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SMART LEVEE IN POLAND. FULL-SCALE MONITORING EXPERIMENTAL STUDY OF LEVEES BY DIFFERENT METHODS

Abstract *This paper presents the two types of control and measurement networks used in the experimental levee, built as part of the ISMOP project. The first control and measurement network is based on pore pressure and temperature sensors; additionally, it contains fiber-optic technology. The second network includes design experimental sensors that were constructed for the development of solutions that can be used in existing flood embankments.*

Keywords ISMOP, smart levee, pore pressure measurement, temperature measurement

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1. Introduction

Every few years, catastrophic floods cause significant damage to the economy and infrastructure of many developed countries. In response to this threat, new projects aimed at protecting river basins required by the Water Framework Directive [11] and the Floods Directive [12] are being developed. Research projects aimed at the development of comprehensive levee protection systems are also being conducted.

European experiences in levee monitoring indicate the use of many technical solutions. Two approaches can be differentiated: a local approach – concerning the levee condition, and a global approach – comprising of the issues of water management and flood safety. The global approach was implemented in the Imprints, WeSenseIt, and (the most advanced) UrbanFlood projects. In Poland, such an approach is implemented by the National Water Management Authority (KZGW) within the framework of the IT System of the Country's Protection (ISOK) project. The local approach was adopted in the projects of the Cemagref (today's Irstea), IJkdijk, Dredg-Dikesor and also in the Polish project – IT System of Levee Monitoring (ISMOP) [1, 9, 10, 18, 23, 25, 26, 28].

For a number of years now, the regular measurement of the temperature of earthen hydrotechnical structures is considered to be one of the most-effective methods of assessing the routes of water dissipation and, thus, the condition of these structures [17, 24].

The mechanism that uses the analysis of soil temperature changes inside levees or dams is based on the phenomenon of water transporting heat from the water into the levee. The thermo-monitoring method analyzes the relationship between the velocity and location of temperature changes inside a levee and the amount of water migrating through the pores of the structure.

The presence of water in the pores of the soil as well as its ability to migrate indicates changes in the filtration factor or the formation of preferred pathways, which ultimately lead to leakage.

The measurement of pore pressure of the water inside the levee is also a common solution used due to the possibility of obtaining valuable information about the phenomena occurring within the structure:

- the differences in pressure within the embankment may indicate areas of preferred seepage paths, leading to leakage;
- measurement of the pressure in the air-side area of the levee allows us to verify the correct functioning and integrity of the drainage system (more often used in the case of dams and water reservoirs); a pressure drop may be an indication of internal erosion, which causes the material to be washed out of the embankment, thus blocking the filter area;
- increased pressure in the levee foot area may signal underseepage.

Monitoring the pore pressure at several measuring points and having knowledge of the actual structure and properties of the material from which the embankment was built allows us to determine the degree of hydration of the structure. This makes it possible to calculate both the filtration coefficient and the levee stability factor [16, 27].

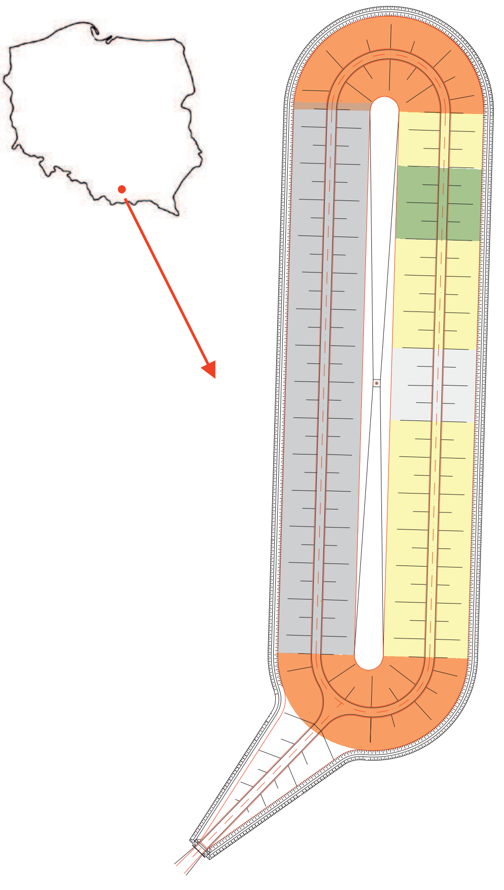


Figure 1. The diagram of the levee with the map specifying the location on in the province/country.

Integrated automatic monitoring systems are utilized on most dams in the form of Automated Technical Dam Control Systems (ASTKZ). They include a series of sensors that monitor changes in the water and earth pressure, land movement, discharge of water, temperature, gap openings, and others. They are spot sensors that record anomalies in their immediate vicinity. In recent years, more-effective linear monitoring solutions have been implemented (in particular, in the area of temperature measurement). For this purpose, a fiber-optic sensor cable is used. This enables the detection of leaks and filtrations as hydrothermal field anomalies. Monitoring systems are being installed more and more often on flood-protection embankments [3, 14, 26].

July 2013 saw the launch of ISMOP, an IT-based Levee Monitoring System designed by AGH University of Science and Technology in Krakow, in collaboration with SWECO Hydroprojekt Kraków Sp. z o.o. and Neosentio, and funded by the National Center for Research and Development 2013 as part of the Program for Applied Research (No. PBS1/B9/18/2013). The idea behind the project is to develop a comprehensive system to support the activities undertaken by state authorities and local governments in the area of flood protection by providing current information on the dynamics and intensity of the processes occurring in the earthen embankments. The innovative part of the project is the use of a number of sensors to monitor the changes in the core along with a comparison of the data with the results of numerical simulations [13] – coupled mechanical, hydrological, and thermal models.

This article presents a system for monitoring the changes that occur within the experimental core of an earthen levee on the basis of reference and experimental control and a measurement network. The research is carried out on an experimental levee built on a 1:1 scale (width × length × height: 58 × 208 × 4.5 m) located in the village of Czernichow (approximately 30 km west of Krakow). It consists of two parallel levee segments in the shape of an ellipse constructed of different soils characterized by variable filter coefficients in the range of 10^{-5} m/s to 10^{-8} m/s (Fig. 1) with a built-in control and measurement network.

2. Control and measurement network (AKP)

The control and measurement system consists of two elements: the control and measurement equipment (AKP) built into the experimental levee, and the automatic measurement system (ASP) that collects, processes, and visualizes the data obtained from the experimental measurements.

