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Integration of multi-source geospatial data for the assessment of geoengineering hazards during construction and operation of hydrotechnical structures

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Abstract: The essence of monitoring systems is providing information on changes in the geometry of the examined objects as a result of processing the acquired geospatial data using computational algorithms. Most geodetic monitoring systems integrate two different measurement techniques: tacheometry and Global Navigation Satellite System (GNSS). Geodetic techniques allow for obtaining the georeference for other data, however, due to the requirement of optical visibility of measurement points, they cannot be used everywhere. Non-geodetic (geotechnical) techniques usually provide relative values without georeferencing, but devices can operate automatically in a location that is visually inaccessible, without constant operator supervision. The problem is the physical integration of devices within different techniques and their diversity in terms of the structure of the geometric data provided and their accuracy: inclinometer sensors and hydrostatic levelling inform about changes without reference to the external reference system of the object.

The article proposes a methodology for integrating geodetic observations and data from selected geotechnical sensors. Non-geodetic techniques very often provide data with higher precision compared to the results of geodetic measurements, which allows to some extent to control the geodetic measurements results, providing the system as a whole with greater reliability, understood as the ability to eliminate outliers, as a result reducing incorrectly interpreted "notifications" and "alerts" about the object's condition. The added value of the presented article is the concept of combining highly accurate sensors with reliable geodetic measurements into a unified system. Combining the advantages of both solutions in order to increase the safety of hydrostatic facilities.

Keywords: displacement monitoring, geodetic monitoring, geotechnical monitoring, hydrostatic levelling, inclinometers, structural health monitoring

INTRODUCTION

Monitoring of hydrotechnical structures is a key task for ensuring the safety of people and property. The beginnings of dam safety monitoring date back to the 1890s. The beginnings of geodetic monitoring of dams are considered to be 1891, when the displacements of the Eschbach gravity dam began to be monitored in Germany (Speckhann, Kreibich and Merz, 2020; Qin *et al.*, 2021). In 1925 and 1926, in the United States, observations of buoyancy pressure and stress and strain observations began to be carried out, respectively, on the America-Fords Dam and the Stevenson Arch Test Dam in Idaho (Huang, Zhou and Hua, 2005; Jeon *et al.*, 2008). In the 1950s, a series of accidents related to dam failures drew the attention of all countries of the world to monitoring their safety. The scope of monitoring the facility has expanded from covering only the main dam structure to full monitoring of the main structure, foundation, abutment and surrounding dam environment. Such monitoring is often referred to as dam health monitoring (DHM). The main goal of any DHM program is to identify, as early as possible, any anomaly in the dam responses, which can result in upcoming danger and allow the dam owner a sufficient time to implement a corrective measure (Prakash *et al*., 2022; Deng *et al*., 2025). Monitoring methods have evolved from initial manual inspection, basic surveying and qualitative assessment to the current automated structural monitoring systems that integrate high-precision data acquisition, disaster analysis and prediction and notification functions.

Dam hazards can be divided into two categories: natural hazards and hazards related to human activity. Natural hazards include strong winds, floods, prolonged droughts, seismic movement, landslides in the area of the dam and reservoir. Hazards related to human activity include design and construction errors, as well as improper operation and maintenance. The behaviour of the dam under the influence of external factors is described by: deformations and displacements, the course of filtration (water levels or pressures and pressure gradients, filtration velocities and costs). A serious threat to the safety of the facility is the occurrence of uplift, settlement, crack or internal cracks. In order to detect threats in time, the following elements are measured:
– upper and lower water levels,
– precipitation and water levels at reservoir inlets (inflow forecast),
– meteorological conditions (precipitation, air temperature),
– water temperature (dammed and leaking) and of structures and subsoil,
– buoyancy and pressure and level of the filtration water table in the subsoil and body of embankment dams,
– filtration (drainage) flows,
– all linear and angular displacements, relative and absolute,
– deformations of dam materials (e.g. concrete in heavy dams or soil in embankment structures) and subsoil.

It should be noted, however, that the above-mentioned elements are measured using different sensors in different units of measurement. Their joint analysis allows for achieving the best results, hence the importance of striving to link them.

The aim of the conducted research was to indicate the possibility of combining geodetic measurements (tacheometry and levelling) with geotechnical measurements (inclinometers and hydrostatic levelling). Currently, these measurements are performed independently and the values obtained from geodetic measurements refer to absolute changes and from geotechnical sensors to relative changes. Different reference systems make it impossible to conduct a global analysis of the quantities obtained using these methods. Therefore, their connection and, as a result, common analysis will allow for better detection of potential threats to the object. This type of interconnection is not widely used and is a novelty that will allow the development of dam control systems.

