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Modernising the control network for determining displacements in hydraulic structures using automatic measurement techniques

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Abstract: Over the last two decades, geodetic surveying has seen significant advancements with terrestrial and unmanned aerial vehicle (UAV) laser scanning, alongside automatic observations being increasingly utilised throughout the construction process.

In the context of dam structures, periodic geodetic displacement measurements are a compulsory component of control measurements and safety assessments. In Poland, however, control measurements have largely remained rooted in traditional techniques such as classic linear and angular measurements and precise levelling. These methods are typically carried out within distinct control networks, i.e. without dual-function observation points and targets. Furthermore, network points (pillars, targets) have often not been renewed since their installation several decades ago, and glass discs, used for crown measurements in the baseline method, frequently face damage.

Changes in property ownership and modifications in environmental regulations are compounded by these issues, which often impede the proper upkeep of the sight line.

The article proposes the adaptation and reconstruction of control networks to incorporate automatic observation techniques, including linear and angular measurements. This approach includes activities aimed at reconstructing and supplementing damaged network structures, modernising the geodetic process of determining structure displacements, and enhancing the accuracy, credibility, and reliability of geodetic displacement measurement results.

The article presents the findings of an inventory assessment conducted on the existing control network infrastructure, focusing on the analysis of displacements for structures with diverse constructions and functions – a concrete dam (class I) and a water damming weir with a water intake. Furthermore, it presents practical conclusions regarding the efficient organisation of geodetic control measurements.

Keywords: automatic measurements, control network, dams, engineering geodesy, geodetic displacement measurements, LiDAR

INTRODUCTION

According to Kledyński (2011a, p. 54), "monitoring and diagnosing hydraulic structures provides knowledge about the technical condition of the structure, i.e., its load-bearing capacity and usability. Therefore, these processes[1] form the basis for formulating appropriate assessments." A specific type of assessment – especially in the case of damming hydraulic structures – is the safety assessment.

[1] Which include various control measurements (authors' note).

The concept of monitoring engineering structures is very broad and, with the development of measurement and diagnostic capabilities (Kledyński, 2011a; Kledyński, 2011b), it covers multiple aspects engaging an increasing number of specialists from various fields. The beginnings of interest in ensuring the safety of dams date back to ancient times when the first structures of this type were created. The tragic consequences of dam disasters, technical progress, and the development of scientific research have led to the rapid development of dam control techniques.

Monitoring damming structures is an interdisciplinary task, and in the assessment of the safety of hydraulic structures, it is necessary to combine various measurement techniques, computational techniques, and the experience of specialists from various fields of engineering. Control measurements, collection and processing of data about the structure, and preparation of the technical condition assessment of the dam are performed by hydrotechnicians, geotechnicians, surveyors, hydrologists, geologists, structural mechanics, concrete and building material specialists, and many others.

In Poland, geodetic control measurements and inventory measurements to determine the technical condition and safety of hydraulic structures are required by the law (Ustawa, 1994; Ustawa, 2017) and related regulations, in particular the Regulation of the Minister of the Environment on the technical conditions required from hydraulic structures and their location (Rozporządzenie, 2007). It is worth emphasising that the Construction Law classifies hydraulic structures as buildings structures. According to the provisions of the law, a hydraulic structure must be used and maintained in accordance with the national regulations, including technical provisions, applicable standards, and the principles of technical knowledge, in a way that ensures the safety of the structure and the safety of use. Structures should be subjected to at least once a year periodic control to check the technical condition and at least once every five years to check the technical efficiency and utility value of the entire building structures. Hydraulic structures are also subject to additional inspections resulting from the water law. In addition, it is necessary to carry out control of the safety of the structure in case of:

– detection of unusual phenomena during the current operation of the structure,
– passage of a flood wave,
– unusual, intense ice phenomena.

Owners or managers of these structures are obliged to ensure their proper technical condition, safety, and proper functioning, as well as to carry out research and measurements enabling the assessment of the condition and safety of the structure, especially in terms of seepage, the state of discharge devices, and changes in the upstream and downstream pool of the structure. Depending on the class of the structure, various parameters may be subject to control, including vertical displacements (settlements and uplifts), horizontal displacements and inclinations, deviations from the vertical, deflections, vibrations, and linear, angular, and shape deformations, as well as the condition of concrete – its properties and cracking of its mass and surface.

Modern measurement technologies provided ever greater possibilities for more accurate monitoring of changes occurring in engineering structures, as well as speeding up measurement work, minimising the number of gross errors, and reducing the costs and time of measurements. As a result, they ensure a more reliable assessment of the technical condition and safety of hydraulic structures. The integration of measurements, including the numerical modelling of the structure's behaviour and various types of data, allows a more comprehensive, understandable, and transparent assessment (Zaczek-Peplinska, 2018; Zaczek-Peplinska and Kowalska, 2022).

Research work and control measurements using terrestrial laser scanners (TLS), low-altitude photogrammetric measurements (UAV), and airborne laser scanning (ALS) are already being conducted in various hydraulic structures. However, these technologies are still only used as supplements to traditional measurement methods: precise levelling for determining horizontal displacements and measurements in the angular and linear network for determining horizontal displacements of targets on the structure.