The control and measurement equipment includes a reference network that is based on specific historically proven technologies and serves as a reference for the new measurement equipment designs, which makes it possible to obtain results based on alternative technological solutions and distributed measurement using the MESH topology proposed by NeoSentio Sp. z o.o.

3. Reference control and measurement equipment

The reference control and measurement equipment (AKP) installed in the experimental levee consists mainly of Glötzl sensors designed specifically for geotechnical measurements. Keeping pace with global trends, GESO fiber-optic sensor cables featuring linear temperature distribution measurement technology were installed along with the Lambrecht METEO station, which constitutes an integral part of the built-in control and measurement network and supplies the data for the analysis that takes changing meteorological conditions into account during experimentation, directly affecting the condition of the tested levees.

The AKP equipment consists of the following measuring instruments:

- 35 sensors for the measurement of the water-column pressure in the core of the porous levee – PP4 RS VW 0.7 sensors with a vibrating-wire transducer;
- 6 sensors for the measurement of the earth (pressure) stress exerted on the base of the levee core – EE VW 20/30 K2 C sensors with a vibrating-wire transducer;
- sensors for the measurement of the temperature inside the levee;
- thermistors – integrated within the housing of the pore water pressure sensors and earth pressure, which enable the measurement of temperature exactly in the same spots where the earth and water pressures are measured;
- GESO DATA S fiber-optic temperature sensor – two fiber-optic sensor cables each with a length of 625 m, laid in the form of two loops that start and end in a data concentrator;
- devices for measuring the atmospheric background – the METEO station (rain gauge, air temperature sensor, humidity sensor, sensor for measuring wind direction, sensor for measuring wind speed, and barometric pressure sensor);
- instruments for measuring horizontal land displacements – 6 ABS 50 inclinometer columns placed in the levee core, each 7 m long, adapted to measurements that require high precision at low horizontal displacement values.

The PP4 RS VW 0.7 sensors for measuring pore pressure are in the form of cylinders made of acid-resistant stainless steel with a diameter of 40 mm and length of 230 mm. In the lower part, there is a filter made of cemented carbides through which the water pressure is transferred to the measuring chamber into the membrane connected to a stretched vibrating wire. The water-column pressure acting on the outer surface of the membrane contributes to the deflection, causing a change in wire tension that is translated to a change in the resonant frequency [25]. What sets them apart is (pressure sensor with vibrating wire technology) their high durability, long-term reliability, and the fact that they are supplied power only at the moment of measurement (in contrast to sensors equipped with current or voltage transducers).

A limitation is the risk of damage to the electronics due to lightning – an effective solution in this regard is the application of a surge-protection system. Their response times are virtually instantaneous, and they are also more accurate than open piezometers (where readings are error-prone due to the delayed response time of the piezometer to changes occurring in water-level fluctuations). Such a method of supplying power minimizes the use of electrical components in the sensor, increasing its service life on the one hand and reducing the amount of sludge precipitated from water on the active filter surface area on the other. To further increase the accuracy of the measurements, a decision was made to use a filter with a large active surface area ($57\,\mathrm{cm}^2$) [5, 3, 8] (Fig. 2, 3). These sensors are made in a two-wire technology with the output signal in hertz (Hz). These sensors are equipped with a temperature sensor integrated in the housing. The technical specifications of the above sensors are provided in Table 1.

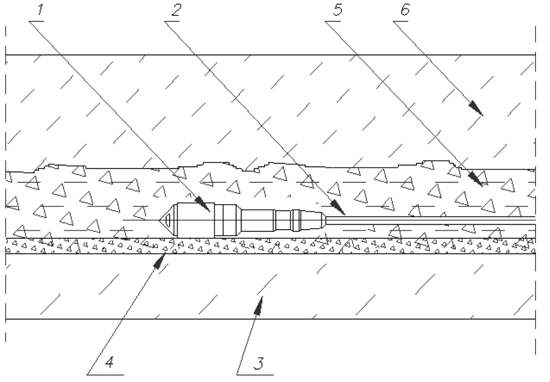


Figure 2. Porometer installation diagram: 1 – sensor PP4 RS VW 0.7, 2 – cable PE 4 × 0.5, 3 – underlayer of earth, 4 – sand bed, 5 – wet, fine earth, 6 – next layers of earth [4].

Figure 3. Installation of porometer: a) sensor prior to the installation of the filter, b) filters prior to the installation, c) filter installation, d) sensors after the installation of the filter [4].

Table 1
General specifications of PP4 RS VW 0.7 pore water pressure sensors.

Material	Stainless steel
Filter	type: sintered metal area: $57\,\mathrm{cm}^2$ (∅ 40 mm, length 50 mm) density: 4.9–$5.3\,\mathrm{g/cm}^3$ porosity: 33–38% specific flow coefficient: $3\,\mathrm{m}^2\times10^{-12}$ (laminar); $8\,\mathrm{m}^2\times10^{-7}$ (turbulent) Porometer, ∅ pore size: $6\,\mu$m
Supply	24 V DC
Measuring range	0 to 0.7 bar
Resolution	±0.02% f.s.
Measuring accuracy	±0.1% f.s.
Temperature range	−20 °C to +800 °C
Accuracy of temperature	0.3 °C
Overload protection	50% of measuring range
Operating frequency	2 kHz–3.3 kHz

To measure the earth pressure exerted on the base of the levee core, EE VW 20/30 K2 C sensors with a measuring range of 0–2.0 bar were used. The sensors are equipped with a vibrating-wire transducer, which ensures stable long-term operation. The main measuring component in the sensor is the pressure pad (with dimensions of 200 mm × 300 mm), which is in the form of a closed chamber filled with hydra-ulic fluid and connected directly to the membrane in the measuring chamber.

The earth pressure acts directly on the pad, causing its deformation relative to its original state. The fluid transfers the load (pressure) to the measuring chamber on the membrane. The membrane is permanently connected to a taut vibrating wire attached to the vibrating-wire transducer. The entire system is connected directly and tightly to a connecting cable, which makes it possible to read the wire vibration values in the measurement system (Fig. 4, 5).

One limitation is the risk of damage to the electronics as a result of a lightning – an effective solution in this regard is the application of a surge-protection system. These sensors are made of two-wire technology with the output signal in Hz. The technical specifications of the sensors used for the measurement of the earth pressure are shown in Table 2.

