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Distributed Optical Fibre based Pore Water Pressure Sensor for Early Warning of Geohazards

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ABSTRACT: Geohazards due to the increase of pore water pressure are adverse geologic conditions capable of causing widespread damage or loss of property and life. To predict the potential consequences of rising water pressure in the subterranean, modest and more accurate methods are necessary. Recent advances in optical fibre sensors enable spatial continuity along with fibre, which is incapable of discrete sensing systems. In this study, the ability of a distributed optical fibre sensor embedded into three silicone rubber membranes in series has been tested for pore water pressure measuring. A backscattered reflectometer has been used to measure the strain variations along the optical fibre. Subsequently, the strain variations along the membranes have been analyzed against the water pressure. It was revealed that the measured strain readings are proportional to the applied hydrostatic pressure. Accordingly, real-time measurements can be obtained frequently from a remote location as the optical fibres can transmit the measured data for long distances.

1. INTRODUCTION

The high content of moisture: saturated or partially saturated thus the presence of water pressure is a significant factor out of many that affect land stability. Increased pore water pressure in the soil can weaken it and increase its tendency to deformation or failure. This happens as the water pressure pushes the soil particles away followed by the reduction of effective stress between soil particles. (Gholamzade and Khalkhali 2021)Basalt samples from Deccan have shown with the increasing amount of moisture content in the soil a significant exponential decrease of tensile strength, Young's modulus and uniaxial compressive strength while with a linear decrease in cohesion and Point load index. (Verma, Thareja, and Singh 2014) As a result, the soil loses its ability to withstand the shear stress thus causing disasters: landslides, erosion, liquefaction or any other form of instability. However, the relationship between water pressure and land stability is quite complex, non-linear and uncertain. (Zhao et al. 2016; Perrone et al. 2008)

The evaluation of the water content in the soil is quite challenging, yet has been carried out using soil moisture sensors (TEROS 10 and TEROS 12 measure volumetric water content) (Peranić, Čeh, and Arbanas 2022), standpipe piezometer (Picarelli et al. 2022), tensiometer (Ridley and Dight 2015), Micro-Chilled-Mirror Hygrometer (Watanabe et al. 2012) pneumatic or electrical sensors based on strain gauges or vibrating wires (Schenato et al. 2016). Anyhow these methods are to be pointed sensing (not capable to extend to long-range sensing) and indirect methods of measuring pore water pressure.

In evaluating the impact of pore water pressures on slope stability Perrone et al. have been using Casagrande piezometers at different depths and full-length inclinometers in clayey silt followed by calcarenite formation, assuming zero water pressure at the ground level. The study highlights that porewater pressure depends on stratigraphy and soil properties and greatly affects ground stability. (Perrone et al. 2008).

The ability of large range applications, minimal invasiveness and remote powering make it possible to use optical fibre cables in pressure sensing; either Distributed Optical Fibre Sensing (DOFS) of Fibre Bragg Grating (FBG). In structural health monitoring also, pressure has been set as a parameter of monitoring. OFS (Optical Fibre Sensing has been widely used in leak detection in industrial pipelines in terms of pressure. Meanwhile, pressure sensing with OFS has been highly effective in pressure regulation in certain valves in pipe networks. (Jayawickrema et al. 2022)

Since uncoated optical fibres are nearly insensitive to the hydrostatic pressure the best way to make a measurement is to convert that pressure into another parameter; strain or birefringence that can be achieved by optical fibres. (Schenato et al. 2020). The widely explored method for water pressure sensing using an optical fibre sensor is based on the principle of Fabry-Perot interferometry. a Fabry-Perot cavity has two reflecting surfaces that reflect a portion of the incoming light back and forth. Changes in pressure cause the cavity's length to shift, changing the interference pattern of the reflected light. By monitoring this shift, it is possible to determine the water pressure. (Niu et al. 2022) (Friedemann, Voigt, and Mehner 2022).