The need to introduce modern measurement technologies and automation in determining displacements and deformations of engineering structures is increasingly reported in the literature. For example, the study by Pasternak (2023) compared four different measurement techniques: photogrammetry AUV, airborne laser scanning, terrestrial laser scanning, and linear and angular measurements – Figure 1 (Spreafico *et al.*, 2015; Haerani

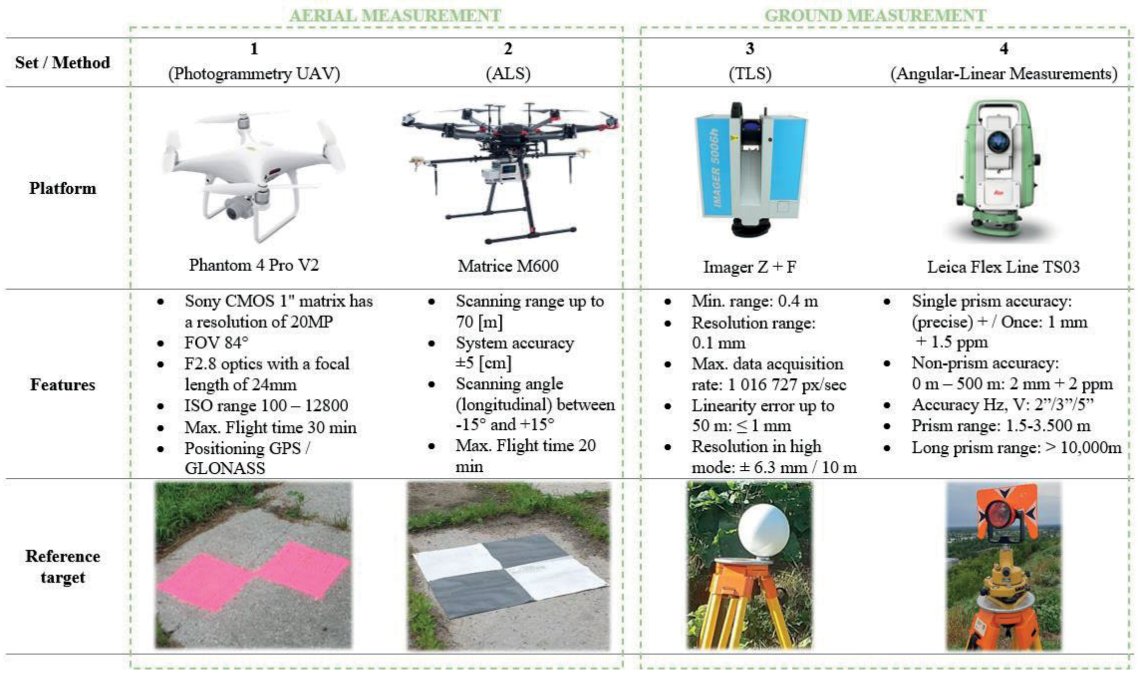
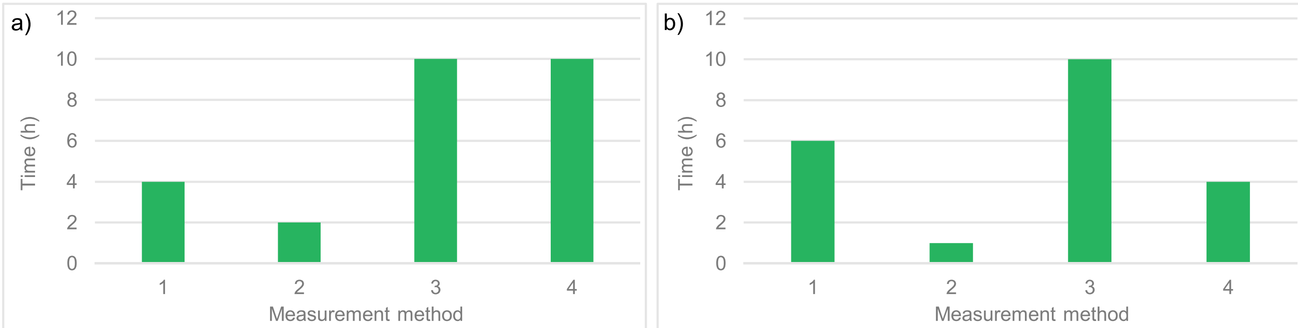


Fig. 1. Overview of various measurement techniques; source: Pasternak (2023)

et al., 2016; Stumvoll, Schmaltz and Glade, 2021) in the context of their effectiveness in determining displacements. The analysis was performed from an economic point of view, taking into account aspects such as time (execution of fieldwork, conducting office processing) and the number of people needed to perform the measurement. The results of the comparison of the proposed measurement methods 1 and 2 presented in Figure 2 show a clear advantage both in terms of the time of measurement, office processing, and the number of people needed to perform field measurements. However, the most accurate results were obtained using traditional methods: trigonometric levelling and linear and angular measurements.

geotechnical and hydrotechnical sensors and inclinometers indicate changes occurring between the elements of the structure and in the ground. Geodetic data and data from sensors complement each other and provide a certain mutual control of indications.