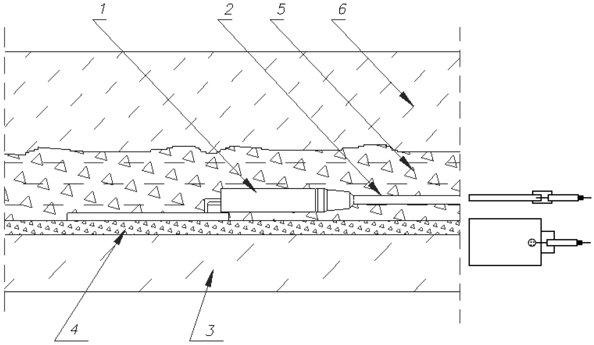


Figure 4. Installation diagram for pressure pad sensors: 1 – sensor EE VW 20/30 K2 C; 2 – cable PE 4 × 0.5 ; 3 – underlayer of earth; 4 – sand bed, 5 – wet, fine earth; 6 – next layers of earth [4].

Figure 5. Installation of earth stress sensor [4].

Table 2
General specifications of pressure pad sensors EE VW 20/30 K2.

Material	Stainless steel
Pressure pad size	200 × 300 mm
Supply	24 V DC
Measuring range	0 to 2.0 bar
Resolution	±0.05% f.s.
Measuring accuracy	±0.1% f.s.
Temperature range	−20 °C to +800 °C
Accuracy of temperature	0.30 °C
Overload protection	50% of measuring range
Operating frequency	2 kHz–3.3 kHz

Two sensors were used to measure the temperature of the soil inside the levee: thermistors integrated within the housing of the pore-water-pressure and earth-pressure sensors (which enable the measurement of temperatures exactly in the same spots where the earth and water pressures are measured) and a GESO DATUM Data-S fiber-optic sensor cable (the range of the sensor cable per channel being max. 2 km). The technical specifications of the applied fiber-optic cable are provided in Table 3.

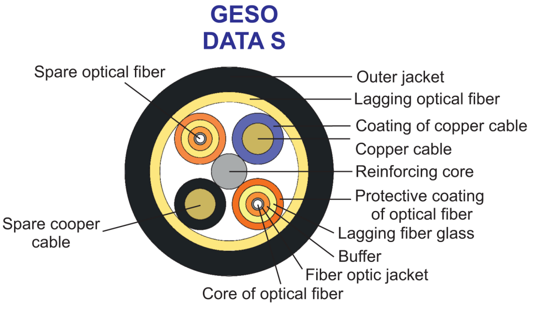
Table 3
General specifications of pressure pad sensors EE VW 20/30 K2.

Material	Fiber-optic cable ∅13 mm
Supply	10–30 V DC
Measuring range	−100 °C to +600 °C
Spatial resolution	at 1 m
Temperature range	−20 °C to +800 °C
Measuring accuracy	0.110 °C

The use of fiber-optic cables is a current global trend in the construction of measurement and control networks for hydraulic engineering structures (ICOLD – International Commission on Large Dams [3, 5]). The cable is used for the continuous measurement of temperature distribution along the sensor cable (optical fiber), maintaining high resolutions for space, time, and temperature.

Unlike most of the previously used fiber-optic cables that only allow for passive measurement (i.e., measurement of the natural thermal background at a given moment), the ISMOP project [7, 8] uses a hybrid fiber-optic cable with a built-in extra copper wire that enables active measurement in addition to the classic passive measurement by using an additional heat source; i.e., the copper wire heated at any time (Fig. 6) makes it possible to detect the local filtration and erosion processes occurring in the levee during the period of river swelling from a zone ranging from a few to a few dozen centimeters around the heat generator [6].

a)



b)

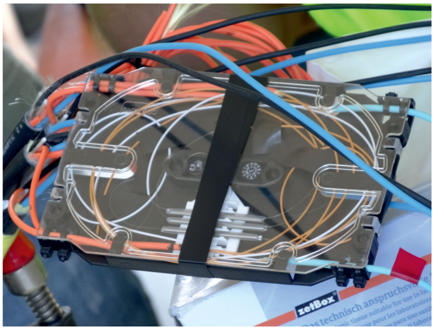


Figure 6. Cross-section of fiber-optic cable (a) and its installation in levee (b) [4].

The device is controlled and operated via a computing unit (PC). The measuring device can be adapted for long-term online monitoring and integrated with control systems and measurement data-processing systems.

4. Reference automatic measurement system (ASP)

The Automatic Measurement System (ASP) was created based on the SCADA iFIX system designed by GE Intelligent Platforms, an SQL database server using Microsoft SQL Server and Microsoft Excel software installed on a 64-bit Microsoft Windows operating system working on a server/PC.

The **ASP Czernichów** measurement system includes the following software components:

1. iFIX suite, together with the ASP application.
2. MB2 driver used for communication via RS 485 connectors with VersaMax controllers and Datalogger devices connected to sensors.
3. The AP Sensing DTS software used for the operation of the reflectometer to which the optical fiber cable is connected.
4. SQL Database Server using Microsoft SQL Server software.
5. MS Excel spreadsheet application.

The iFIX suite includes tools that are used to generate visualizations using animated multi-color graphics, present current and archival data (in a numerical or chart form), archive data, submit reports, display alert messages, execute computations, dynamically exchange data (DDE) with other applications running on a Windows OS (e.g., spreadsheets, databases), exchange information with the databases through the

ODBC interface, and work with other computers in a network (NetBios/MS WIN, TCP/IP, DECNet, Novell).

The SQL database server is used to save the collected and analyzed data in mass storage (hard drive). This enables fast access to the stored data and the effective operation with clients through a local computer network.

Microsoft Excel is used for presenting waveforms of meteorological measurements, measurements of the temperature inside the levee, earth stress, and pore water pressure as well as the tabular summaries of these measurements.

The control and measurement equipment combined with the dispersed structure based on Data loggers designed by AMEplus Sp. z o.o. and the Versa Max driver created by GE Intelligent Platforms make it possible to perform measurements and send the measured values to the data concentrator via structural cabling. Along with the ASP system equipment, this allows for the cyclic performance of automatic measurements and data protection, archiving, and visualization.

