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A ground-breaking Distributed fiber-optic Pressure Sensor for geohydraulic applications

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Abstract

Distributed fiber optic (DFO) technology has provided significant insight into various engineering problems by enabling high spatial resolution and accurate *temperature* and *strain* measurements. Recently, a novel distributed fiber-optic pressure sensor (DPS) has been developed at the University of Applied Sciences of Eastern Switzerland (OST), which may change the paradigm of monitoring geohydraulic structure monitoring. The key innovation of the sensor is its ability to measure *hydrostatic pressure* with high spatial resolution and over long distances.

This study provides a comprehensive characterization of this novel sensor for two different applications. In the first application the DPS was tested in a water column to measure the vertical hydraulic pressure. In the second application the sensor is tested in a laboratory-scale dike (1:4). The DPS was embedded directly into the earth structures, providing real-time monitoring of pore pressure variations during saturation. For both applications, the DPS measurements were compared with conventional pressure and piezometer sensors, demonstrating good agreement.

The results of these two applications illustrate the potential of the DPS to revolutionize geohydraulic monitoring and improve our understanding of dynamic processes in water-related structures. The implementation of this technology promises to improve the safety, predictability, and performance of critical infrastructure.

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1. Introduction

Over the past decade, distributed fiber optic technology (DFO), based on the natural backscattering of the light within the glass fiber, has emerged as a valuable instrument for monitoring civil engineering structures (Inaudi & Glisic, 2005). Its rapid adoption can be attributed to its ability to provide accurate strain and temperature measurements with high spatial resolution over long distances (Hauswirth, 2015). Additionally, DFO sensors exhibit resilience in harsh environments, effectively resisting corrosion and electromagnetic interference (Schenato, 2017).

Numerous efforts have been made to extend the application of fiber optic technology to include additional physical parameters such as hydrostatic pressure. This latter is an important parameter in several geohydraulic applications, including the detection of pore water anomalies indicative of internal erosion (Fell et al., 2003), the measurement of wave heights in the surf zone, the tracking of tidal variations, and the assessment of river elevations during floods (Arkwright et al., 2014). Schenato et al. (2020), for example, have developed a sensor that uses a compressible plastic housing to which the sensing fibers are attached. The pressure is derived from the stretching of the sensing fiber under external pressure applied to the housing. This innovative design achieves a remarkable resolution of about 5 Pa and an accuracy of 10 hPa, with a spatial resolution of 8.5 cm. Similarly, Höttges et al. (2023) have proposed a novel distributed pressure sensor (DPS) in which a sensing fibre is attached to a cylindrical compressible tube in a helix shape. The pressure is calculated by measuring the radial contraction of the helix sensing fiber. The main advantage of this solution lies in its simplified design, which is compatible with industrial production and easier field installation. The sensor has a sensitivity of 100 Pa, with an accuracy of 15% RD (relative deviation of reading) for a spatial resolution in the order of a few centimeters.

This paper provides an extended characterization of the developed DPS, demonstrating its suitability for various applications in the monitoring of geohydraulic structures. It includes both the validation of the sensor for existing applications and the exploration of its potential for new proposed applications.

2. Distributed Pressure Sensor – DPS

2.1. Sensor main concept

The sensor consists of a helix sensing fiber wrapped around a cylindrical compressible central element (Figure 1). The hydrostatic pressure is obtained by using a calibration coefficient that converts the radial strain of the central element measured by the DFO to hydrostatic pressure. The inner part of the central element is filled with aramid yarns (Figure 1), which ensure tensile strength up to 20'000 N. The DPS is also equipped with a distributed temperature sensor in the core of the central element, where 2 single mode (SM) fibers and 2 multimode (MM) fibers are mounted in a loose plastic tube filled with a special gel (Figure 1). As Höttges et al. (2023) pointed out, the key parameters that affect the pressure sensitivity are the diameter of the central tube, the helix pitch length, and the wall thickness of the outer layer.