Even 10–20 years ago, the designs of dam control networks did not consider the possibility of automatic measurements. The geodetic networks currently used to study the displacements of structures are not adequately protected, and their condition often does not allow for the simple installation of an automatic measurement system. The further part of the article presents two examples of hydraulic structures: a concrete dam (class I) and



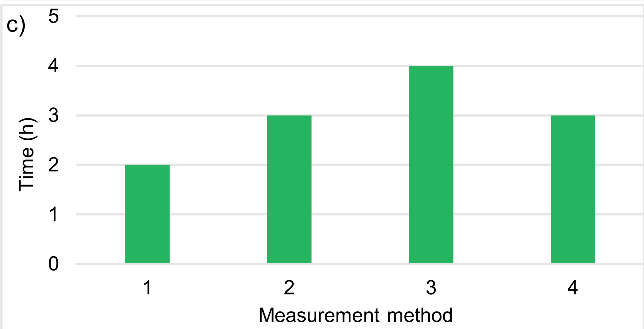


Fig. 2. Comparison of the applied methods in terms of: a) data acquisition time (h), b) point cloud development time (h), c) the number of people necessary to perform the measurement; measurements methods: 1 = photogrammetry UAV, 2 = airborne laser scanning (ALS), 3 = terrestrial laser scanners (TLS), 4 = angular-linear measurement; source: Pasternak (2023), modified

The comparison indicates that the best solution for monitoring large-scale engineering structures with a high level of safety risk in the event of a facility failure would be the automation of geodetic measurements and the introduction of an integrated automatic system for technical control of the dam (physical sensors for hydrogeology/hydrotechnics, seismic and geotechnical applications) with measurements for determining vertical and horizontal displacements. This would reduce the time required for data acquisition and the involvement of employees, and allow for "on-demand" measurements and data transmission in near-real time (Karsznia, 2022), and further research towards the application of Light Detection and Ranging (LiDAR) technologies (TLS and ALS) (Ramos-Alcazar, Marchamalo-Sacristán and Martínez-Marín, 2015; Li *et al.*, 2021; Zaczek-Peplinska and Kowalska, 2022). Automation of geodetic control measurements of hydrotechnical facilities will shorten the measurement time and avoid the need for employees to perform work in hard-to-reach places and at heights. Such activities, in addition to increasing the reliability and completeness of measurement data, also increase the safety of surveyors performing measurements. It should be noted that the measurements of absolute displacements in the external reference system show the actual state and changes within the entire facility and in its vicinity covered by the control network. Data recorded by

water damming weir with a water intake, problems with maintaining their control network, and proposals for adapting the network for (i) precision trigonometric levelling and (ii) automatic angular and linear measurements to determine horizontal displacements. The basic principles of automation and modernisation of control measurements of structures have been described many times in various publications (Zaczek-Peplinska, 2007), however, the issue of maintaining the measurement network and its adaptation is not so often addressed. The field cases described in this article and proposals for adapting the network for introducing automatic measurements were drawn from the experience of the GEOalpin company.

STUDY MATERIALS AND METHODS

AUTOMATIC GEODETIC MONITORING SYSTEMS

Systems for monitoring the state of an engineering structure have been developed for many years by both manufacturers and suppliers of geoinformation technologies (Topcon, no date; Leica GeoMoS, 2015; Leica Geosystems AG, 2018; Trimble Monitoring, 2023), (Świdziński and Janicki, 2016), as well as scientific institutions (Jäger and Spohn, 2017). There are many dedicated tools, the creation of which was inspired by specific needs. For example, the paper (Wilde *et al.*, 2017) describes the main points of such a system in the context of monitoring the roof of the Forest Opera in Sopot. Other similar systems have been described in numerous publications – for example (Karsznia, 2008; Yi and Li, 2013; Zaczek-Peplinska, Pasik and Popielski, 2013; Karsznia and Tarnowska, 2014; Woźniak and Odziemczyk, 2017).

Examples of the first implementations of automatic geomonitoring systems in Poland are those at the KGHM Polska Miedź SA mining company (Świdziński and Janicki, 2016), the Lignite Mine in Bełchatów (Pol. Kopalnia Węgla Brunatnego „Bełchatów") (Karsznia, Skalski and Czarnecki, 2010), or during the construction (and still ongoing expansion) of the second line of the Warsaw Metro (Pol. Metro Warszawskie) (Królikowski, 2023). In highly industrialised countries of the world, the development of automatic geodetic monitoring systems has been observed for several decades. There are many examples of their implementation on hydraulic structures (Henriques and Casaca, 2003; Gökalp and Taşçi, 2009). There are also numerous textbooks presenting the assumptions and basic conditions of such systems, published in many languages – mainly in English and German (Sanso and Gil, 2006; Möser *et al.*, 2013). One can also find many similar studies in Polish, for example Wolski (2008).

Despite the undeniable advantages of automatic displacement monitoring systems, in Poland, apart from the previously mentioned KGHM Polska Miedź SA at the "Żelazny Most" reservoir, such types of systems have not been integrated into the automatic technical dams control systems (structural health monitoring systems – SHM). Geoalpin sp. z o.o. – a Polish engineering surveying company prepared the first proposals for the implementation of automatic solutions on dams. Such systems require the following basic conditions for control networks:

- vertical and horizontal displacements should be determined in one integrated linear and angular network, supplemented by a network of precise levelling benchmarks only inside galleries and on the crowns of structures – something that is not included in the current "Guidelines for conducting research, measurements, assessment of the technical condition and assessment of the safety status of water damming structures" developed by the Technical Dam Control Center (Pol. Ośrodek Technicznej Kontroli Zapór IMGW-PIB – OTKZ) (Sieiński and Śliwiński, 2020);
- positions of motorised total stations playing the role of linking points between groups of control and reference points should be located in line in front of the structure (on the downstream pool, on islands, or on both sides of watercourses) and their position should be controlled by integrated GNSS antennas (Global Navigation Satellite System – former GPS);
- control points (targets) should be stabilised in the form of precise wall prisms that can be automatically detected by Automatic Target Recognition (ATR) by total stations at observation points;
- sight lines from observation points should be maintained and protected from development by the provisions of the Water Law (or executive acts);
- the reference point network should meet the following technical conditions: (i) their location should be outside the range of influence of the monitored structure, (ii) points observed from total station positions should be equipped with precise prisms and GNSS antennas to control the stability of the system, (iii) other reference points should be observed using only GNSS; (iv) necessary control of system stability should be using linear and angular measurement techniques and precise levelling every 3–5 years (necessary maintenance of benchmarks and positions with forced centering on poles);
- power supply and teletransmission for instruments should be protected;
- the system should be integrated with the automatic system for technical control of the dam (structural health monitoring) on a single web-based platform, which would allow the introduction of a single alert system and automatic preparation of reports for technical condition assessments and hazard assessments.

Thus prepared control network does not have to be permanently equipped with measuring equipment. There are monitoring solutions that require the deployment of instruments and GNSS antennas at linking points (observation points) and reference points, and the performance of a control measurement 2–6 times a year, with the deployment of the system with secured lines of sight taking about 2–3 h and the measurement itself not taking more than 2 h (including control and calibration measurements after deploying the system). It should be noted that systems allowing for constant monitoring have the highest reliability indicators.

The current state of maintenance of geodetic control networks on hydraulic structures leaves much to be desired. In numerous instances, a comprehensive overhaul of the existing infrastructure would be necessary to accommodate the installation of an automatic geodetic monitoring system. This infrastructure renovation would entail modifying the distribution of points across all groups – benchmarks, control points on the structure, and linking and reference points.

In 2005, the need for modernising control networks in Poland was underscored in a paper presented at the Technical Dam Control Conference in Zakopane (Prószyński and Zaczek-Peplinska, 2005). Regrettably, almost two decades have passed since then, yet the progress remains insignificant. Numerous structures still demand significant reconstruction and adaptation to current measurement technologies.

Ideally, these renovations should already incorporate the requirements of automatic monitoring. This proactive approach would make the later installation of the system feasible.

EXAMPLES OF THE PRESENT STATE OF CONTROL NETWORKS

The inventory process involved the control network of a heavy concrete dam, height of 32.5 m, built in the 1940s. The most significant challenge with this structure is the use of antiquated types of sight targets for observing the crest using the baseline method (Photo 1). The application of these temporarily placed markers on the structure inhibits the automation of monitoring measurements. Using steel sight targets on the dam's downstream wall, fashioned in the form of painted cubic blocks with contrasting colours, likewise precludes the utilisation of automated measurements. Additional challenges are posed by the overgrown vegetation obscuring sightlines at the observation stations of the horizontal reference point network (Fig. 3).

Photo 1. Targets for observing the crest displacement using the baseline method (phot.: *J. Zaczek-Peplinska*)

facility's maintenance operations, thereby reducing future costs associated with the implementation of an automatic system.

RESULTS AND DISCUSSION

THE STRATEGY FOR MODERNISING CONTROL NETWORKS

Through our inventory and design work, we have developed primary proposals for revamping the control network for various structures. This is based on the premise of maintaining the positions of control points on the structures to ensure continuity of interpretation and ongoing monitoring.

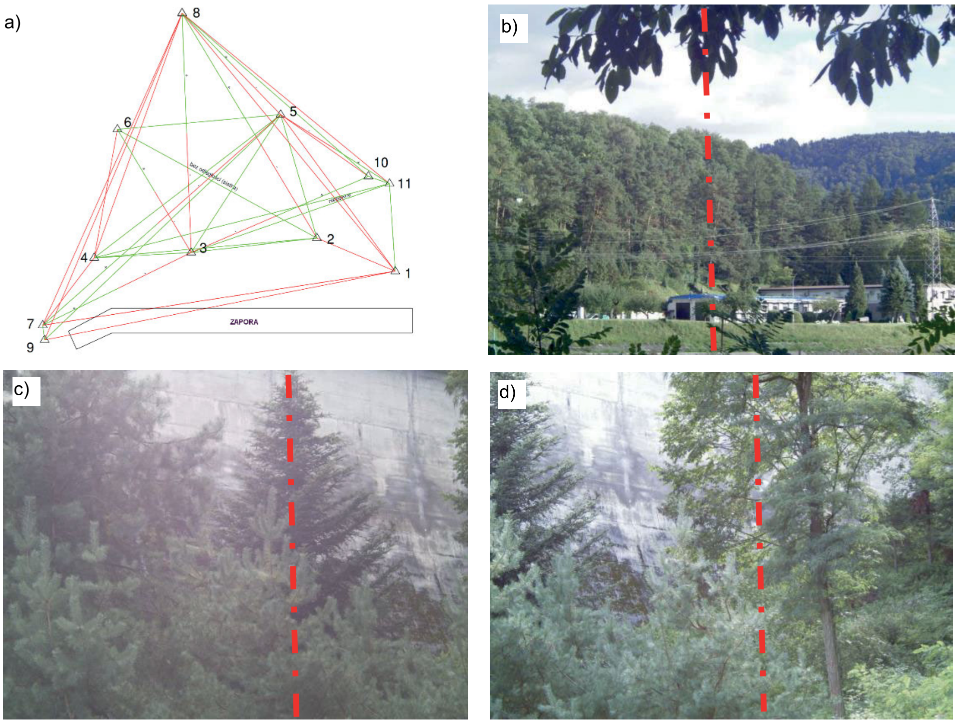


Fig. 3. Inventoried network of reference points for the control network to study the displacement of the concrete dam: a) sketch of observations from reference points, b) sight line from point 8 to point 1; c) sight line from point 4 to point 153; d) sight line from point 15 to point 155; source: own elaboration and photos taken through the total station's telescope (phot.: *M. Budzisz*)