The appropriately selected Li2YCYv (TP) signal wires were designed for connecting the sensors to the data concentrator. The entire data collection and transmission system is designed to use a 230 VAC power supply fed from a supply located in a container via YKY (NYY-J) cables with the appropriately selected wire cross-sections. Data loggers were designed in the concentrator for the communication and collection of signals between the data collection system and vibrating-wire sensors, and 100 MB Ethernet connections were designed for the transmission of data from the fiber-optic sensor cable.

The concentrator to which signals are fed from the measuring sensors by means of copper cables is connected to the PC through its Ethernet. Its equipment includes [4, 5, 8]:

- a PLC controller for collecting and buffering data from the sensors;
- 2 VWS Data loggers for collecting and buffering data from the pore water pressure, water temperature, and earth stress and temperature sensors;
- an uninterruptible power supply (UPS) to enable the operation of the devices for some time after a power failure;
- surge protectors for measuring the sensors and the 230V power supply line;
- components for fiber-optic cable communication between the concentrator and the fiber-optic sensor cable.

The ASP computer network collects and stores data on local drives. This includes the iFIX application and MS SQL Server database. The server can communicate with external devices – a PLC controller designed by GE Intelligent Platforms and a VWS Datalogger. Transmission of the data from the data concentrator station to the central measurement database station is done using a MODBUS protocol. A system diagram is shown in Figure 7.

The measurement results are displayed on the SCADA system screens showing the approximate placement of the measuring sensors (Fig. 8).

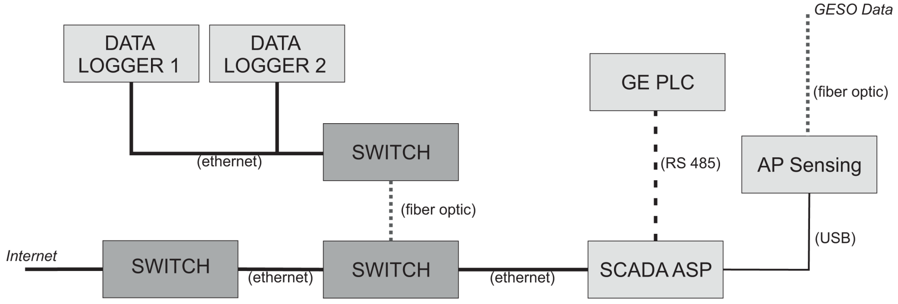


Figure 7. Detailed diagram of Automatic Measurement System (ASP).

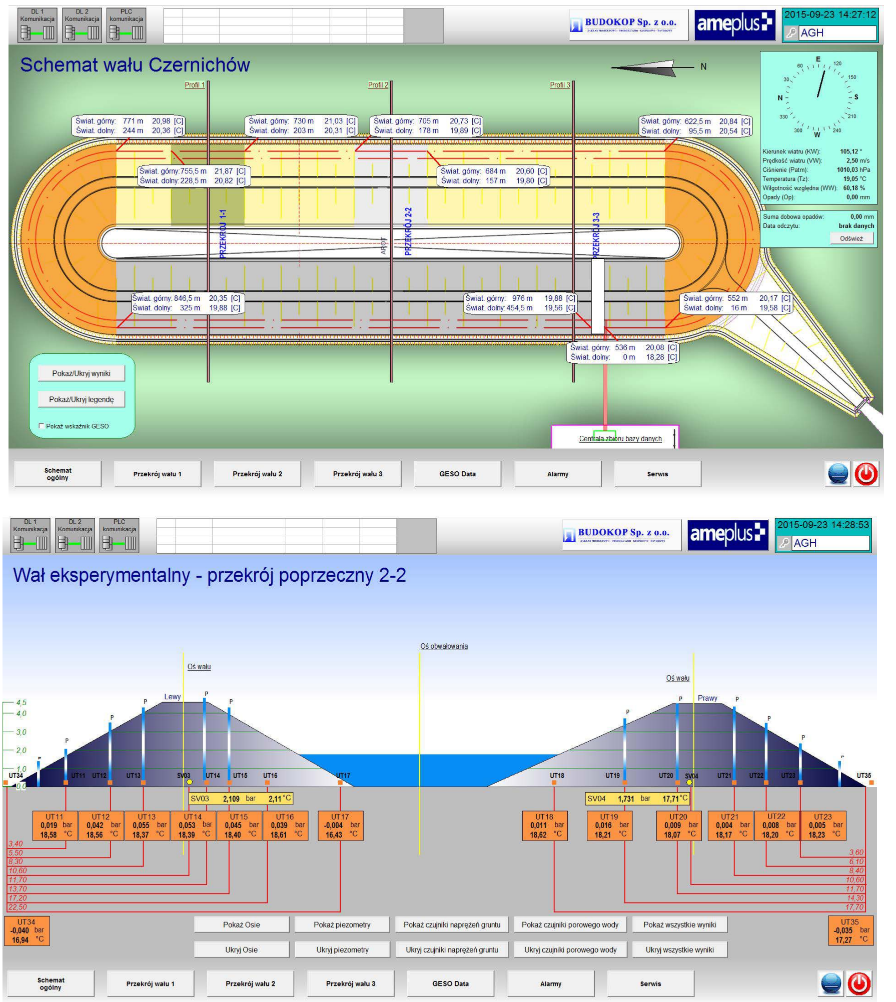


Figure 8. The SCADA system screens.

5. Experimental control and measurement network

The designed full-scale levee test site was also equipped with an experimental sensor network. This was designed and constructed based on the experience of implementing similar measuring systems [21, 22, 24] and on the Neosentio engineers' own conclusions based on experience derived from their past experiments [20].

The projected subsystem performs measurements and provides data to the upper layers of the ISMOP system while simultaneously pursuing several series of objectives:

- confident measures – providing the correct measurement data regardless of operating conditions;
- measurement frequency – dynamically adapting to the current scenario (less-frequent measurements during dry periods, more often during times of flood risk);
- density measurement – construction of sensors allowing for multipoint monitoring in dense locations;
- communication – quick and secure collection of measurement data sets from all sensors, fast and confirmed data transfer to the processing and analytic center;
- energy efficiency – all components of the measurement system are designed for long-term autonomous operation – low power consumption of the sensors during measurements, and low power consumption of the transmitters during network wireless operation and data transfer;
- resistance – to changing environmental factors or destruction – the modular construction is modular, the principal components are installed in ground or underground, not hindering the maintenance of the levee (for example, during grass mowing);
- open standards – data exchange and communication with the upper layers of the levee monitoring system is based on standard protocols;
- economic factor – construction of all components of the system are devised to minimize production costs, long-term labor, and depreciation, helping to reduce installation and maintenance costs.