Recent studies have explored the use of various materials for membranes, such as silica (Zhang et al. 2014) and aluminium foil (Niu et al. 2022). Additionally, multilayer membranes composed of silicon dioxide, platinum, and aluminium nitride have also shown promise (Friedemann, Voigt, and Mehner 2022). Other than that an advantageous method is measuring the pressure induced strain in a membrane: rubber, nitrile rubber, carbon fibre, polyurethane or stainless steel. (Aime et al. 2021). The method of embedding optical fibres into a flexible membrane has been tried by Aime et al. (2021), Wong et al. (2018) and Schenato et al. (2016) with temperature compensation at the same time, while Aime et al. (2021) has tasted for a strain sensor composed of an optical fibre cable embedded into a glass fibre reinforced polymer membrane and validates the enhanced pressure resolution in distributed sensing rather than FBG.

In this study, it is aimed to study the capability of extending the use of elastomers to combined with optical fibre cables to identify and measure pressure through a less complex mechanism. Once the sensors are implemented vertically in water prone areas the pressure at different levels below the surface level can be assessed. The extended design includes the outer casing which allows the flow of water to each membrane. With reference to the measured water pressure together with land orientation and the type of the soil, any developing land motion can be identified. Thus, a geohazards can be alerted.

2. MATERIALS AND METHODS

The pressure sensing technology compromises a silicone membrane with an optical fibre embedded in it. In order to determine the correlation between pressure applied to a membrane and its strain in the direction of optical fibre cable placement, a silicone membrane was simulated using Creo Parametric 3D CAD software. As shown in Figure 1, a 35 mm diameter membrane was constrained and the pressure was applied to the mid-region (22 mm, the diameter of the hole of the aluminium square hollow section in the real experiment setup). The pressure ranges from 1 kPa to 10 kPa with a step of 1 kPa which is equivalent to hydrostatic pressure of a water column of 1 m to 10 m with a step of 1 m.

In the simulation process, the maximum strain was plotted against the respective pressure value to develop the correlation between the two parameters. The experiment was followed by the data validation.

In preparing the pressure sensing membrane a 2-

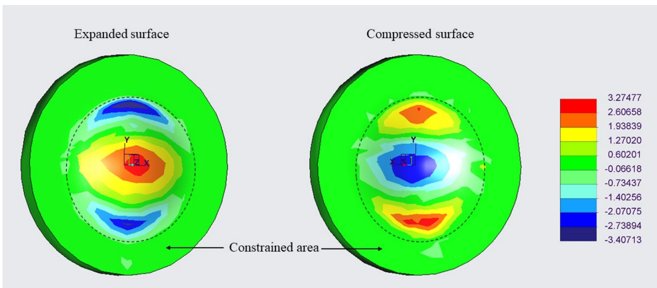

Figure 1. CAD simulation for the silicone membrane and corresponding strain measurements at expanded and compressed sides when the pressure is 5 kPa