During the inventory of the control network for the weir with a water intake, built in the 1970s, we found the lack of stabilisation of one of the pillars despite complete documentation and annual displacement determination plans using the baseline method (Fig. 4) and an insufficient network of points (two fixed benchmarks and one on the retaining wall, with a minimum of five reference benchmarks required) located on the swampy ground on the water intake side (Fig. 5). There is no possibility of continuing the determinations of absolute displacements of the weir crest with the current network structure.

The aforementioned examples of control network degradation for the examination of displacements in hydraulic structures are merely a snapshot of the issues identified. These issues impact the manner in which manual measurements are executed and the ensuing quality and reliability of their results. In numerous instances, refurbishment of the network is essential. Adapting the network for automated measurements and incorporating cutting-edge measurement technologies can be integrated into the

In the case of a concrete dam, the fundamental requirements include:

- enhancing or altering the form of target stabilisation towards precision prisms, and increasing the number of targets (this change, despite using automatic measurement, does not significantly impact the time and costs related to periodic measurement; furthermore, it ensures the completeness of the measurement data, even when observing all targets becomes unfeasible due to circumstances such as repair works or the lack of an unobstructed line of sight);
- modifying the method of measuring the baseline on the dam's crown and vector measurements in the reference point group (outside the structure) to periodic control measurement utilising GNSS satellite techniques (these adjustments eliminate the need for the line of sight, particularly from points situated on sites no longer owned by the company);
- densifying the network of observation positions for angular and linear measurements using points with lightweight

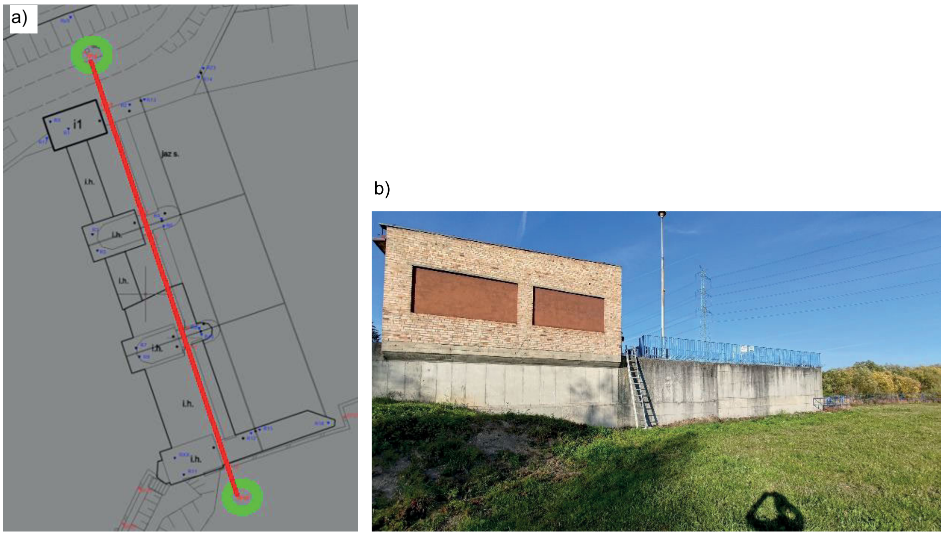


Fig. 4. Baseline for the weir: a) design of the installation, b) area where construction work was left unfinished (no possibility of stabilising an observation post of the suitable height); source: own elaboration, phot.: *L. Saloni*

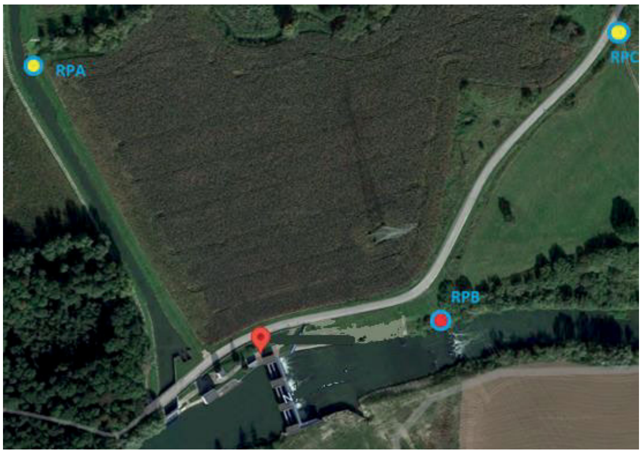


Fig. 5. Location of the fixed points currently employed for monitoring weir displacements; benchmark RP6 is situated on the damaged concrete sections of the weir; source: own elaboration based on Google Maps

construction (these points' displacement would be monitored within the automatic system);
- partially transitioning the precision leveling benchmark network to points that enable automatic measurement using the trigonometric leveling technique.

These fundamental modifications are graphically represented in Figure 6.