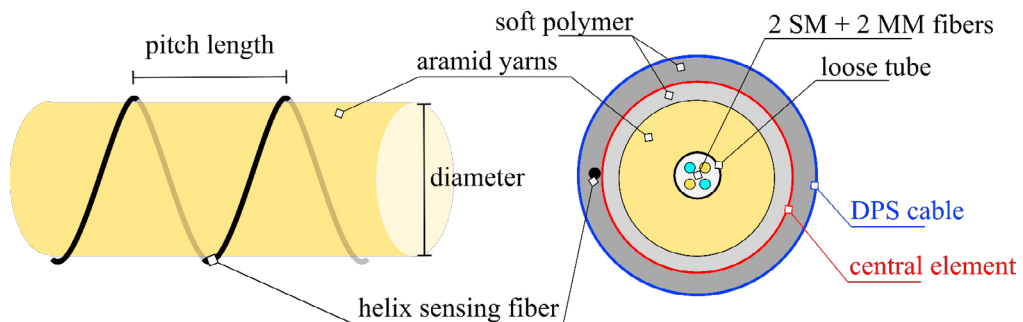


Figure 1. Scheme of the developed DPS cable according to Höttges et al. (2023).

2.2. Sensor calibration

The DPS was calibrated in a pressure chamber by testing the sensor under different hydrostatic pressure loads. The chamber consists of a 2 m long iron pipe where the sensor can be inserted through special feed through. The pressure was regulated using standard pressure controllers with a resolution of 0.1 kPa and an accuracy of 0.15 % FS (full range output). The calibration was performed with pressure loads relevant to the required application, focusing in river dikes, ranging from 0 kPa to 50 kPa (equivalent to 5 m water column). The pressure was gradually increased from 0 kPa to 50 kPa and then decreased to 0 kPa in 5 kPa increments. In addition, negative pressure down to -25 kPa was applied as part of the calibration process. After each increment, a measurement was taken with a fiber optic interrogator. An optical backscatter reflectometer (OBR) based on Rayleigh backscattering was used for all test results presented. Similarly, the temperature sensitivity of the DPS was tested in an oven by heating from 20°C to 60°C and then cooling to -40 °C in 20°C steps for 2 heating (H) / cooling (C) cycles.

The results of the pressure and temperature calibration test are shown in Figure 2. Figure 2 (a) and (b) illustrate the spectral shift measured with the helix fiber of the DPS inside the pressure chamber and oven, respectively. The reference measurement corresponds to the first measurement, which was 0 kPa for the pressure test and 20 °C for the temperature test. Figure 2 (c) and (d) are obtained by averaging the spectral shifts for each incremental pressure steps of the DPS within the chamber and incremental temperature steps within the oven, respectively. The pressure calibration coefficient $C_{p,Helix}$ represents the slope of the regression line derived from the averaged results of Figure 2 (c), while the temperature coefficient $C_{T,Helix}$ is also derived from the regression line of Figure 2 (d). The obtained pressure coefficient $C_{p,Helix}$ is 2.23 GHz/kPa and the temperature coefficient $C_{T,Helix}$ is -9.05 GHz/°C. The resulting coefficients could then be used to convert the measured spectral shift to pressure or temperature. During the temperature test, it was also determined the temperature coefficient of the core fiber $C_{T,Core}$ to be -1.74 GHz/°C.