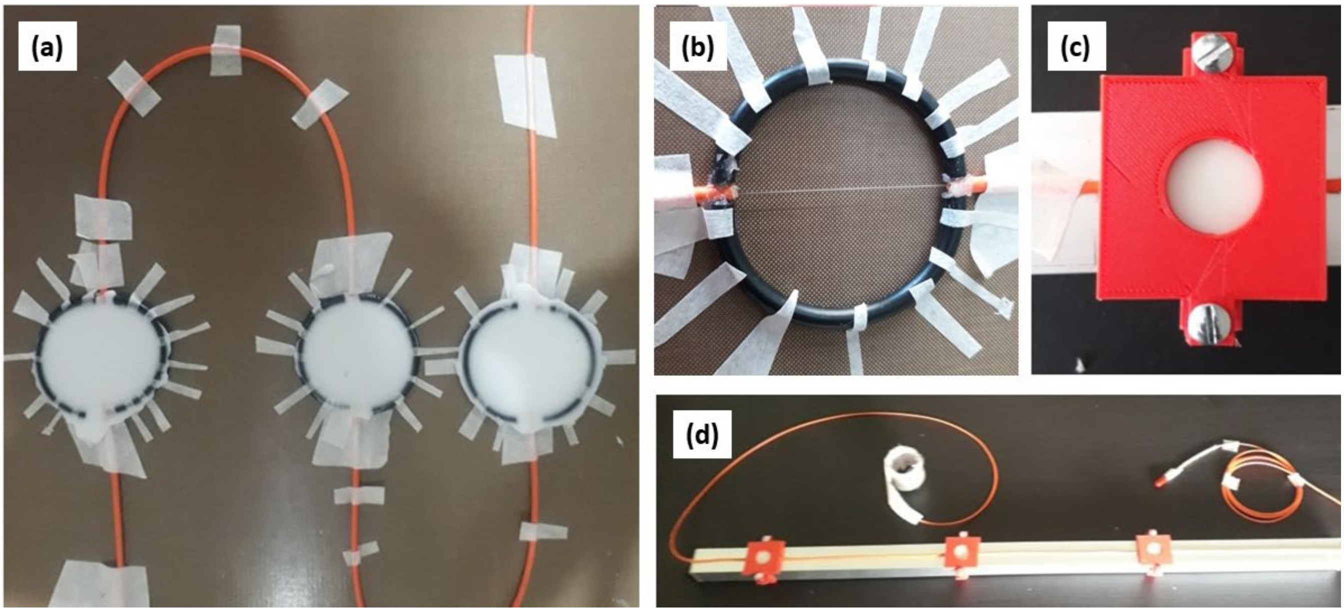

Figure 4. Fabrication process of sensors (a) dried silicone rubber membranes in the moulds (b) bare optical fibre cable before pouring silicone rubber (c) silicone rubber membrane tightened to the aluminium bar (d) fully fabricated sensor array

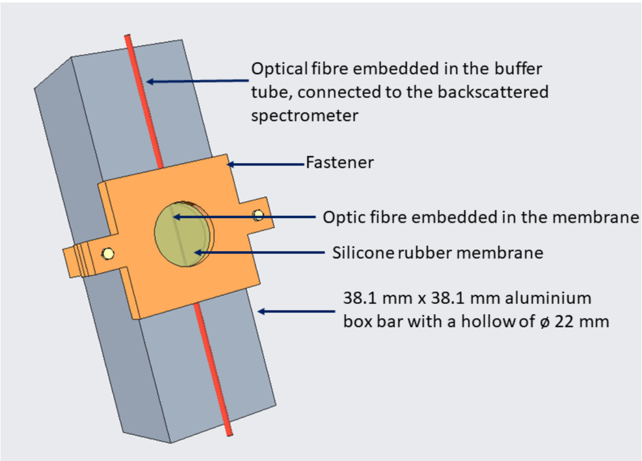

Figure 3. Pressure sensing element mounted on the aluminum square hollow section

part silicone (RTV 586) was mixed with the 2% of the curing agent by weight. Due to its high degree of elasticity, silicone RTV 586 can stretch and deform when subjected to stress before recovering to its original shape when the load has been removed. This material's elasticity allows it to tolerate repeated compression and elongation without permanently deforming. With the addition of 2% of the hardener the tensile strength of the membrane was maintained at 2.28 MPa.

SMF 28 125 μm single-mode bare optical fibres were placed in moulds as depicted in Figure 02 such that the fibre lies in the midplane of the membrane and silicone was poured into the mould. The moulds were kept in the vacuum oven at room temperature for 2 minutes at -0.08 bars to eliminate any air trapped inside. The silicone-filled moulds were pressed between 2 glass plates for 24 hours.