Preliminary accuracy analyses (a priori) of the displacement determination in the hybrid networks were performed for both proposed solutions, utilising angular-linear measurements, trigonometric levelling, and GNSS measurements. These analyses demonstrated adequate precision for the evaluation of the structures' condition and associated risk. The illustration represents a draft of the fundamental modifications in the geometry and control network setup for a high concrete dam.

For a smaller weir, we particularly propose altering the monitoring of the crown using the baseline method:
- abandoning the direct measurement on the crown due to the impracticality of positioning points defining the baseline on both river banks along the crown's axis and the presence of technical equipment and safety barriers on the crown;
- establishing observation posts in front of the structure on the downstream pool; the constancy of these observation posts would be controlled via periodic vector measurements in the reference point network;
- augmenting the reference point network to encompass both river banks, ensuring points are located on stable lands owned by the water supply company;
- positioning targets (prisms) on the crown structure on the upstream pool, rather than baseline points on the crown;
- installing an automatic system for monitoring control points on the structure – this system would involve a simple, temporary setup of motorised total stations during control measurement periods (twice a year).

The fundamental suggestions are depicted schematically in Figure 7.

Preliminary accuracy analyses (a priori) of displacement determination in the hybrid networks were conducted for both proposed automated solutions, utilising linear and angular measurements, trigonometric levelling, and GNSS measurements. These analyses demonstrated sufficient precision for the evaluation of the structures' condition and related risks. Utilising the combination of motorised Leica TPS 1201 total stations and GNSS antennas, and Leica GMP 104 prisms employed as targets, the following accuracies were achieved:
- the precision of determining the horizontal displacement of a control point on the crown of the concrete dam: ±0.1 mm, with automatic observations taken from 6 viewing stations;
- the precision in identifying the deviation of a controlled point using the baseline method perpendicular to the weir's crown (smaller structure): ±0.2 mm, when applying observations from two observation posts defining a baseline parallel to the structure's crown.

In both outlined projects, a key feature of the proposed automatic system is an integrated database of control points, complete with visualisation and archival modules. It is noteworthy that the system solutions for both the installation and software can diverge significantly, extending beyond the IMSGeo service proposed by GEOalpin Ltd (IMSGeo, 2021).

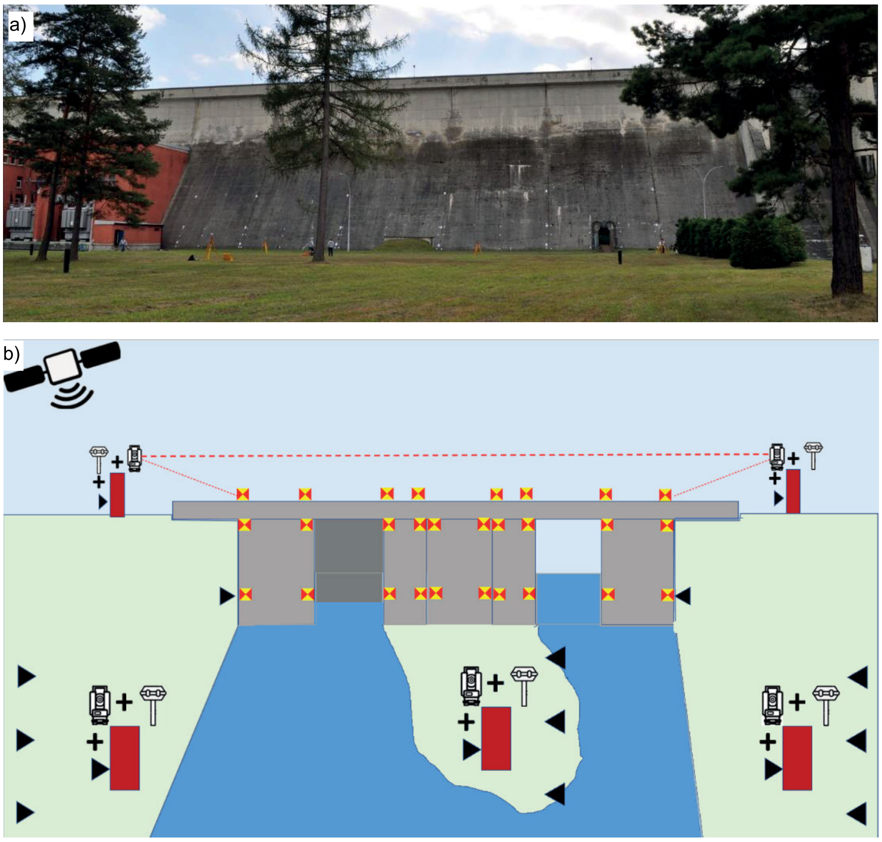


Fig. 6. Suggested approach for a control network of the concrete dam: a) view of the structure (photo taken from the island: location of the middle pole in the draft), b) draft of the fundamental alterations in the geometry and infrastructure of the control network; source: own elaboration, phot.: *J. Zaczek-Peplinska*