Geodetic monitoring involves determining geometrical relationships between the location of specific measurement points on the monitored object. Periodically recorded changes are the result of various phenomena occurring in the case of a given object. Geodetic monitoring allows for determining the occurrence of changes between the information contained in the project, in the forecast of behaviour and the actual state. It also allows for control of the dynamics of the following changes. Geodetic monitoring of dams includes classic measurement techniques: tacheometry, precise geometric levelling (currently no possibility of automation) and trigonometric levelling, Global Navigation Satellite System (GNSS) measurements (Acosta *et al*., 2018; Agapie *et al*., 2021; Reguzzoni *et al*., 2022; Wiget, Sievers and Walser, 2023).

Currently and in its most advanced form, monitoring of a dam structure is carried out using an individually designed for each facility Automatic Dam Technical Control System (Pl.: Automatyczny System Technicznej Kontroli Zapór – ASTKZ, in the idea, it corresponds to structural health monitoring – SHM). The system consists of control and measurement equipment consisting of sensors responding to various values characterising the condition of the facility and its surroundings, and an appropriately programmed computer that enables remote initiation of measurements, collection of their results (acquisition), processing and analysis, reporting, and notification of the occurrence of permissible (warning) or limit (alarm) values. The ASTKZ / the SHM should ensure (Kledyński, 2011): reliability and appropriate accuracy of measurement sensors, constancy of sensor readings over time, where conditions allow – the possibility of periodic comparison of automatic measurement results with the results of geodetic measurements, reliability of data transmission from sensors to the computer supervising the operation of the system, safe collection of measurement data, ongoing analysis of measurement results and alerting in accordance with the safety thresholds adopted for a given facility determined on the basis of model predictions of behaviour.

The constant development of sensors and measurement technologies makes the measurement equipment more and more accurate and available in a wider range; their prices are also decreasing. The resistance of sensors to corrosion and difficult working conditions in the facility is improving. These devices sometimes have built-in signal processing modules with internal memory and can work in a network, which makes it possible to connect more sensors to one cable. Dam's SHM is crucial for damage detection and warning before a disaster (Sivasuriyan *et al*., 2022). Stress and strain are critical parameters, numerous SHM studies based on inclinometric strain sensors have been conducted (Yavaşoğlu *et al*., 2018). Linking the indications of ASTKZ/SHM sensors with displacements determined using geodetic techniques is a key solution for a complete monitoring system, taking into account data obtained using various techniques from sensors whose location is determined in the geodetic coordinate system and the indications concern the observed geometric changes: inclination, displacement, deformation or strain parameters. It should be remembered that the accuracy of the system is determined by the resolution and accuracy of its components.

One of the most important factors influencing the occurrence of geohazards are water fluctuations in the reservoir and changes in water conditions, groundwater levels and pore pressure under the facility, in the immediate vicinity of the dam, on the banks, slopes and adjacent areas. ASTKZ/SHM systems offer the possibility of including in the system the recording and presentation of data from piezometers (open and closed), probes for measuring groundwater levels, quantitative filtration meters and its speed. Linking these data in the form of model dependencies with observed geometric changes of the facility is impossible. A simplified form of analysis is to compare the actual displacements and deformations of the facility with forecasts calculated on the basis of numerical modelling, forecasts with assumed boundary conditions: water level in the reservoir, differences in water table fluctuations, maximum speed of filling/emptying the reservoir, soil parameters and geological structure.

In the further part of the article, the authors focused on the issue of integration of data from automatic tacheometry and readings from inclinometer chains and hydrolevelling chains.

Monitoring *in-situ* is an important aspect of geotechnical projects to ensure safety and optimise design measures. However, existing conventional monitoring instruments are limited in their accuracy, durability, complex and high cost of installation and requirement for ongoing real time measurement. Advancements in sensing technology in recent years have created a unique prospect for geotechnical monitoring to overcome some of those limitations. For this reason, micro-electro-mechanical system (MEMS) technology has gained popularity for geotechnical monitoring (Sun *et al.*, 2024; Wu *et al.*, 2024). Sensors using MEMS technology combine mechanical and electrical elements. Sensors based on MEMS technology have advantages to traditional sensors in that they are millimetre to micron sized and sufficiently inexpensive to be ubiquitously distributed within an environment or structure. This ensures that the monitoring of the *in-situ* system goes beyond discrete point data but provides an accurate assessment of the entire structures response. The capability to operate with wireless technology makes MEMS microsensors even more desirable in geotechnical monitoring where dynamic changes in heterogeneous materials at great depth and over large areas are expected. Many of these locations are remote or hazardous to access directly and are thus a target for MEMS development.