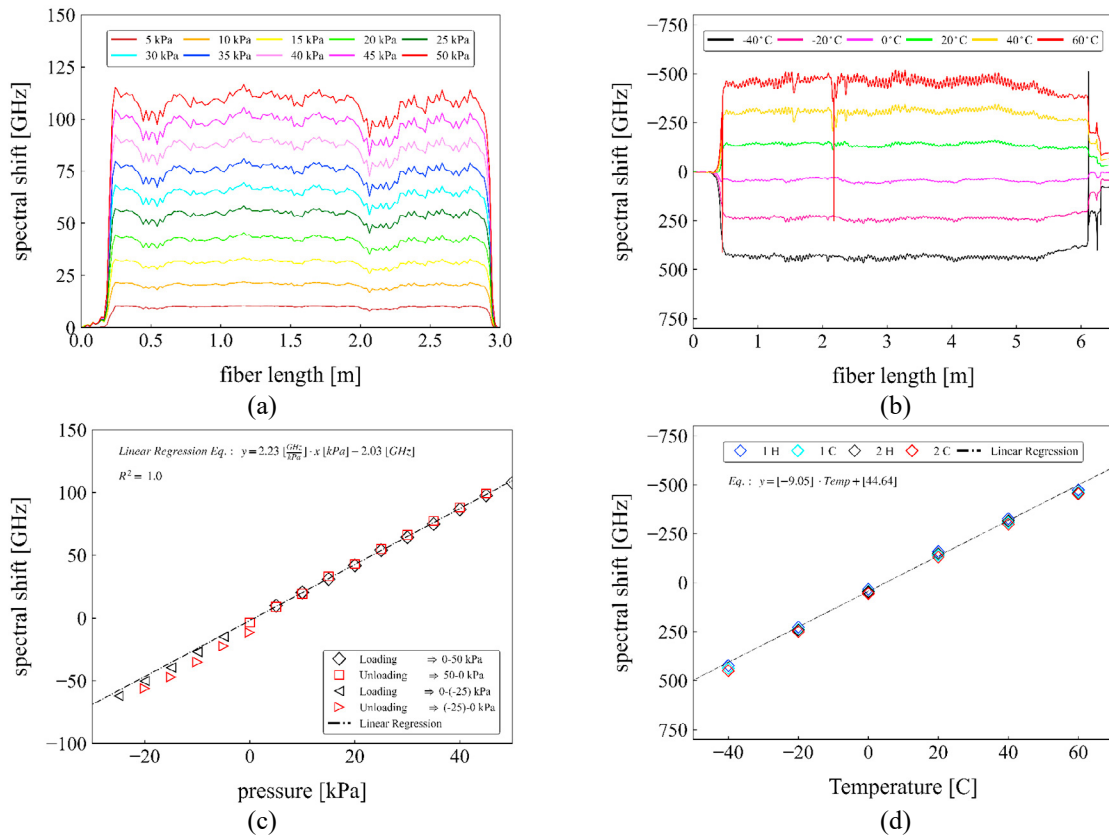


Figure 2. Spectral shift of the DPS inside (a) the pressure chamber and (b) inside the oven during the loading test; averaged results for each (c) pressure step and (d) for each temperature increase.

3. Validated applications

3.1. Water column test

The feasibility of measuring the hydrostatic pressure for realistic conditions by the DPS was evaluated through a water column test. The sensor was mounted vertically on a wooden support inserted in a 4 m deep tank as shown in Figure 3 (a). This latter was initially empty and then gradually filled with 1 m water column increments up to 4 m water column. For each step, the spectral shift of the DPS helix fiber as well as the temperature fiber in the core of the DPS was measured with the fiber optic interrogator used for the calibration test (e.g., the OBR). The results are shown in Figure 3 (b) for the helix fiber and in Figure 3 (c) for the temperature fiber of DPS core (Figure 1). Note that the spectral shift obtained are relative to a reference measurement of the first measurement when the tank was empty. For both graphs, the second y-axis is obtained employing the calibration coefficient ($C_{p, helix}$ and $C_{T, Core}$) determined in the calibration tests (section 2.2). As pointed out by Höttges et al. (2023), when large temperature variations are expected, as observed in this test (Figure 3 (c)) during the water filling, the thermal effect needs to be compensated. The compensation is performed by subtracting the spectral shift relative to the temperature change from the DPS helix measurement using the temperature coefficient $C_{T, Helix}$. The results after the compensation are shown in Figure 3 (d), where the increase in hydrostatic pressure along the DPS sensor is plotted for the load steps from 1 m to 4 m. Note that since the DPS was installed as a loop, all results plotted are symmetrical at a fiber length of approximately 5 m (Figure 3 (a)). The results show a clear linear dependence, as expected, indicating that the sensor accurately measures hydrostatic pressure with high spatial resolution.