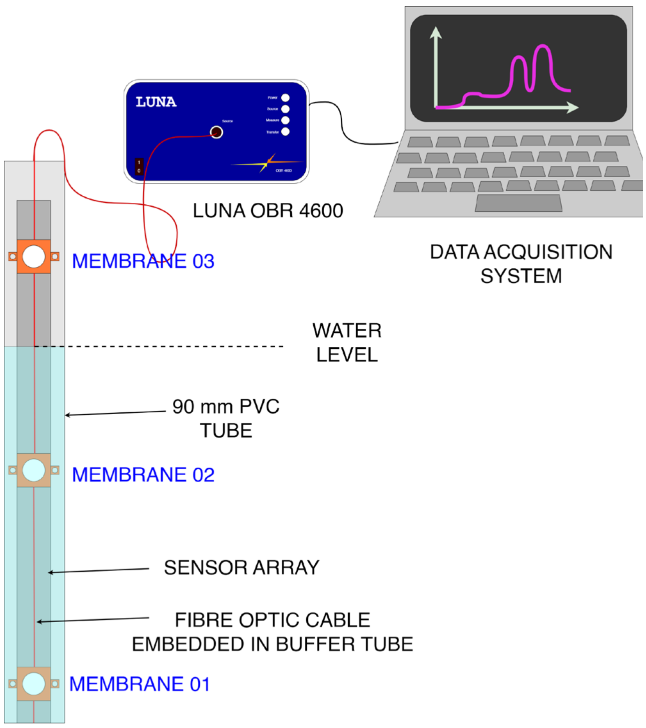

Figure 2. Experiment setup; Water is filled in to the PVC tube and the respective data is collected through the backscattered spectrometer and fed in to the data acquisition system

Then the sensors were mounted on an aluminium square hollow section (SHS). As shown in Figure 3, the aluminium SHS features a 22mm hole located behind the membrane, which enables the membrane to expand. Additionally, the edges of the SHS are sealed to maintain a consistent atmospheric pressure and prevent water from entering. As illustrated in Figure 4, the array of sensors was placed inside a vertical tube.

The sensor was connected to the LUNA OBR 4600. During the data acquisition process the Luna OBR 4600 was configured to be on 1555.870 - 1577.155 nm scan range. The system specifications also include a group index of 1.5, 1 mm spatial resolution and a 10 mm gauge length.

The experimental set-up was built up to induce hydrostatic pressure at each sensor level as described in Figure 4 once the tube is filled with water at different heights the water pressure will be induced on the membrane making the membrane stretched. Since a strain is developed in the membrane.

3. RESULTS AND DISCUSSION

Using the CAD simulation, the correlation between the pressure and the strain was extracted. Figure 5 depicts the stain variation along the membrane in YY direction. The negative values stand for compressions which are expected around the constrained area while the maximum positive strain is achieved in the midpoint of the membrane.

The pressure at the midpoint of the membrane was graphed against the respective strain. As expressed in Figure 6 the strain developed was changing linearly with the pressure allowing the pressure sensing in terms of strain, which is possible with fibre optics.