MATERIALS AND METHODS

SELECTED SENSORS USED IN MONITORING OF HYDROTECHNICAL OBJECTS

There are many examples of integration of measurements from different sensors and methods in the literature on the subject (Scaioni *et al.*, 2018; Zaczek-Peplinska and Kowalska, 2022). In order to increase the efficiency and safety of routine inspections, more and more solutions are used in geodetic monitoring of dams, allowing for automatic acquisition of data in real mode. However, the basic measurement method is still contact measurement (levelling, tacheometry), which ensures the determination of individual displacements or point deformations. Measurements using satellite techniques (GNSS) are introduced as a completely independent system to obtain information on the three-dimensional deformation of the object. However, this technology does not provide sufficient accuracy and full coverage of the area, especially in narrow and deep valleys, where there are large horizon obscurations. Another frequently introduced method is terrestrial laser scanning (TLS), which provides precise point clouds allowing the determination of the object's deformation. Fibre optic factors and temperatures are used for measurement inside dams. Dam inspections also require direct image inspection of the damaged area using cameras or unmanned aerial vehicle (UAV) technology (Zhao *et al.*, 2021).

The article presents the possibilities of integrating multi-source data using inclinometric measurements and hydrostatic levelling as an example in order to build a coherent system for monitoring the behaviour of a hydrotechnical object. The article presents the possibility of integrating data from a classic geodetic network measurement with inclinometric measurements and hydrostatic levelling measurements using connecting points as shown in the diagram on Figure 1. Although displacements are determined using both inclinometers and hydrostatic levels, these values are referred to local coordinate systems. Having measurements from many sensors and methods on one object, but in different coordinate systems, is difficult in global interpretation. Many systems for monitoring dams are based on a common alerting system, the coherence of which comes down to sending messages from completely separate systems, and only then does a human interpret and mutually link these data.

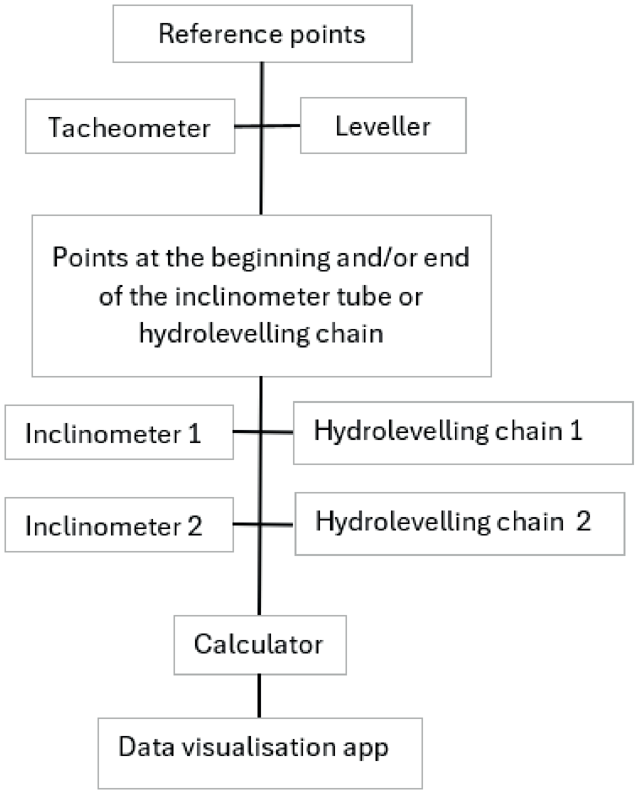

Fig. 1. Diagram of sensor system integration; source: own elaboration

The next integration steps will start with measuring reference points, then measuring points at the beginning and/or end of the geotechnical sensor chain and then jointly processing the data in the calculator and visualising it in an appropriate form (table or graph).

DIGITAL INCLINOMETER CHAINS

In recent years, inclinometer sensors have been widely used in many sectors. Over the years, the improvement in the accuracy of the sensors has enabled their application in many areas of civil engineering, such as road construction, deep excavation, and bridge construction (Komarizadehasl *et al.*, 2022). Inclinometers are also widely used in monitoring hydraulic structures.

To perform the measurement, the inclinometer is placed inside a casing installed in the ground or in the body of the dam. The inclinometer casing has perpendicular guide grooves that allow the measurement of the horizontal displacement of the soil or structure. The angle of inclination along the casing is measured every 0.5 m. The total horizontal displacement at the top of the casing is obtained as a cumulative comparative calculation to the deepest point of the casing known as the fixed point (Ganjalipour, 2021).

The revolution in inclinometer measurements is the introduction of MEMS solutions. The MEMS-based dynamic inclinometer integrates both a three-axis gyroscope and a three-axis accelerometer to measure the tilt in real time. The combination of a gyroscope and an accelerometer provides reliable and accurate dynamic tilt measurements. Typically, the accelerometer and gyroscope data are combined and processed using a set of algorithms based on extended Kalman filters. By using MEMS sensors, it is possible to increase the number of sensors and representative monitoring points and improve the reliability and accuracy of the results. It has been shown that the combination of MEMS with traditional monitoring instruments, together with the potential to build comprehensive wireless monitoring networks and low power consumption, provides a unique opportunity in geotechnical investigations (Barzegar *et al.*, 2022). The MEMS inclinometers enable vertical and horizontal monitoring of installed tubular housings. The inclinometer consists of high-performance MEMS sensors and a digital electronic board, placed inside a steel body with four spring-loaded wheels and a waterproof connector.