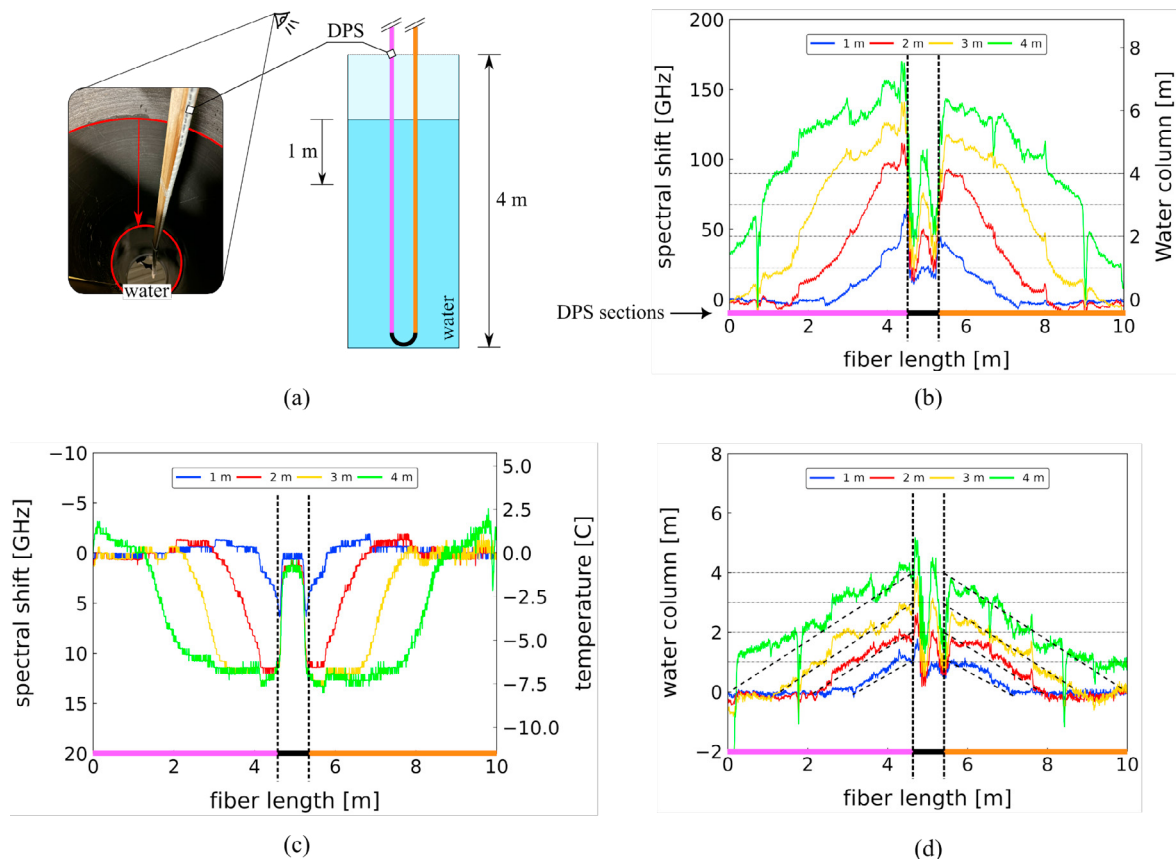


Figure 3. (a) Column water test scheme; spectral shift obtained by measuring the DPS helix fiber (b) and the DPS temperature fiber (c) during the load test; (d) results of the DPS helix fiber compensate and represented in water column.