When the experiment is carried out the strain

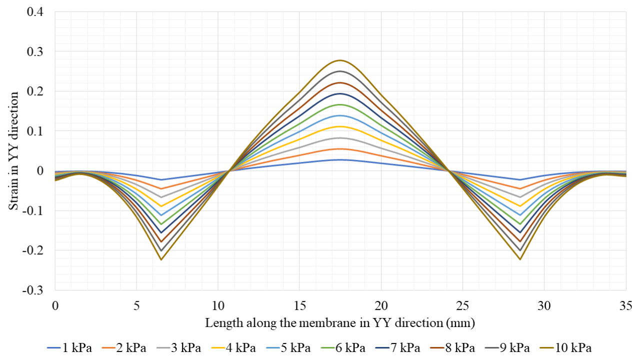

Figure 5. Simulated pressure variation along the membrane from 1 kPa to 10 kPa

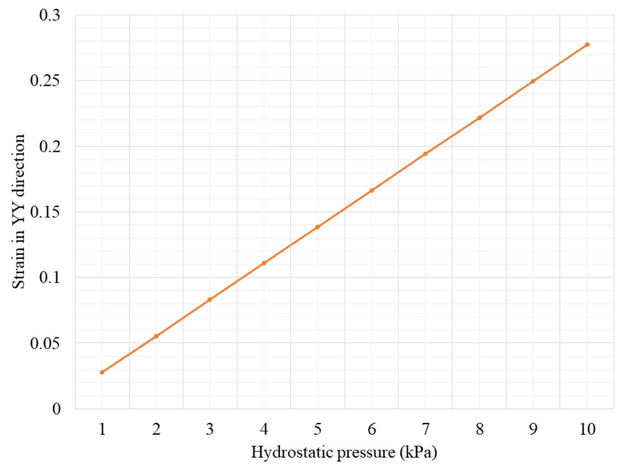

Figure 6. Correlation between pressure and the strain

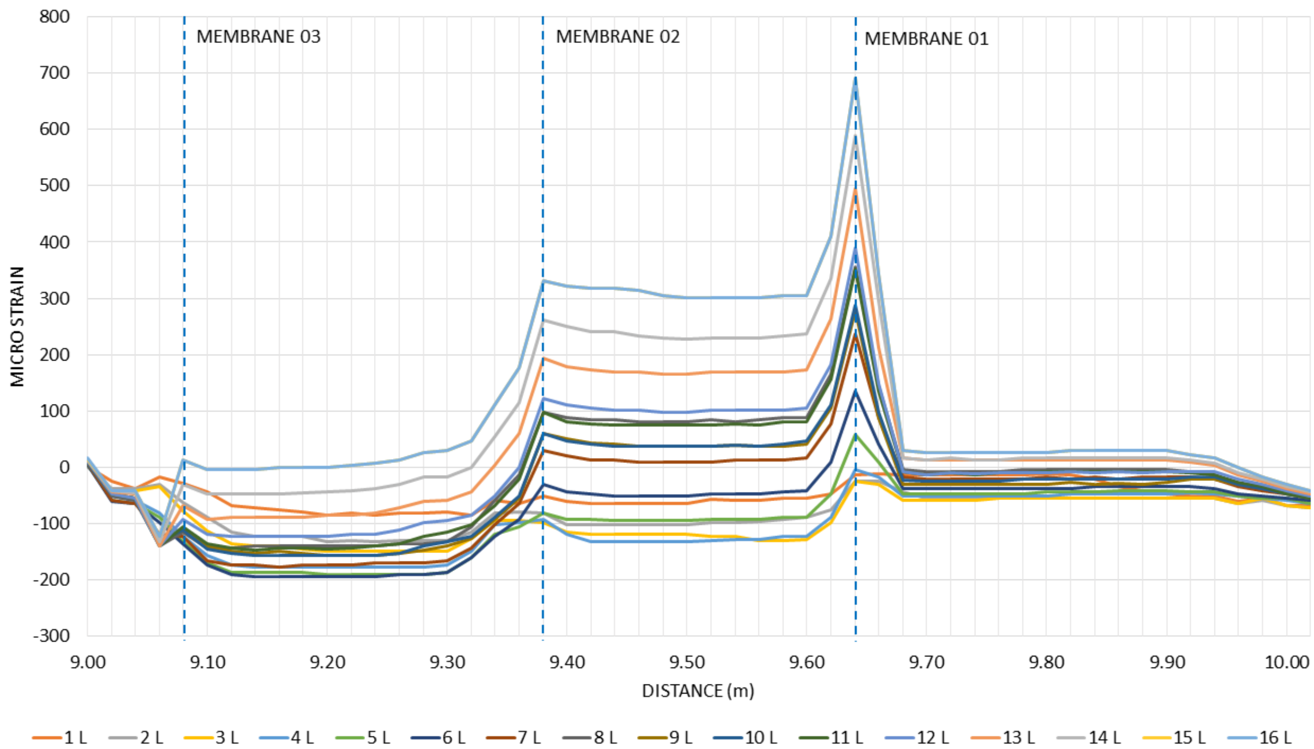

Figure 7. The strain induced in each membrane with respect to the volume of water filled.