HYDROSTATIC LEVELLING

Hydrostatic levelling is a method that uses Bernoulli's laws to determine vertical displacements of engineering structures such as bridges, viaducts, overpasses, tunnels, tall buildings, historic structures, specialist engineering structures, etc. Hydrostatic levelling systems use measurement sensors in the form of a reference sensor and sensors placed at controlled points. The reference sensor is a sensor placed in such a place and at such a point that, in theoretical assumptions, is not subject to vertical displacements and displacements are determined in relation to its height. The idea of the hydrostatic levelling on example of the H-Level system by Sisgeo is presented in Figure 2. In hydrostatic levelling, it is necessary to take into account such parameters as: atmospheric pressure, gravity, density of the liquid flowing through the measurement sensors. It should be remembered that the above parameters are determined with certain mean errors

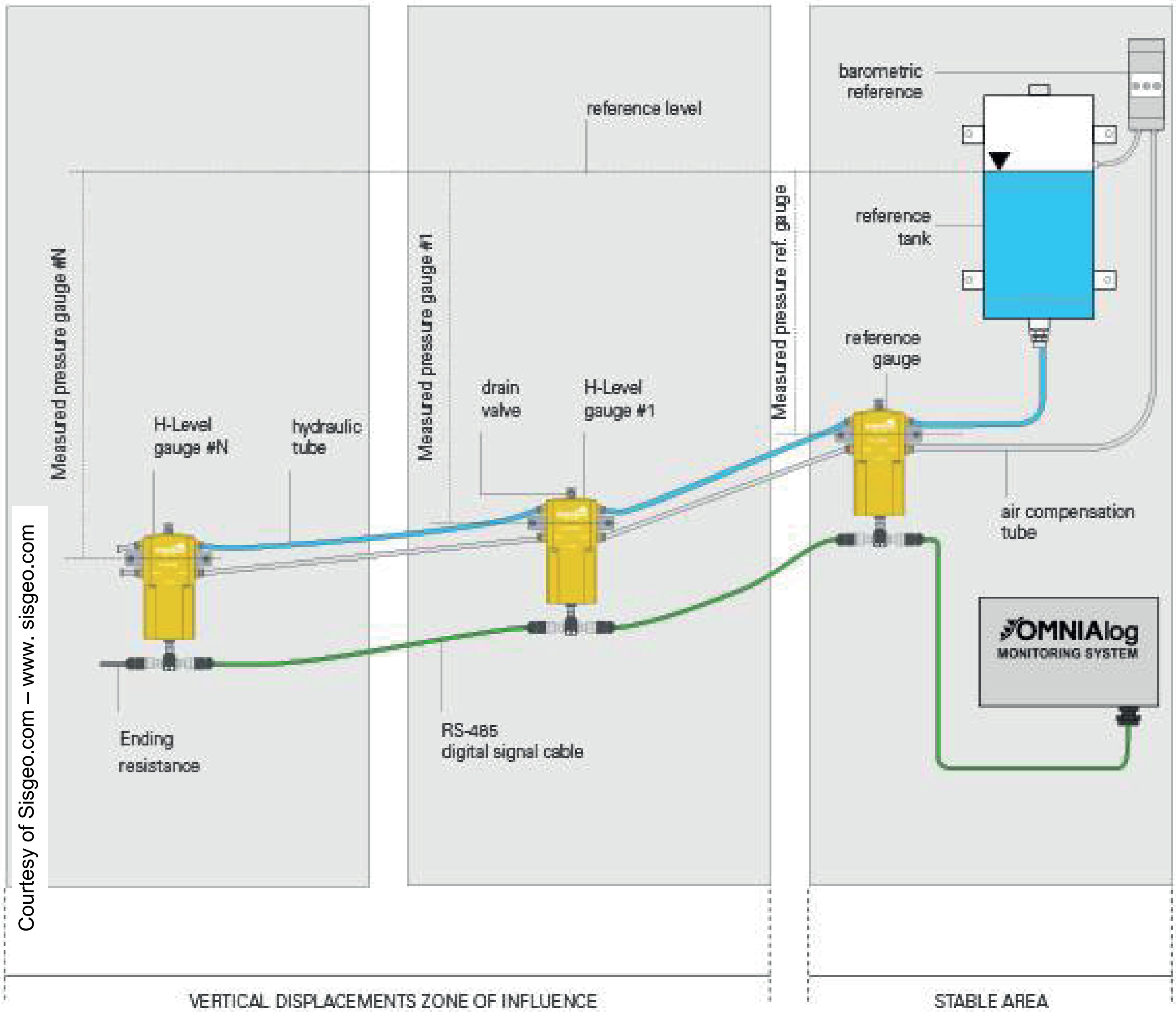

Fig. 2. The operating principle of the H-Level system by Sisgeo; source: https://sisgeo.com/products/settlement-gauges/h-level-liquid-level-systems/

that affect the estimation of the accuracy of the results of vertical displacements (Muszyński and Rybak, 2010; Kamiński, 2022).