3.2. River dike monitoring

The suitability of the DPS for monitoring pore water pressure in river dike was validated in a small-scale laboratory test by comparing the results obtained with the DPS to those of conventional digital pressure sensors during dike saturation. The dike (Figure 4) was built with a height of 100 cm, a slope of 1:2 and a channel width of 150 cm at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) of the Swiss Federal Institute of Technology (ETH) in Zurich. The dike was constructed using homogeneous materials, specifically well-graded gravel (GW) with a relatively high vertical permeability k_v of $6.7 \cdot 10^{-2} \text{ m/s}$. To drain the water from the dike, a drainage filter was mounted at the bottom of the dike of the downstream toe (see the overview scheme in Figure 4). The DPS and the conventional pressure sensors were installed at the same elevation, approximately 10 cm above the channel bottom (z-axis). An array of 8 pressure sensors were mounted in center (at 75 cm in the y-axis) of the dike with a spatial distance of 40 cm in the x-axis. The pressure sensors employed were piezoresistive sensors with an accuracy of 1 mm wc for pressure ranges from 0 mm to 1000 mm. The DPS was installed in the x-axis direction with three different configurations: (i) the DPS with porous filter stones, (ii) the DPS with saturable tube and (iii) the DPS free (e.g., without any casing). The two different types of casings are designed as rigid piezometer filters to protect the DPS from any earth pressure variations due to erosion or sediment accumulation and to provide only hydrostatic pressure measurements in the sections where they are placed. During the installation, the saturable tubes (shown in blue in Figure 4) and the porous filter stones (shown in gray in Figure 4) were saturated with water to avoid measurement errors and response delays due to lack of saturation. Conversely, the saturable tubes (shown in green in Figure 4) were intentionally not saturated to see the difference between the two procedures (saturation and non-saturation during the installation). The results corresponding to the not saturated filters are not shown in this paper as the signal is distorted, indicating that the casings should be saturated during the installation.

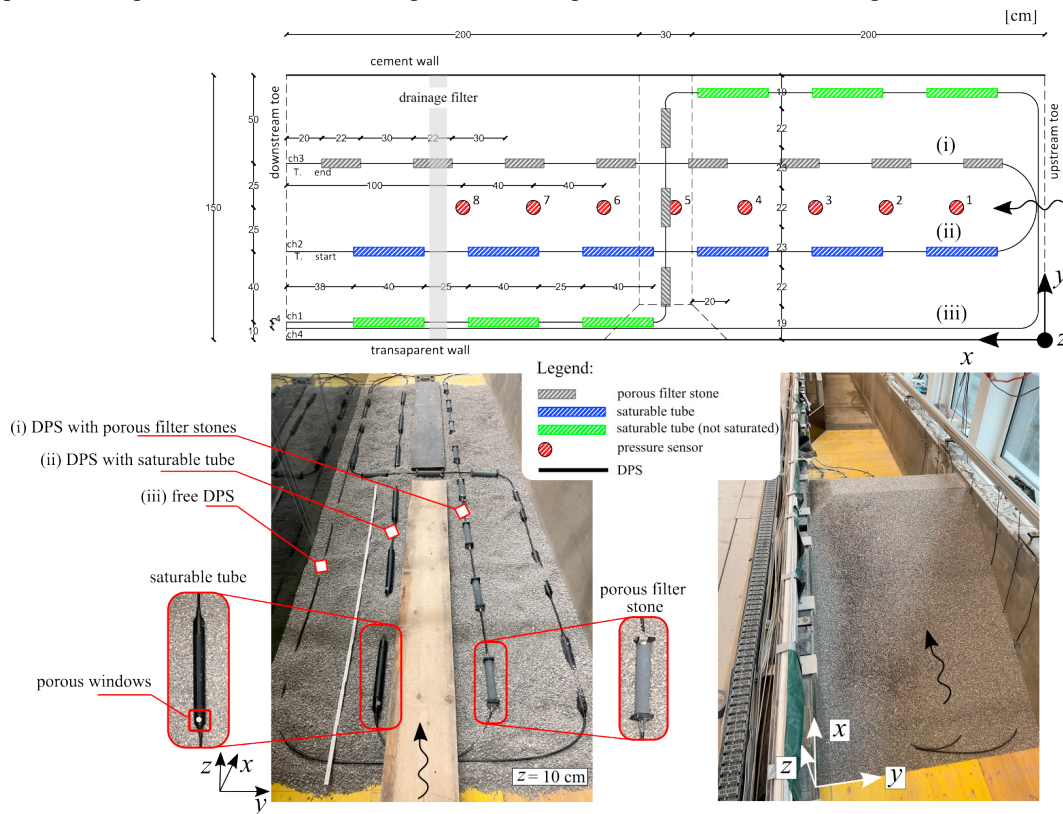


Figure 4. Details of the dike installation.