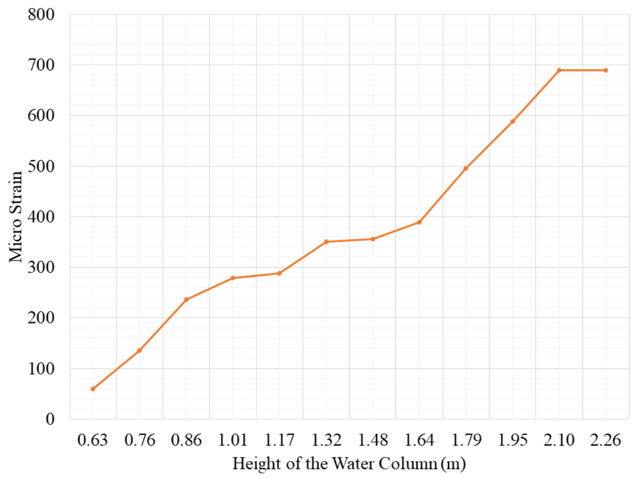

Figure 9. The relationship between the height and the strain.

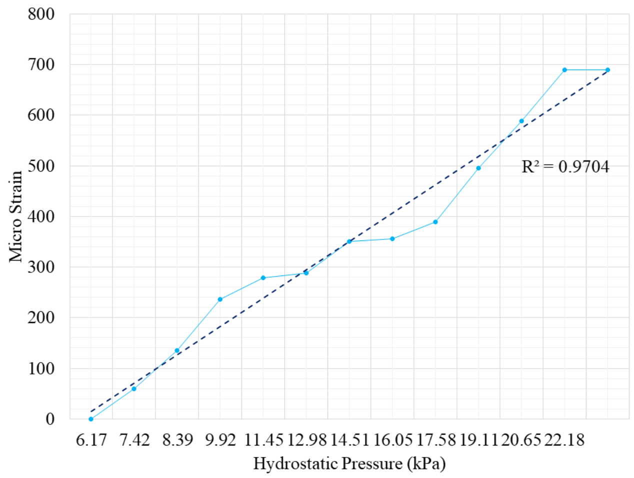

Figure 10. The relationship between the hydrostatic pressure and the strain.

data was extracted with the backscattered reflectometer. The optical fibre span was reduced to the length of the sensor array and the strain induced on the optical fibre cable by the water column was extended to Figure 7. The peaks can be clearly seen from three discrete points as the water column height was increased.

As the height of the water column increases, the pressure acting on the membrane also increases in magnitude. Each subsequent peak has a higher value than the previous one due to that reason. The largest elongation was noticed at membrane 01 because of high hydrostatic pressure.

The strain induced between the hikes are identified as results of tension due to the elongation of two beside membranes. After converting the volume of the water column to its corresponding height, it was calculated the strain at each membrane. Considering the midpoint of membrane 01 in YY direction, readings for the strain