An example of a system used in hydrostatic levelling is the H-Level solution from Sisgeo (Photo 1). The H-Level is an automatic liquid level measurement system that enables accurate, long-term monitoring of vertical displacements using a network of connected sensors. This system can effectively measure displacements in the range of 0 to ~500 mm with high accuracy (±0.02 mm). Precise hydrostatic levelling sensors can be installed both inside and outside the facility. All sensors in the system are connected to each other with the same liquid tube, and then they are connected to the liquid expansion tank, which is located above the entire measuring system. This method of system construction allows forcing the appropriate pressure inside it. Vertical displacements of individual sensors mounted on the structure cause changes in pressure inside the system, which is measured at the location of the sensors. When the sensor moves vertically, the corresponding liquid height will change accordingly, independently of all other sensors. Since the fluid pressure can be measured very accurately at each sensor, vertical movement can be calculated from the density of the fluid used. Each sensor is also connected to the other by an air tube to normalise the reference pressure between sensors. In automated systems, data is streamed online within minutes of measurement, so that the movements of the structure can be monitored in real time.

An important element that affects the accuracy of results obtained using hydrostatic levelling measurements is the temperature difference between individual system sensors. In order to minimise the effect of thermal gradient, consider installing sensors with implemented automatic compensation of temperature differences between sensors and strive to arrange measuring devices on one level. In the case of hydrostatic sensor installation in places where significant temperature fluctuations may occur, consider using insulation, both for the sensors themselves and for liquid and air lines.

Photo 1. An example of a system used in hydrostatic levelling is the H-Level solution from Sisgeo; source: https://www.geo-instruments.pl/en/projects/monitoring-building-69-wolska-street

Hydrostatic levelling is a supplement to conventional measurement techniques, especially in places where their use is difficult or even impossible, e.g. measurement in building basements, or measurement of many measurement points at once, located in a complex system of objects. A key aspect in the context of integrating hydrostatic levelling with other geodetic techniques is the mutual connection of the determined vertical displacements in different coordinate systems.

SELECTED GEOTECHNICAL SENSORS: LOW-COST INCLINOMETRIC AND HYDROSTATIC TYPE POSSIBLE FOR USE IN STRUCTURAL HEALTH MONITORING

When discussing the issues related to the use of geotechnical sensors in the context of establishing networks for monitoring engineering objects, it is impossible not to mention the economic aspect. Until recently, the use of sensors such as inclinometers or hydrolevellers was associated with significant costs because only a few companies in the world were involved in their production and distribution. One of these companies is the Italian company Sisgeo, whose sensors can be considered reference in relation to solutions from other companies. For this reason, these were cost-intensive solutions, which meant that this type of measurement sensors were mainly used on objects of strategic importance, in the monitoring of which the economic aspect plays a secondary role, e.g. in the case of dams.

Currently, hydrotechnical sensors from the Far East are slowly entering the global and European markets (Ćmielewski *et al.*, 2020; Cacciuttolo *et al.*, 2023; Lozano *et al.*, 2024). The accuracy and technical parameters declared by their manufacturers do not differ significantly, and sometimes exceed the parameters that characterise European solutions. Examples of such sensors are products from ZC SENSOR or ZHYQ (Fig. 3).

One of the biggest advantages of Far Eastern sensors is their relatively low price, which makes them a more accessible option for companies with a limited budget and can therefore be used on a wider range of engineering structures. Additionally, these

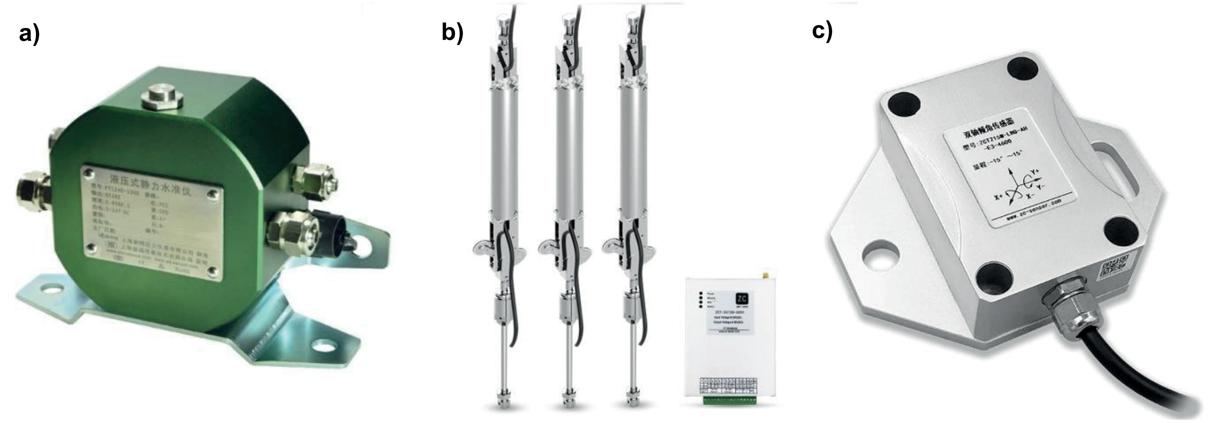

Fig. 3. Examples of hydrotechnical sensors: a) ZHYQ hydroleveller, b) in-place inclinometers, c) ZC SENSOR inclinometer; source: own elaboration based on: https://www.zhyqsensor.com.au/products/hydro-leveling-sensor/ and https://www.inclinesensor.com/