The test procedure consisted of two steps: 1) the water level (z-axis) was raised to 15 cm and maintained at this level for about 3 h to avoid a temperature shock to the DPS caused by water infiltrating the dike; 2) the water level

was then increased from 15 cm to 90 cm in 600 s. During the second step, the pore water pressure was measured every 10 s with the DPS and every 10 ms with the pressure sensors. After the second step, the water level was supposed to be maintained at 90 cm, but unexpectedly the dike began to collapse after about 360 s due to toe erosion caused by high seepage and the insufficient seepage discharge from the drainage filter, see also Figure 5

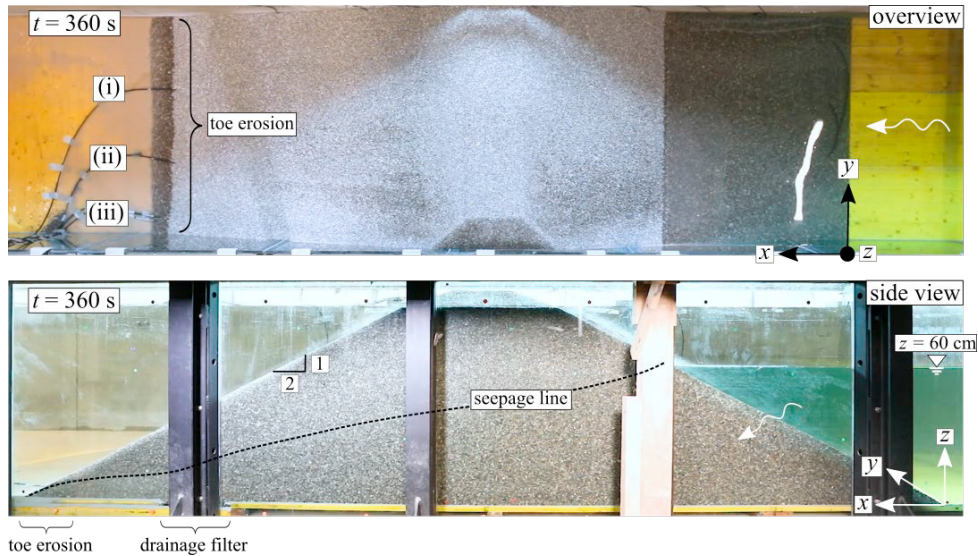


Figure 5. Overview and side view of the dike during the saturation test 360 s after the start of the second step.

The pressure potential, expressed in cm water column, obtained with the DPS and the conventional pressure sensors during the saturation of the dike (second steps) are shown in Figure 6. In particular, Figure 6 (a), (c) and (b) show the results for the three different DPS configurations: with the porous filter stones (i), with saturable tube (ii) and the free cable (iii). Figure 6 (d) represents the results after the start (at time 360 s) of the toe erosion. The pressure potential obtained with the DPS is calculated using the calibration coefficient $C_{p,helix}$, as explained in section 2.