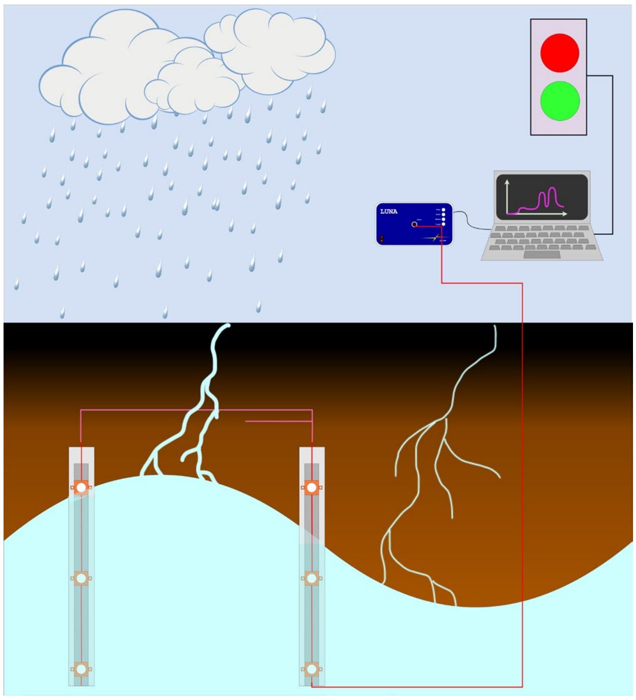

Figure 8. Extended sensor array for future applications

behaviour with respect to the height are graphed in Figure 8. Hence the height and the hydrostatic pressure shows a linear relationship for fluid with constant density, the pressure follows the same curve for fluids with constant density and gravitation acceleration, and the relationship between height and hydrostatic pressure is linear. Hence the pressure follows a consistent curve as the height at all points.

Considering the strain induced in the optical fibre cable as the independent variable and the magnitude of the pressure as the independent variable a linear regression model has been developed as depicted in Figure 9. According to the linear regression model, the R2 is equal to 0.9704; approximately 97.04% of the variance in the dependent variable is explained by the independent variables in the model. The model has demonstrated a remarkable ability to capture a substantial portion of the data's variability and exhibit powerful predictive capabilities, as evidenced by the high degree of goodness of fit.

4. FUTURE WORK

The current setup can be modified to be implemented in watery areas with certain adjustments. Once the underground water penetration is allowed to the membrane series, through the expansion of that the pressure is identified beneath the soil as mentioned in Figure 10.

Through plenty of experiments, a big set of data for pressure can be gathered which can be trained to detect the hazard causing line, thus a geographically unstable conditions can be warned.

5. CONCLUSIONS

In the experiment, the relationship between the hydrostatic pressure and the induced strain is tested while an increment of strain with the pressure is observed. The pressure-strain behavior can be developed into a linear regression model and the behavior is linear. The clear variation of strain in the presence of pressure with a coefficient of determination of 0.9624 makes it possible to extend the setup to measure the water pressure inside the soil with the aid of a proper penetration method of water to the membrane together with calibration.

The proposed sensor has the potential to precisely measure pore water pressure. A model combined with water pressure sensing and land properties can be developed in the future to address any developing geohazards in water prone areas.

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7. REFERENCES

Aime, Laura F J, Thomas Kissinger, Stephen W James, Edmon Chehura, Alberto Verzeletti, and Ralph P Tatam. 2021. “High Sensitivity Pressure Measurement Using Optical Fibre Sensors Mounted on a Composite Diaphragm.” Optics Express 29 (3): 4105. https://doi.org/10.1364/OE.416715.

Friedemann, Marvin, Sebastian Voigt, and Jan Mehner. 2022. “Pressure Sensor Catheter Based on Fiber Tip Fabry-Pérot-Interferometer and Fiber Bragg Grating for Temperature Compensation: Fiber-Optic Hybrid Sensor Catheter for Invasive Pressure Measuring.” Current Directions in Biomedical Engineering 8 (2): 404–7. https://doi.org/10.1515/cdbme-2022-1103.

Gholamzade, Mojtaba, and Ahad Bagherzadeh Khalkhali. 2021. “Slope Stability Analysis Under Pore-Water Pressure: A Case Study in Zarm-Rood Earthfill Dam, Iran.” Preprint. In Review. https://doi.org/10.21203/rs.3.rs-498150/v1.

Jayawickrema, U.M.N., H.M.C.M. Herath, N.K. Hettiarachchi, H.P. Sooriyaarachchi, and J.A. Epaarachchi. 2022. “FIBRE-OPTIC SENSOR AND DEEP LEARNING-BASED STRUCTURAL HEALTH MONITORING SYSTEMS FOR CIVIL STRUCTURES: A REVIEW.” Measurement, June, 111543. https://doi.org/10.1016/j.measurement.2022.111543.

Niu, Panting, Shun Wang, Songyang Zhang, and Rui-Bo Jin. 2022. “Simultaneous Measurement of Water Pressure and Temperature Based on a Simple Fabry-Pérot Sensor.” IEEE Photonics Technology Letters 34 (12): 629–32. https://doi.org/10.1109/LPT.2022.3177221.