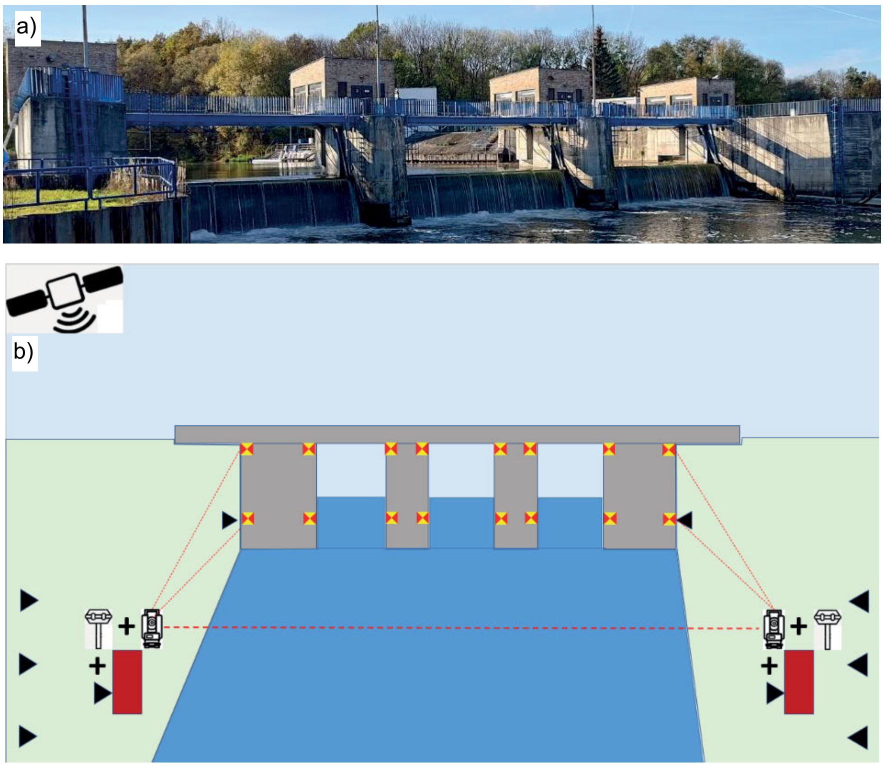


Fig. 7. Suggested approach for a control network of the weir: a) view of the structure, b) draft of the fundamental alterations in the geometry and setup of the control network; source: own elaboration, phot.: *L. Saloni*

KEY INSIGHTS FROM THE RECENT INVENTORY OF CONTROL NETWORKS

The inventory and design work has yielded several practical insights concerning the current state of the networks, offering guidance for those responsible for network condition and organising control measurements.

On the majority of the structures, the introduction of modern measurement techniques and network modernisation is lacking. This is primarily due to the absence of requisite staff competencies and stringent financial constraints resulting from the transformation of the supervisory system over hydraulic facilities and the facilities' acquisition by energy companies. There is a continued reliance on network construction techniques from the 1960s–1980s.

The maintenance of structures and targets is neglected despite the evident wear and tear over time. In addition, individuals responsible for geodetic measurements struggle with performing measurements correctly because methods such as baseline measurements on structure crowns have become uncommon.

Motorised instruments for quick and reliable measurements are standard in contemporary engineering geodesy practice and geodetic investment services (in Poland, as defined by professional rights no. 4). Unfortunately, due to the lack of prisms on hydraulic structures, surveyors are compelled to resort to manual measurement techniques. This approach increases both the time and costs of work and necessitates larger measurement teams.

Furthermore, the potential of control measurement techniques using GNSS satellite measurements, which are commonly used elsewhere, is undervalued in hydrotechnics in Poland. These could prove extremely beneficial in managing often extensive reference networks.

A primary challenge in maintaining a control network, given the annual shifts in measurement contractors due to tender procedures, is the absence of control and measurement device catalogues. Unlike the standard practice for detailed geodetic control points or implementation control points established for the construction and operation of engineering structures, a clear record is not maintained for hydraulic structures. Each network point should be catalogued and possess a specific card/metric describing the location, device type with parameters (for instance, forced centering parameters), methods used to secure the instruments, and changes introduced during operation.

A pervasive issue in this field is the inadequate safeguarding of reference networks. Ideally, these networks should be positioned outside the influence zone, i.e. beyond the structure in question. However, in many instances, both formal and actual control over these networks have been lost. Points are often situated on private properties where access is inconvenient or sometimes even impossible due to new residential and commercial developments, fences, or alterations to previously unpaved roads. This predicament arises from changes in property ownership around hydraulic structures and the indifference of new private owners towards public utility assets, a stark contrast from the communist era (1945–1989) when the lands around the structures were state-owned and thus network maintenance was much less problematic.

A significant challenge to the credibility and reliability of control measurement results in Poland results from the current practice of commissioning measurement work. An annual public tender where the lowest price is the sole determining factor encourages measurements to be performed carelessly by those who may lack the necessary theoretical knowledge and practical experience in geodetic displacement monitoring. Regular and periodic control of a hydraulic structure can be likened to routine medical check-ups where it is advisable to continue care with a single specialist. Just as frequently changing the physician may adversely affect the patients' situation, likewise, a similar practice may be problematic for the safety of engineering structures. Hence, periods covering individual control measurement contracts should span at least 3–5 years, enabling the introduction of innovative techniques and high-quality work. The goal should be more than merely applying superficial changes to fit the lowest price bracket, at the expense of quality. Such practices do not foster the safe use of these structures.

Moreover, the overly brief descriptions in tender documents, specifying significant conditions of the order, fail to define the standards for executing measurements or for delivering data and results. Documentation and reports are often truncated, with critical data omitted due to substandard work and non-adherence to fundamental principles of measurement data processing. Failure to supply or incorrect supply of initial data can disrupt the continuity of periodic observations and impede the accurate interpretation of established displacement trends.

