilling the grooves, a signal increase was noticed, as expected.

However, the sand humidity can influence the optical signal attenuation according with the groove area. Before the water rising started, the optical signal of S050 was influenced by sand humidity and when the experiment was carried out the signal transmitted by S050 showed lesser changes than the signal transmitted by S025. Additionally, due to optical fibers composition, namely poly-methylmethacrylate, which is a hydrophobic material, the water pressure effect on the groove fulfillment must be considered. For smaller area grooves, the needed water pressure for a full contact between the water and the hydrophobic material (to fully fulfill the groove) must be superior than for higher area grooves [20]. Such explanation, justifies the difference between signal amplitude changes of sensors S050 and S025, when submitted to the soil column test.

The calculus of the pressure necessary for the water penetration in the optical fibers grooves of sensors S050 and S025 can be gathered through expression 1 [20], where $\gamma$ is the surface tension and $\theta$ is the contact angle, and $r$ is the radius of the groove.

$$P = -2 \times \gamma \times \cos(\theta)/r$$

(1)

Considering $\gamma=0.072$ Nm$^{-1}$ (for water), $\theta=120^\circ$ (for polymeric materials), $f_{S050}=0.0025$ m and $f_{S025}=0.00125$ m, the necessary water pressure for penetration in the fibers grooves is 57.6 Nm$^{-2}$ and 28.8 Nm$^{-2}$, for sensors S025 and S050, respectively. Nonetheless, the opposing phenomenon, the pressure force required for water to exit the grooves, was also observed.

Indeed, the average between the changes in the optical power during the water level increase test, by comparative analysis between the values of the optical power, collected when the water level was at the base (or 0.00 m) and when it was at the top (or 2.00 m), were of 0.0035 and 0.0131 for S050 and S025. In this experiment, the sensor S025 presented higher sensitivity and a better linear behavior than the results by the sensor S050.

The confidence level of the linear results, measured during the water level increase simulation, in the soil column, were of 96% for S025 and 81% for S050. It was also observed that the sensor S025 needed 20 min longer for the signal stabilization than S050.

If the measurement points of the optical power were compared between S050 and S025, namely 0.0073 u.a. and 0.0247 u.a., one can perceive that the optical signal of sensor S025 is 3.37 times more powerful than the optical signal of sensor S050. This observation about the optical signal is particularly important because it shows that potentially sensor S025 will present a better performance at greater depths than sensor S050, considering that the same signal power is used for both sensors.

However, in respect to sensor’s work, due to possibility of the sand grains fill the optical fibers grooves, it is recommended that the sensors be watched on clean water always that the signal amplitude does not presents significant variations when the liquid level changes.

Additionally, the dispersions between all results collected in the test column and all the linear fits are plotted in Fig. 7. It can be seen that the results showed a low dispersion between them. In fact, this endorses the linearity behavior of the optical power when submitted to changes in the water level both in the presence or absence of soil.

4. Conclusions

The proposed water level sensors, presented a suitable performance for measurement of variations on water level, with an adequate sensitivity, based on changes on the optical power. The two proposed sensors can be used for in situ applications of water level monitoring. However, the sensor S025 presented better signal performance than S050.

The advantages of employing such sensors, in structural health monitoring systems, to monitor groundwater levels, are the simplicity of the measurement system and a suitable sensitivity, added to the low manufacturing, interrogation and maintenance costs.

Acknowledgments

Esequiel Mesquita acknowledge CAPES through the fellowship number 10023/13-5, Fundação CAPES, Ministério da Educação do Brasil. Paulo Antunes acknowledge Fundação para a Ciência e Tecnologia (FCT) for the Postdoctoral fellowship SFRH/BPD/76735/2011.

References

Biographies

Esequiel Fernandes Teixeira Mesquita was born in Irauçuba, Ceará, Brazil, on April 1989. In 2012 he received the bachelor degree in Civil Engineering by Universidade Estadual Vale do Açaí. He is PhD-student in Civil Engineering at Faculty of Engineering of University of Porto with doctoral fellowship from CAPES Foundation, Ministry of Education of Brazil. He has experience in materials characterization and durability of reinforced concrete structures, and he current research interests include structural health monitoring, optical sensors, structural risk assessment, structural safety maintenance, assessment, strengthening and repair of existing structures and built heritage conservation.

Tiago de Brito Paixão was born in Lagoa, Portugal, on June 1991. He received a Physics Engineering degree in 2014 from Universidade de Aveiro. Currently he is attending a Master’s degree in Physics Engineering at Departamento de Física from Universidade de Aveiro, Aveiro, Portugal. He is current research interests include the study of optical fiber sensors for pressure, level and acoustic measurements.

Paulo Fernando da Costa Antunes was born in Melhada, Portugal, on May 1977. He received a Physics Engineering degree in 2005, the M.Sc. in Applied Physics in 2007 and the PhD in Physics Engineering in 2011 from the Universidade de Aveiro, Portugal. Currently he is working under a post-doctoral research fellowship from Fundação para a Ciência e a Tecnologia in the Instituto de Telecomunicações and in the Departamento de Física from the Universidade de Aveiro, Aveiro, Portugal. His current research interests include the study and simulation of fiber Bragg gratings, optical fiber sensors for static and dynamic measurement, data acquisition, and sensor networks for structural monitoring.

Francisco Carvalho de Arruda Coelho was born in Sobral, Brazil on September 1956. He received the bachelor degree in Civil Engineer in 1979 by Universidade de Fortaleza and in 2001 concluded your PhD in Ingeniería de Caminos, Canales y Puertos by Universidad Politécnica de Madrid. He is Professor with Universidade Estadual Vale do Acaraú and President with Instituto de Estudos dos Materiais de Construção (IEMAC). He is expert in materials and construction components and actually your interests are focus in pathology and reinforcement of the structures, damage characterization and durability of the reinforced concrete.

Pedro Miguel Vaz Ferreira was born in Luanda, Angola, on October 1971. He graduated in Civil Engineering in 1995 and, in 2002, he obtained his doctorate degree in Geotechnical Engineering by the Universidade Federal do Rio Grande do Sul in Porto Alegre/RS, Brazil. He is a lecturer in Geotechnics at the Civil, Environmental and Geomatic Engineering Department at University College London. His research interests focus on laboratory single element testing on composite and natural geotechnical materials and the development of instrumentation to better understand soil–structure interaction.

Paulo Sérgio de Brito André was born in Luanda, Angola, on April 1971. He received the Bachelor in Physics engineering in 1996, the PhD degree in physics in 2002 and the Agregação title (habilitation) in 2011, from the Universidade de Aveiro, Portugal. In 2013, he joined the Instituto Superior Técnico, University of Lisbon, as an Associate Professor, where he is lecturing courses on Telecommunications. His current research interests include the study and simulation of photonic and optoelectronic components, optical sensors, integrated optics, photonic graphene applications, and passive optical networks. Paulo André is a senior member of the Institute of Electrical and Electronics Engineers (IEEE).

Humberto Varum was born in Salreu, Portugal, on October 1970. He is Full Professor in the Structures Division of the Civil Engineering Department at University of Porto, Portugal. He is engaged in large-scale experimental testing and nonlinear analytical modeling of structural systems. In his teaching, he has specialized in the seismic engineering, theory of structures, and conservation of structures. His current research interests include assessment, strengthening and repair of existing structures, structural testing and modeling, reliability of structures, earthquake engineering, and built heritage conservation.