sensors are often widely available on the global market through popular Far Eastern sales platforms, which makes them easier to purchase. It should also be noted that Far Eastern manufacturers often introduce new technologies faster than traditional brands, which gives users of their products access to the latest solutions. However, it is worth noting that there are possible limitations to the use of Far Eastern measurement solutions resulting from the fact that, despite the fact that Far Eastern sensors are becoming more advanced, they may still have quality or durability issues, especially compared to devices from recognised manufacturers such as Sisgeo or GEOKON. The accuracy parameters and operating conditions of commercially available inclinometers, tilt meters and hydrolevellers, taking into account the Far Eastern markets, are presented in Tables 1–3.

Table 1. Accuracy parameters and operating conditions for commercially available inclinometers

Sensor name	Measuring range	Number of axles	Accuracy	Resolution	Operating temperature	Country
SISGEO 0S432HD15S0	from −15 to +15°	2	<±0.01% FSR <±2.00 mm per 30 m ±0.003°	0.0001°	from −30 to +70°C	Italy
GEOKON Model 6300	from −10 to +10°	1	±0.1% FS ±0.02°	0.003°	from −20 to +80°C	USA
ZC SENSOR ZCT-CX300B	from −30 to 30°	2	0.005°–0.01°	0.001°	–	China
MAS VIPI-S-DA	from −30 to 30°	2	±5 mm per 30 m (±0.01°)	0.0035°	from −20 to +60°C	China
BSIL (CGEO-IPIA)	from −15 to 15°	2	±0.1% FS ±0.03°	0.003°	from −20 to +80°C	China
GEOVAN GV-2402	from −10 to 10°	–	±0.05% – ±0.1%	–	from −25 to +85°C	Korea
Vigor technology SST2200	from −10 to 10°	2	±0.005° – ±0.01°	0.002°	from −40 to +85°C	China
Tah-li Digital in-place inclinometer	from −30 to 30°	–	±0.002°	0.0002°	from −40 to +80°C	Singapore
ENCARDIOEAN-56	from −15 to 15°	2	±0.1% FS ±0.02°	0.002°	from −20 to +80°C	India

Explanations: FSR = free spectral range, FS = full scale. Source: own elaboration.

Table 2. Accuracy parameters and operating condition for commercially available tilt meters

Sensor name	Measuring range	Number of axles	Accuracy	Resolution	Operating temperature	Country
SISGEO 0S543HD3600	from −180 to 180°	3	<±0.02° (<±0.0055% FSR @360°)	0.0001°	from −30 to +70°C	Italy
ZC SENSOR ZCT2xxM-LBS-Ax-H5-460x	from −15 to 15°	2	0.005°–0.01°	0.001°	from −40 to +85°C	China
BWSENSING BWH527	from −30 to 30°	2	0.005°	0.0007°	from −40 to +85°C	China
BWSENSING BWM827	from −30 to 30°	2	0.005°	0.001°	from −40 to +85°C	China
BWSENSING BWM427	from −90 to 90°	2	0.01°	0.001°	from −40 to +85°C	China
GEOVAN GV-2401	from −10 to 10°	2	from −0.1% to 0.1%	–	from −25 to +85°C	Korea
Vigor Technology SST162	from |5°| to |180°|	2	from −0.05° to +0.05°	0.01°	from −40 to +85°C	China
RION TECH ACA626T	from |10°| to |90°|	2	0.003–0.03°	0.001°	from −40 to +85°C	China
RION TECH ACA826T	from |3|° to |90°|	2	0.002–0.01°	0.0005°	from −40 to +85°C	China
WIT HWT6053-485	X from −180 to 180°, Y from −90 to 90°	6	0.001	0.001	from −40 to +85°C	China

Source: own elaboration.

Table 3. Accuracy parameters and operating conditions for commercially available hydrolevellers

Sensor name	Measuring range	Accuracy	Resolution	Operating temperatures	Country
SISGEO 0HLEV050D02	0–500 mm	±0.07%FS	0.002%FS	from −20 to +70°C	Italy
ZHYQ PT124B-226	0–500 mm	±0.05%FS	–	from −20°C to +85°C	China

Explanations: FS as in Tab. 1. Source: own elaboration.