Temperature sensors are located in both the area monitored by the installed fiber-optic cables and in a deeper areas of the levee body. This allows us to assess the speed of any seepage and plot the temperature distribution for 3D modeling.

The designed sensor location takes the following into account:

- limitations resulting from the existing regulations; i.e., their location should also be possible in existing flood embankments;
- possible ways of installing and assembling the sensor network in existing flood embankments – minimization of levee structure violation (especially those parts of the levees have been recently renovated);

- density resulting from the requirements of the physical models (the assumed grid size of the model is 5 m). After additional research based on the conclusions from our experiments, the optimum density of the sensor locations will be determined;
- limitations of wireless communication mechanisms between measurement nodes (discussed later in the paper).

The system performs measurements and transmits data based on (Fig. 9):

- Matrix of temperature and pore-pressure sensors installed inside the levee. The location of the sensors is optimized for the fastest detection of anomalies in the monitored measurements (while keeping other conditions constant) due to hydraulic conditions. The optimization procedure is described in detail in Majerski & Kessler's work [19]. All sensors are connected by a communication bus cable within the individual measuring profiles.
- Measurement Nodes (MNs), which are at local points of the managing and comunicate with sensors implemented in one or more profiles, managing the process of receiving and storing data. Measurement nodes communicate with each other (based on a linear form of MESH Topology Network [15], and indirectly with the main hub ? Edge Node for transmission of the collected data.
- Edge Nodes (EDs) – constituting a gateway to the upper layers of the ISMOP system and central management of the measurement node network in the levee segment. Communication with the measurement nodes is bidirectional, allowing for the realization of measurement network tasks following the scenarios received from the central system.

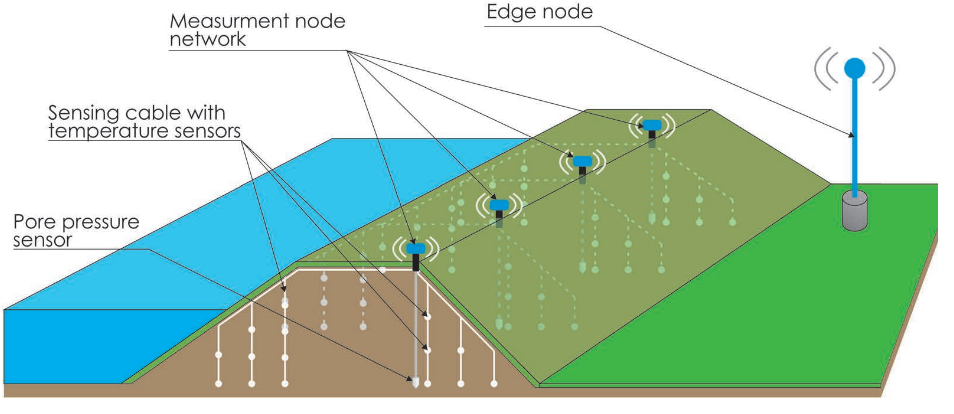


Figure 9. Schematic illustration of the idea of measuring network – matrix of sensors, number of measuring nodes, and external base station from edge node.

Both temperature and pore-pressure sensors installed in the experimental measurement network must have met certain criteria in the fields of accuracy and reliability in their measurement, cost-effectiveness, energy efficiency, and ability to install them in existing flood embankments under the applicable legal standards in Poland [6, 7].

Based on further analyses where the availability of the sensor chips and costs of purchase and other associated with the application in the measuring constructions was concerned, it was decided to implement widely-used digital temperature sensors (DS18B20), which present sufficient sensitivity defined as the resolution and accuracy of the measurements (Table 4).

Table 4
DS18B20 sensors' parameters.

Manufacturer	Dallas Semiconductor
model	DS18B20
Resolution	12 bit – 0.0625 °C
Operating range	−10 °C +85 °C
Voltage	3.0 V–5.5 V
Power consumption: operating/standby	1.5 mA/1 μA
Communication standard, protocol	Digital 1wire
accuracy(1) Typical/max	±0.5 °C/±0.5 °C
price	€ 1.00
availability(2)	high

(1) In range being the subject of analysis; i.e., from −5°C to 30°C.
(2) At the design stage. Currently, in most cases, the availability of sensing chips has improved significantly, which may influence further project applications.

Experimental sensors are placed in 74 sensing profiles in the levee. Each profile includes 14 temperature sensors positioned at different depths in 6 vertical measuring slots with precisely defined locations. There are one to four sensors in each vertical borehole. If there is more than one temperature sensor in a vertical section, the distance between them is standardized to one meter. This allows us to monitor any changes of soil temperature at different depths.

Additional surface sensors enable us to analyze the thermal background due to the influence of the air temperature, solar radiation, wind direction, presence (or lack) of water, diversity of the soil from which the levee is built, and (indirectly) the presence of a vegetative layer (shading). The measurement network also contains two temperature sensors positioned in opposite "corners" of the levee tank, which are used to measure the water temperature before saturation.

The distance between the profiles is set at 5 m and 2.5 m. The difference depends on the section of the levee. Profiles are denser in segments built of soil with a higher permeability coefficient.

Figures 10 and 11 illustrate a scheme with the location of sensing profiles, vertical boreholes, and sensors.

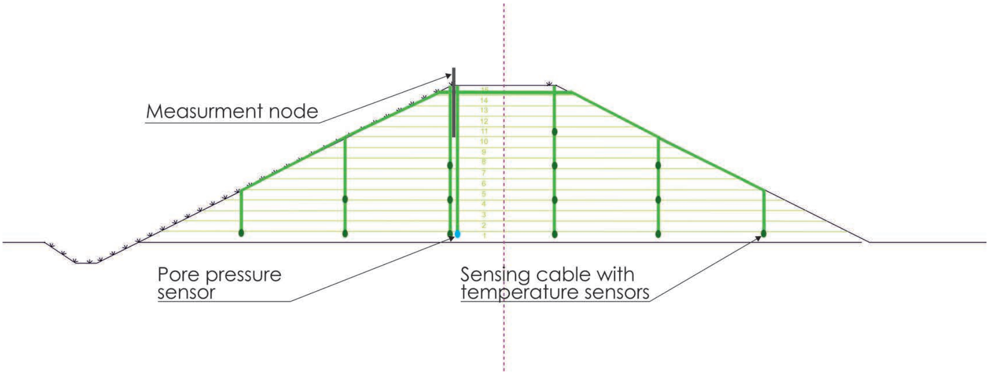


Figure 10. Scheme of installation point of temperature sensors.