“OBR-4600-UG6_SW3.10.1.Pdf.” n.d. Accessed May 9, 2023. https://lunainc.com/sites/default/files/assets/files/resource-library/OBR-4600-UG6_SW3.10.1.pdf.

Peranić, Josip, Nina Čeh, and Željko Arbanas. 2022. “The Use of Soil Moisture and Pore-Water Pressure Sensors for the Interpretation of Landslide Behavior in Small-Scale Physical Models.” Sensors 22 (19): 7337. https://doi.org/10.3390/s22197337.

Perrone, Angela, Roberto Vassallo, Vincenzo Lapenna, and Caterina Di Maio. 2008. “Pore Water Pressures and Slope Stability: A Joint Geophysical and Geotechnical Analysis.” Journal of Geophysics and Engineering 5 (3): 323–37. https://doi.org/10.1088/1742-2132/5/3/008.

Picarelli, Luciano, Caterina Di Maio, Paolo Tommasi, Gianfranco Urciuoli, and Luca Comegna. 2022. “Pore Water Pressure Measuring and Modeling in Stiff Clays and Clayey Flysch Deposits: A Challenging Problem.” Engineering Geology 296 (January): 106442. https://doi.org/10.1016/j.enggeo.2021.106442.

Ridley, A. M., and P. M. Dight. 2015. "Soil Suction — What It Is and How to Successfully Measure It." Australian Centre for Geomechanics. https://doi.org/10.36487/ACG_rep/1508_0.2_Ridley.

Schenato, Luca, Rajendran Aneesh, Luca Palmieri, Andrea Galtarossa, and Alessandro Pasuto. 2016. "Fiber Optic Sensor for Hydrostatic Pressure and Temperature Measurement in Riverbanks Monitoring." Optics and Laser Technology 82 (August): 57–62. https://doi.org/10.1016/J.OPTLASTEC.2016.02.015.

Schenato, Luca, Andrea Galtarossa, Alessandro Pasuto, and Luca Palmieri. 2020. "Distributed Optical Fiber Pressure Sensors." Optical Fiber Technology 58 (September). https://doi.org/10.1016/j.yofte.2020.102239.

Verma, Dhananjai, Rahul Thareja, and T.N Singh. 2014. "Influence of Water Content on Geotechnical Properties of Deccan Basalt, Maharashtra, India." International Research Journal of Geology and Mining 4 (4). https://doi.org/10.14303/irjgm.2014.024.

Watanabe, Kunio, Megumi Takeuchi, Yurie Osada, and Kazumasa Ibata. 2012. "Micro-Chilled-Mirror Hygrometer for Measuring Water Potential in Relatively Dry and Partially Frozen Soils." Soil Science Society of America Journal 76 (6): 1938–45. https://doi.org/10.2136/sssaj2012.0070.

Wong, Leslie, Ravin Deo, Suranji Rathnayaka, Benjamin Shannon, Chunshun Zhang, Wing Kong Chiu, Jayantha Kodikara, and Hera Widyastuti. 2018. "Leak Detection in Water Pipes Using Submersible Optical Optic-Based Pressure Sensor." Sensors (Switzerland), November. https://doi.org/10.3390/s18124192.

Zhang, Yinan, Jie Huang, Xinwei Lan, Lei Yuan, and Hai Xiao. 2014. "Simultaneous Measurement of Temperature and Pressure with Cascaded Extrinsic Fabry–Perot Interferometer and Intrinsic Fabry–Perot Interferometer Sensors." Optical Engineering 53 (June): 067101. https://doi.org/10.1117/1.OE.53.6.067101.

Zhao, Yannan, Yuan Li, Lifen Zhang, and Qiuliang Wang. 2016. "Groundwater Level Prediction of Landslide Based on Classification and Regression Tree." Geodesy and Geodynamics 7 (5): 348–55. https://doi.org/10.1016/j.geog.2016.07.005.