An additional element that may limit their use on a large scale may be problematic technical support and service availability, which may be severely limited, which may be a problem in the event of device failure.

Another problem may be the lack of compliance with European standards – not all sensors from the Far East meet the rigorous European standards for precision and safety, which may limit their use in some industries.

To sum up, sensors from the Far East are a competitive alternative to products such as Sisgeo, offering a wide range of devices with various applications in geodesy, construction and environmental monitoring. Thanks to lower costs and increasing quality, they are becoming an increasingly popular choice on the market. Nevertheless, before using them in networks for monitoring engineering facilities, it is worth carefully assessing their quality, technical support and compliance with the required standards to ensure their effectiveness and reliability in long-term use. For investors and contractors looking to optimise costs without drastically compromising quality, alternative sensors from the Far East may be a viable solution – especially in temporary or budget-constrained projects. In high-risk applications (e.g. monitoring dams or underground tunnels), proven European brands are still often chosen, but even there is room to test and implement Asian alternatives as complementary components.

RESULTS AND DISCUSSION

Integration of geodetic and geotechnical data requires the use of not only an appropriate method of interconnecting measurements, but also a method of processing the obtained results. The article presents the methodology of integrating geodetic data and inclinometric measurements performed in a vertical pipe (Fig. 4) and a horizontal pipe (Fig. 5). In both of these methodologies, the key element is the assumption that inclinometric measurements are developed in relation to a moving point, the coordinates of which *X*, *Y*, or *H* are determined by an appropriate measurement method. This approach allows for a common system for the measurements performed. In addition, it frees the processed data from the theoretical assumption of the stability of the end of the inclinometric profile, in relation to which changes in the position of subsequent points on the profile are determined. The authors' practical experience indicates that this assumption is often incorrect and leads to incorrect results, and sometimes to altering a threat situation that does not occur.

A certain distinction in terms of the integration of inclinometric measurements is the method of calculating the displacement values. In the case of vertical pipes or inclinometric chains (Fig. 4), the readings from the probe or sensors are referred to a point at the top of the profile, the coordinates of which are determined in parallel using the tacheometric method.

In the case where the inclinometric measurement is performed in the horizontal system (Fig. 5), we start by converting the angular values from the inclinometric probe or sensors at the height between each adjacent measuring point, and then we enter the obtained height values into the levelling lines of the measured benchmark network as typical height differences between benchmarks resulting from direct levelling (Fig. 6). The observations from the level and from the inclinometric readings should be appropriately weighted depending on the measurement method.

The last approach presented is the methodology of linking measurements from hydrostatic levelling with geometric levelling (Fig. 7). In this variant, data integration involves not only determining height changes in the same units, but also jointly equalising the data. The element connecting both measurements are benchmarks located at the beginning and the end of the

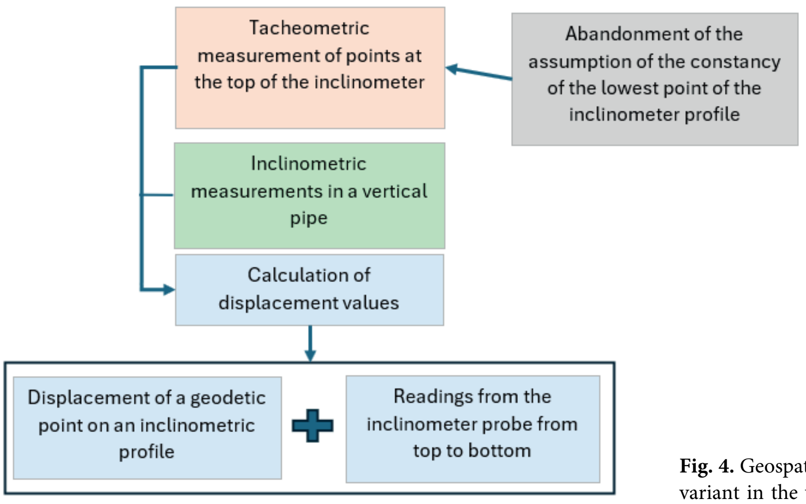

Fig. 4. Geospatial data integration scheme – inclinometric measurement variant in the vertical system; source: own study

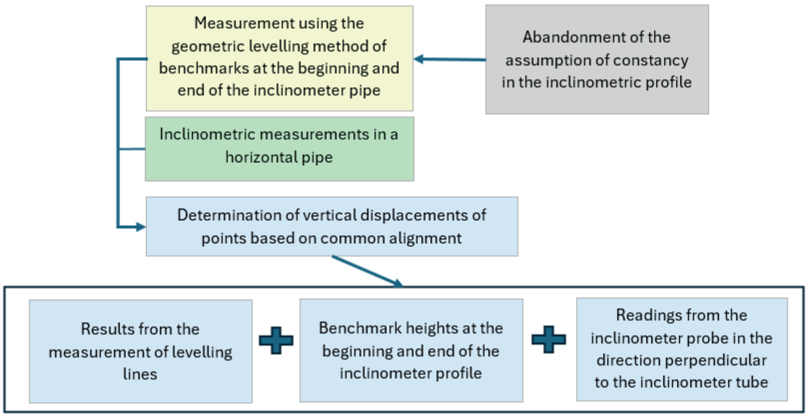

Fig. 5. Geospatial data integration scheme – inclinometric measurement variant in the horizontal system, source: own study