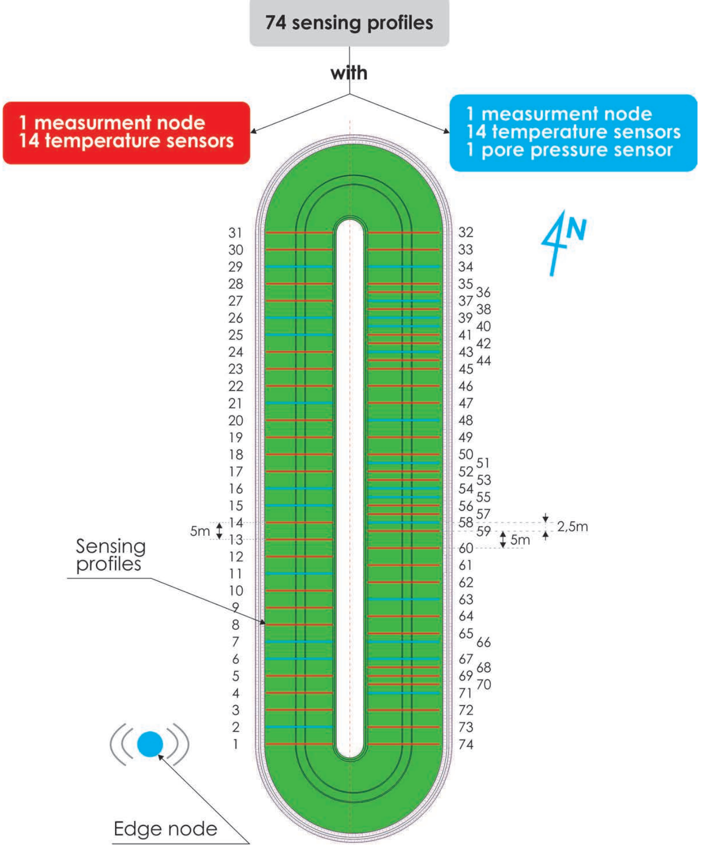


Figure 11. Location of sensing profiles in experimental levee.

6. Experimental linear temperature sensor development

The underlying assumption of innovative temperature sensors was to achieve an effect somewhat comparative to fiber-optic temperature sensors; however:

- giving the ability to install sensors in existing levees in a less-intrusive way;
- reducing the cost of sensors by utilizing popular and easily accessible temperature sensing chips and achieving the requested density;
- making it possible to determine the different densities and localizations of the sensing points according to specific levee localization and construction;
- using sensors that can operate autonomously in remote areas without the need for power lines;
- easy to maintain and exchange.

In the test levee, the experimental temperature sensors are mounted at regular distances (1 m) and have a modular construction, allowing for a later "mass" production of the prefabricated sections for quick installation in the field. It was necessary to compare and select the carrying cables for communication, decide about a safe and fast method of sensor installation, and test the sealing and protective materials as well as the applicable connectors.

A specialized wire-type durable and resistant cable (additionally filled with hydrophobic gel) was used, which in addition to its role in powering and being a communication mean, also meets the structural requirements as a carrier (XzTKMXpwn – Xz – anti-moisture barrier; T – telecommunication; K – cable; M – local with paired wires; Xp – polyethylene insulation; w – hydrophobic gel; n – self-supporting). This cable is widely used in the telephone transmission industry and is used both for suspending above ground and for placing directly into the ground. The cable with the sensors in it was installed in the previously provided small-dimeter boreholes.

One of the prerequisites for digital temperature sensor selection was their possibility to operate in a communication serial bus, thus reducing the number of cables needed. As it was necessary to measure the temperature at different depths, there are one to four sensors installed on a single cable. The sensor chip is shown in Figure 12. The assembly method is shown in Figures 13 and 14.

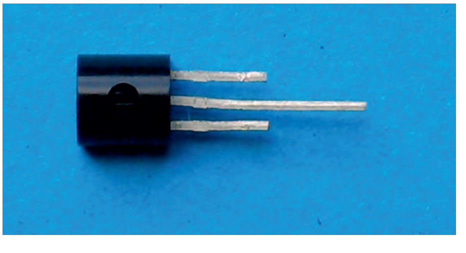


Figure 12. DS18B20 sensor prepared to be mounted as a final one at the end of the sensing cable.

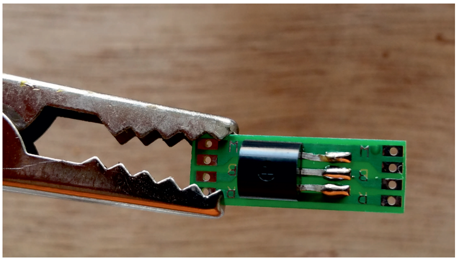


Figure 13. Intermediate sensors mounted along the cable with a dedicated PCB (printed circuit board).

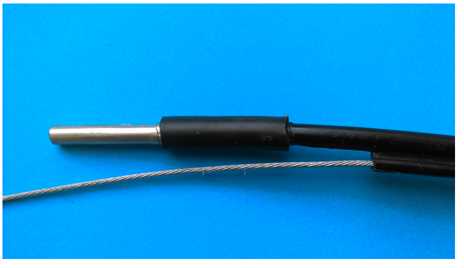


Figure 14. Final/ending sensor on a sensing cable with a security sealing cap. A steel wire is visible, which is later fastened to a leading cone during cable ground installation.

The assembly technology of both the end and intermediate sensors had to secure the tightness and mechanical resistance of the sensing cable in a prescribed installation method – by pressing or impacting. The sealing material used as a filler is optimized not only for its hydrophobic parameters but also regarding its chemical resistance to aggressive substances in the soil, mechanical strength, and flexibility. It needs to meet the criteria for electrical insulation and poor thermal insulation, which could otherwise result in the delayed response of the sensor.

7. Production of experimental sensing cables for installation in the Czernichów levee tank

A series of sensing cables with standardized lengths was manufactured for installing a measurement network in the Czernichow levee tank (Table 5).