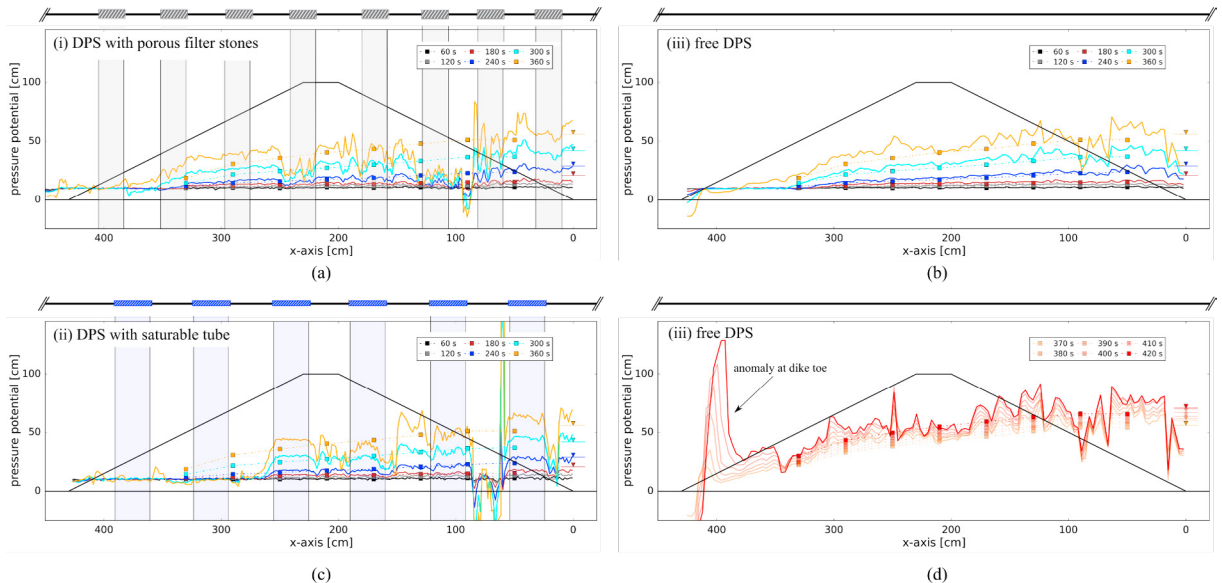


Figure 6. Results obtained with the DPS and the pressure sensors: (a) for the DPS configuration with the porous filter stone (i); (b) for the DPS configuration free cable (iii); (c) for the DPS configuration with saturable tube (ii); (d) results with the DPS free configuration after the start of the toe erosion.

The results show good agreement between the measurements obtained with the DPS and the point pressure sensors. The best results are obtained with the free cable configuration. The results of the configurations with the porous filter stone or with the saturable tube seem to be acceptable for the section where these casings are installed, in particular the signal is constant inside the casing as expected since the hydrostatic pressure should be the same (similar to the pressure chamber), but outside these sections the signal is distorted. The instability due to the starting of toe erosion is detected with the DPS free cable configuration as the information is distributed along the entire length of the dike; however, there is no clear correlation between the measured pressure potential and the phenomena.

4. Ongoing studies and future developments

The key advantage of the DPS is its ability to provide continuous hydrostatic pressure measurements with high spatial resolution (in the centimeter to meter range) over a single cable several kilometers in length at a relatively low investment cost compared to traditional methods that require many discrete piezometer sensors. This unique feature places the sensor as a potential game-changer in geohydraulic structure monitoring, particularly where hydrostatic pressure is significant as a monitoring parameter. Several activities related to the new sensor are currently underway or planned to expand the use of this technology as a monitoring system for other applications.

The DPS has been installed (Figure 7 (a)) in a dedicated full-scale test embankment located at the AIPo (Interregional Agency for the Po River) hydraulic facility in Boretto (Italy). The experimental embankment illustrated in Figure 7 (a), spans approximately 85 m in length, 37 m in width, with a slope ratio of 1:2, and a total height of 4 m. The dam was built with two types of soil: silt, representative of the dikes of the Po, and silty sand, containing coarser material typical of alpine rivers such as the Rhône. The new sensor, along with conventional monitoring systems such as piezometers, tensiometers, and humidity sensors, was installed in various configurations in the "ex novo" sections during construction to simulate the installation of a new structure. Specifically, the DPS was placed in a grid pattern at three different elevations of 0.3 m, 1.3 m, and 2.3 m. Figure 7 (b) shows the mesh for the layer at 1.3 m. In the "existing" part of the embankment, the DPS was installed using the horizontal directional drilling (HDD) technique, replicating the installation of the sensors for an existing structure. The sensor will be tested under different hydraulic conditions (typical of Po and Rhône rivers) by filling the basin with groundwater pumped from an existing well. The division of the dam into four independent sections allows different test scenarios to be run and validation results to be obtained independently.