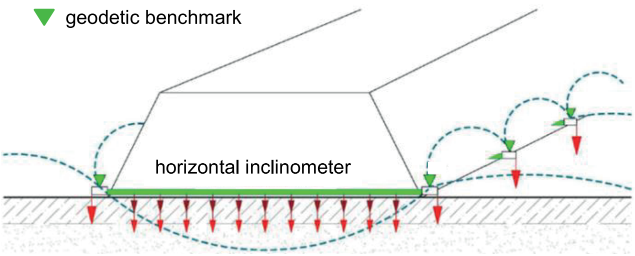

Fig. 6. Example of a connected levelling network with inclinometer measurements in the horizontal system; source: own study

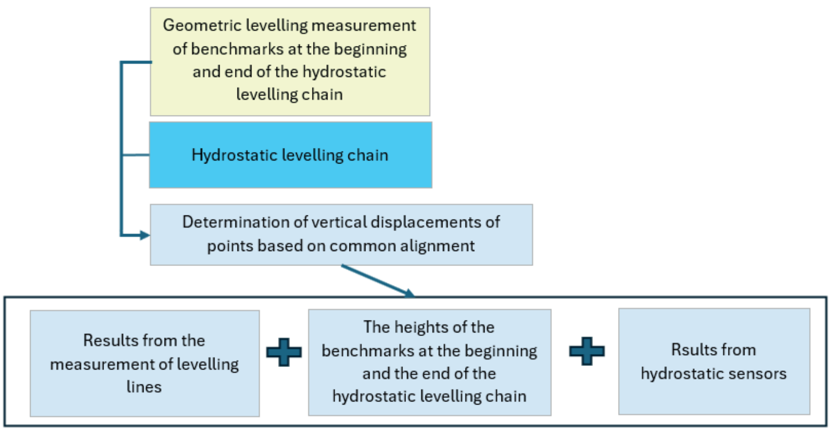

Fig. 7. Geospatial data integration scheme – variant of using the hydrostatic levelling chain; source: own study

hydrostatic levelling chain. The obtained height values are included in the levelling lines of the measured benchmark network as typical height differences between benchmarks resulting from direct levelling. In this case, the leveller observations and readings from hydrostatic sensors should also be appropriately weighted.

CONCLUSIONS

The proposed methodology for integrating geodetic observations (tacheometry, geometric levelling, Global Navigation Satellite System – GNSS) and data from selected geotechnical sensors: inclinometers and inclinometer chains with micro-electro-mechanical system (MEMS) sensors and hydrostatic levelling sensors extends the scope of collected data, but also allows, to some extent, for mutual verification of results and analyses conducted on their basis, reliability, understood as the ability to eliminate outlier measurements, and as a result, reduce incorrectly interpreted "notifications" and "alerts" about the condition of the object.

The key contribution of integrating geotechnical measurement with geodetic measurement results in:

- determination of settlement in a global reference instead of only deformation at the point of installation of the support or inclinometric chain; this statement also applies to the hydrostatic levelling profile;
- increasing the correctness of the estimation of the measurement error of each point in the inclinometric profile (vertical and horizontal) and the hydrostatic levelling profile;
- higher reliability of the system, understood as the ability to eliminate outlier measurements, and as a result, reduce incorrectly interpreted "notifications" and "alerts" about the condition of the object.

To apply the proposed integration schemes, modifications to the methods used so far are required by extending the measurement network for tacheometric measurements with geodetic points on inclinometric and hydrostatic profiles and changing the method of calculating and presenting data so as to take into account the movements of profiles determined from tacheometric measurements.

This method demonstrates a viable framework for modernisation and connection into a single monitoring system: the geodetic control network for examining displacements and elements of Automatic Technical Control System for Dams (ASTKZ, abbrev. from Pol. Automatyczny System Technicznej Kontroli Zapór) / Structural Health Monitoring (SHM) elements. The potential applications of proposed methodology in SHM systems:

- assessment of slope and escarpment stability in real time in an external system,
- possibility to use inclinometric measurements without assuming the constancy of the initial point,
- monitoring the technical condition of buildings in a uniform coordinate system for all devices.

Further steps that need to be taken to implement the proposed solutions include: conducting tests on a real hydrotechnical facility, analysing the accuracy and reliability of the obtained results, taking into account the specific conditions prevailing at the facility, determining the possibility of full automation of the solution in the context of geodetic measurements (using robotic tacheometers or code levels). Also in the case of continuous measurements, a certain problem of the large amount of data acquired needs to be solved.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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