Furthermore, a series of linking cables was manufactured (Table 6) that connect various sensing cables within the profile in one bus. Some of the connecting cables were equipped with temperature sensors as well for the purpose of measuring levee surface temperature.

Table 5
Sensing cables types.

Sensing cable model	Description	NoS	CQ
1x00055015M8-4-F	Cable with ending sensor, length 5.5 m	1	148
2x10035015M8-4-F	Cable with ending sensor, and a single intermediate sensor, 1 m interval, length 3.5 m	2	74
3x10050015M8-4-F	Cable with ending sensor, double intermediate sensors, 1 m interval, length 5 m	3	74
3x10035015M8-4-F	Cable with ending sensor, double intermediate sensors, 1 m interval, length 3.5 m	3	74
4x10050015M8-4-F	Cable with ending sensor, triple intermediate sensors, 1 m interval, length 3.5 m	4	74

NoS – No. of sensors, CQ – Cable quantity

Table 6
Linking cables types.

Linking cable model	Description	NoS	CQ
0x0001000M8-4-F	Linking cable, length 1 m	none	148
0x0003500M8-4-F	Linking cable, length 3.5 m	none	95
0x0005500M8-4-F	Linking cable, length 5.5 m	none	75
0x0004500M8-4-F	Linking cable, length 4.5 m	none	40
1x1753500M8-4-F	Linking cable with a single surface sensor, length 3.5 m	1	9
1x2254500M8-4-F	Linking cable with a single surface sensor, length 4.5 m	1	3

NoS – No. of sensors, CQ – Cable quantity

The sensor network utilizes connection technology based on standard M8 separators and M8 connectors (Fig. 15). Applying them allows for the quick linkage of sensor network elements in segments and, furthermore, facilitates the eventual diagnosis.

Figure 15. Standard M8 connector on a sensing cable with visible RFID tag for individual identification. Standard M8 distributor (male – 2 × male).

8. Pore pressure sensors

The prerequisites for experimental water-pore-pressure sensors was to construct an autonomous installation without an external power supply that is easy to produce and that utilizes widely accessible and relatively inexpensive cells while giving acceptable accuracy and reliability. After an initial analysis of the available pressure sensors, devices from two manufacturers were selected for the experiment (Table 7) Keller Druck – piezoresistive pressure sensors with steel diaphragm (absolute type) (Fig. 16a) and METALLUX SA (Fig. 16b) – piezoresistive ceramic sensors (absolute type).

a) b)

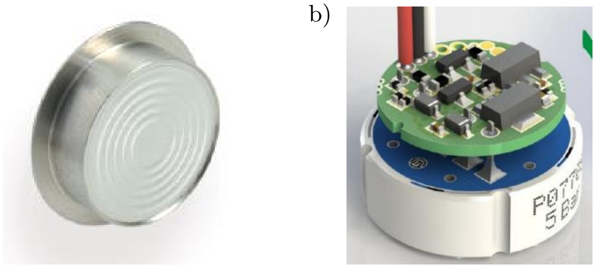


Figure 16. Pressure sensor chips applied in the experiment: a) Keller-Druck chip Paa-9FLD (∅17 mm); b) Metallux chip ME 722 (∅18 mm).

Dedicated modular filters were also developed to protect the measuring cells while enabling the flow of water from the pores of the soil to affect the membrane.

The filters are made of sintered steel (Fig. 17) and are supplemented by stainless steel (AISI 316/316L) cones and mounting flanges. The filter assembly uses a durable epoxy adhesive whose effectiveness and usability was confirmed in mechanical and thermal tests.

Figure 17. Keller-Druck PAA-25D sensor with a modular sintered steel filter (porosity 20 μm).

Pore-water-pressure sensors are located in the central part of the levee-measuring profiles – with spacing at approx. 20 m (at every fourth profile in the western shaft and every eighth profile in the eastern segment of the shaft, in areas of different construction material).

Table 7

Parameters of pressure sensors applied in the project.

Manufacturer	Model	Type	Resolution		Range	Voltage, supply	Energy consumption	Interface, protocol	Accuracy % FS	
			FS	mbar	mbar	[VDC]	[mA]		Typical	max
Sensor: Ceramic OEM Transmitters for installation										
Metallux	ME722	PAA	0.25%	2.5	0–1.5	3.3–5	8	I2C, digital	±0.5%	±1.5%
Sensor: Steel OEM Transmitters for installation										
Keller-Druck	PAA-9FLD	PAA	0.15%	1.5	0–1.5	1.8–3.6	1.5	I2C, digital	±0,15%	±0,7%
Sensor: Sensors prepared for installation										
Keller-Druck	PAA-25D	PAA	0.15%	1.5	0–1.5	1.8–3.6	1.5	I2C, digital	±0,15% FSO	±0,5% FSO
Sensor: Reference										
Keller-Druck	PAA-35X	PAA	0.0025%	0.025	0–1.5	3.5–12	8	RS485, digital	±0.025% FSO	±0.1% FSO

Similar to the temperature sensing cables, a wire with increased stiffness and resistance to environmental conditions (XzTKMXpw $2 \times 2 \times 0{,}5$) was used. As the installation procedure assumes placing the sensor only in the pre-drilled holes with a prepared sand backfill around the filter, there is no need to use a cable with an extra steel cord. A standard M8 connector is implemented to the power and communication cable.

9. The communication system and network management

Another layer of the measurement system constitutes the components responsible for measurement management, storage, and secure data transmission to the central analytical system. The experimental sensor network is dedicated for long-distance linear earthen constructions like levees and is based on a linear mesh grid with Measuring Nodes for each profile and Edge Nodes as gateways for each logical segment of the levee (50–250 MNs per EN). There are two essential components of the sensor network communication layer that were previously mentioned:

- Measurement Node (MN) – equipped with sensors measuring physical parameters, a communication module, and a radio subsystem for communication with other MNs and an Edge Node. It is designed to manage the measurements realized by the connected temperature sensors and water-pore-pressure sensor, power those sensors, undergo an initial assessment of the quality of data provided by its sensors, and transmit both the stored data and data received from other MNs (on the mesh principle). Furthermore, it realizes self-testing procedures.
- Edge Node (EN) – equipped with a communication module and a radio subsystem to communicate with the MNs in its section and equipped with an RS232/RS485 interface for the Modbus protocol [19] used to transfer the aggregated measurement data to the ISMOP central analytical system [2]. The Edge node's role is network management and monitoring, management of measurement scenarios, verification and qualification of data, data transfer, and realization of diagnostic procedures of its internal modules and "subordinate" MNs. In the case of using a wired communication bus with the MNs, the EN is also a power distributor for the network.