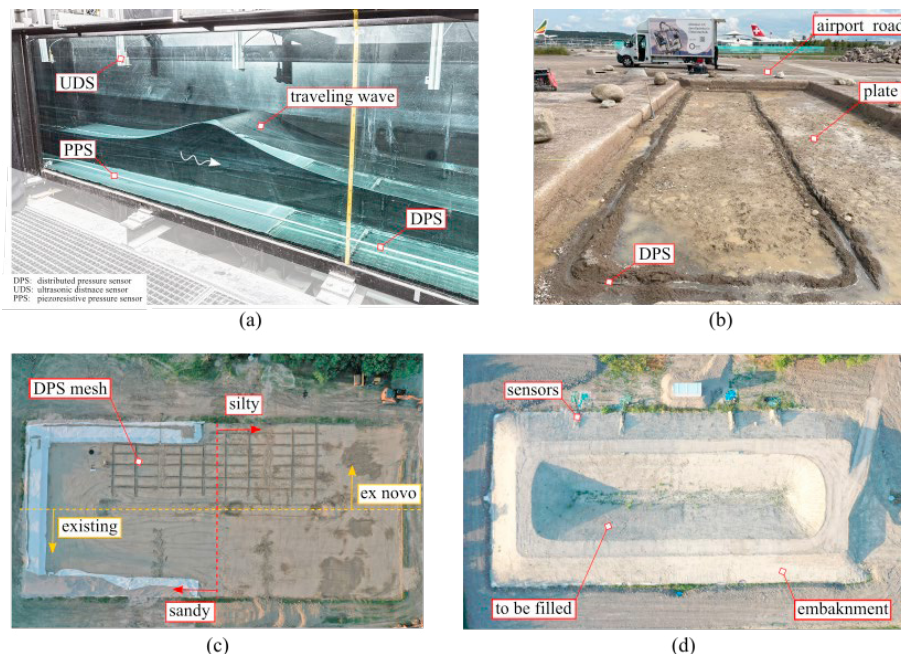


Figure 7. (a) Test embankment at the AIPo facility in Boretto (Italy); (b) installation of the DPS in the test embankment; (c) wave channel test; (d) DPS installation on the foundation layer.

Recently, the new sensor was tested under dynamic wave measurement conditions. Specifically, the ability of the sensor to measure the hydrostatic pressure of a propagating solitary wave at three different relative wave heights was evaluated (Figure 7 (c)). The obtained results were validated with two conventional measuring systems, ultrasonic distance sensors and piezoresistive pressure sensor, showing a good agreement among the three independent monitoring systems (Höttges et al., 2024). These investigations demonstrate that the DPS has the potential to serve as a monitoring system for hydrostatic pressure related measurements in geohydraulic field applications, i.e., coastal and surf zone monitoring or tsunami early warning systems.

The ability of the DPS to measure hydrostatic pressure has already been validated in the pressure chamber (section 2.2) and demonstrated in various tests presented in this paper (section 3). Future efforts will focus on investigating the potential of the DPS to measure anisotropic pressures, such as load transfer in soil or concrete structures. Figure 7 (d) shows the sensor installed on the foundation layer of a rigid pavement to measure the load transfer distribution within the pavement. Similarly, the DPS functionality for measuring erosion (anisotropic unloading) or sediment accumulation (anisotropic loading) will be tested on a laboratory scale by simulating the erosion/accumulation of a riverbed. Furthermore, since the sensor has shown potential to measure negative pressure as demonstrated in the pressure chamber (Figure 2, section 2.2), the DPS will be tested under partially saturated conditions. Finally, the sensor will be further optimized in terms of accuracy, repeatability and installation technique.

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