There is various data transmitted in the network according to its designed functionality:

- measurements;
- configuration data of internal subsystems, and used for topology building of transmissions between network nodes (MNs and ENs);
- diagnostic data with information on network nodes and sensors parameters; e.g., quality of radio signal, firmware version, node status, sensor status (quality of measurements);
- control data – allowing changes in the network's operating scenario (normal, alarm; i.e., flood risk).

10. Solution topology

The network has been designed to allow a density of up to 250 Measurement Nodes (Fig. 18) per levee segment estimated to a length of 1 km and serviced by a single Edge Node (Fig. 19). In the case of failure of a parent Edge Node, all of the assigned MNs begin to communicate through the next neighboring Edge Node, indicating their status respectively.

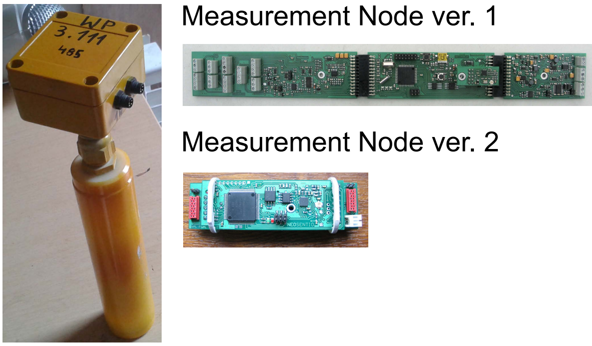


Figure 18. Measurement Node in its casing with visible interfaces to connect sensors, antenna, and wired bus (if necessary); they are successive versions of the MNs' electronics miniaturization.

Figure 19. Edge Node with emergency power supply.

A characteristic feature of the experimental sensor network is the concept of measurement epoch, which is defined as a particular point in time when the measurement data of an entire levee segment is available for transmission to the ISMOP central analytical system. The measurements are performed with proper in advance to meet the required moment for data availability. A possible failure, delays, additional measurements, and data retransmission must be taken into account (Fig. 20).

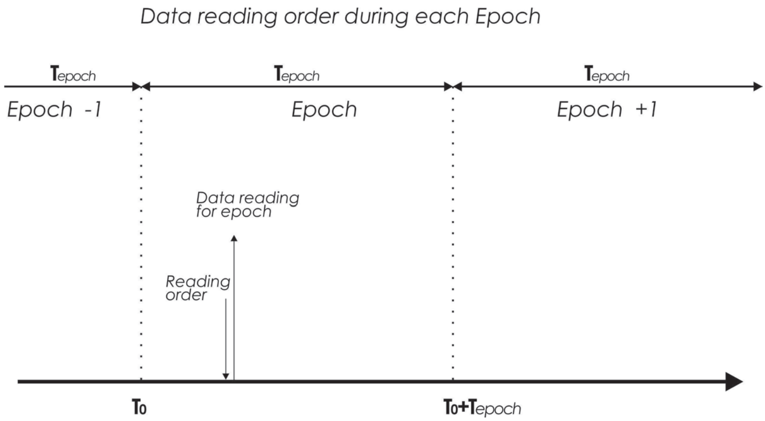


Figure 20. Example of time dependences of requests to read measurement data in the Epoch. Tr – time of measurement data propagation within the sensor-network segment and to the Edge Node and maximum propagation time.

Tables 8 and 9 show the technical parameters of the solutions used in the sensor network subsystems.

Table 8

Technical specification of Measurement Node.

Microprocessor	MSP 430 Texas Instruments
Telecommunication module	CC1101
Communication interfaces	2×RS 485, 2×1wire (or 1×1wire and 1×I2C)
Overvoltage protection	Implemented in bus interconnector box
Power supply/storage	External/Li-Ion battery

Table 9

Technical specification of Edge Node.

Microprocessor	MSP 430 Texas Instruments
Telecommunication module	CC1101 GSM Leon G100
Communication interfaces	3×RS 485, 1-wire
Overvoltage protection	Implemented in bus interconnector box
Power supply/storage	External/gel battery

11. Telecommunication protocol between Edge Node and Measurement Nodes

A proprietary wired communication protocol was developed within the experimental project – a MultiMaster working on an RS 485 bus. It is used for communication with and management of the network nodes and diagnostic equipment. MultiMaster allows for a remote firmware update in the devices, their reconfiguration, and the provision of detailed telemetry data. Unlike Modbus, it enables communication with a multiple-masters and multiple-slaves environment using the mechanism of arbitration. This mechanism's a logic implemented in a telecommunication network comprised of several master-compute nodes and several slave-compute nodes. The protocol resolves conflicts and allows for communication between one of Masters and Slaves based on a reserved token. This protocol is also used as the primary method of measurement-data transmission during the full-scale levee water-filling experiments.

12. Wireless protocol

Another way of communicating within the network is through radio transmission utilizing a proprietary mesh protocol adapted to the specifics of this linear application. The protocol (which must meet preset requirements) is currently under development and in the testing phase. Its main challenge is achieving a low power consumption. Because of the harsh environmental conditions in which a radio transmission will be required to operate, the authors have decided to use a low-range frequency (433 MHz).

13. Summary

Until now, current assessment of levee condition based on periodic inspections of levee fragments [7, 17].Taking into account the growing losses after each catastrophe caused by damage to the embankments, this kind of inspection is insufficient. In the case of newly-built or -repaired levees, it is possible to estimate their ability to carry loads because the utilized material and method of performance is known. In the case of existing levees, obtaining precise data is difficult and expensive. The impact on the reliability of the data is also the implementation of geological and geophysical monitoring, defined only in sections or on a limited area.

The complexity of the filtration and erosion processes in a levee require integrated and continuous monitoring conducted in real time. The system of monitoring the state of the levees should be automated and based on instruments installed inside or in the immediate vicinity of the embankments.

This paper presents a reference control and measurement network, using both point sensors (temperature and pore-pressure sensors) and a linear measurement using a fiber-optic. The design solutions and communication scheme will develop optimal schemes for monitoring the newly built levee.

Research carried out within the framework of the research project ISMOP [26, 19] include the design and execution of experimental and control network – measurement, which will allow for the development of solutions that can be used in existing flood embankments.

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