CONCLUSIONS

The implementation of automated geodetic displacement monitoring systems has proven instrumental in elevating the safety of hydraulic structures and providing more accurate evaluations of structural conditions and associated risk factors. Systematic geodetic measurements, executed within a control network conceived by a diverse team of experts, serve as a critical component in the safeguarding of engineering structures. It is essential to remember that these are the only measurements that show the actual extent of geometric changes in the structure, enabling the verification of predicted structural behaviours based on models using data from sensors capturing changes in physical parameters such as pressure, groundwater levels, or temperature fluctuations.

Hydraulic structures in Poland are not receiving adequate surveying network maintenance. Adapting and modernising the networks, coupled with the deployment of automated measurements, will significantly contribute to the elevation of standards in structure maintenance. It is recommended to introduce cataloguing systems for control points. Contemporary technologies facilitate the creation of simple internal GIS-type databases for structures – such functionalities often comprise an integral part of automatic monitoring systems, where all changes and alerts are systematically archived.

The automation of measurements and adherence to a singular standard for surveying work at hydraulic structures should solve the problems delineated in this article. In this case, even a yearly change in the contractor responsible for network control maintenance would not compromise the quality of control measurement results.

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REFERENCES

Gökalp, E. and Taşçi, L. (2009) "Deformation monitoring by GPS at embankment dams and deformation analysis," *Survey Review*, 41, 311, pp. 86–102. Available at: https://doi.org/10.1179/003962608X390021.

Haerani, N. *et al.* (2016) "On the performance of terrestrial laser scanner for volcanic and landslide hazard assessment in Indonesia 2013 (8131)," in *Proceedings of the FIG Working Week 2016 Recovery from Disaster*, pp. 1–13. Available at: https://www.researchgate.net/publication/304523856_On_the_Performance_of_TLS_for_Volcanic_and_Landslide_Hazard_Assessment_in_Indonesia (Accessed: May 15, 2023).

Henriques, M.J. and Casaca, J. (2003) "Monitoring displacements at large dams by means of precision traverses," *FIG Working Week 2003*. Available at: http://repositorio.lnec.pt:8080/jspui/handle/123456789/17037 (Accessed: May 15, 2023).

IMSGeo (2021) *Projekt: POIR.01.01.01-00-0942/21. Inteligentny system monitoringu obiektów zagrożonych bazujący na automatycznych pomiarach bezinwazyjnych – IMSGeo*. Warszawa: GEOalpin sp. z o.o., Politechnika Warszawska. Available at: https://geoalpin.pl/realizacja-projektu-unijnego/, https://www.gik.pw.edu.pl/zgiisp/Badania-i-nauka/Projekt-POIR.01.01.01-00-0942-21-IMSGeo (Accessed: May 10, 2023).

Jäger, R. and Spohn, P. (2017) *GOCA – GNSS/LPS/LS Based Online Control- and Alarm System Version 5.0*. Karlsruhe: Hochschule Karlsruhe – Technik und Wirtschaft, Institute of Applied Research. Available at: http://goca.info/docs/flyer/GOCA-Flyer_-English.pdf (Accessed: May 10, 2023).

Karsznia, K. (2008) "Wykrywanie słabych punktów. Geodezyjny i geotechniczny monitoring obiektów inżynierskich w ujęciu dynamicznym [Vulnerability detection. Geodetic and geotechnical monitoring of engineering structures in a dynamic approach]," *Nowoczesne Budownictwo Inżynieryjne*, 7–8, pp. 72–75. Available at: http://www.nbi.com.pl/assets/NBI-pdf/2008/4_19_2008/pdf/23_wykrywanie_slabych_punktow.pdf (Accessed: May 15, 2023).

Karsznia, K. *et al.* (2022) "The functionality assessment of geodetic monitoring systems for analyzing structural elements," *XXVII FIG Congress 2022: Volunteering for the future – Geospatial excellence for a better living*. Available at: https://fig.net/resources/proceedings/fig_proceedings/fig2022/papers/ts04d/TS04D_karsznia_zaczek-peplinska_et_al_11414.pdf (Accessed: May 15, 2023).

Karsznia, K., Skalski, Z. and Czarnecki, L. (2010) "System ciągłego monitoringu deformacji odkrywkowych wyrobisk górniczych a bezpieczeństwo prowadzenia robót górniczych [A system for continuous monitoring of deformations in open-pit mine workings and the safety of mining works]," *Przegląd Górniczy*, 10(1055), pp. 167–171.

Karsznia, K. and Tarnowska, A. (2014) "Proposition of an integrated geodetic monitoring system in the areas at risk of landslides," *Challenges of Modern Technology*, 4(3), pp. 33–40.

Kledyński, Z. (2011a) "Monitoring i diagnostyka budowli hydrotechnicznych. Cz. 1 [Monitoring and diagnostics of hydrotechnical structures. P. 1]," *Nowoczesne Budownictwo Inżynieryjne*, 2(35), pp. 54–61.

Kledyński, Z. (2011b) "Monitoring i diagnostyka budowli hydrotechnicznych. Cz. 2 [Monitoring and diagnostics of hydrotechnical structures. P. 2]," *Nowoczesne Budownictwo Inżynieryjne*, 3(36), pp. 36–38.

Królikowski, J. (2023) "Wyzwań od metra – Jak technologie geodezyjne pozwalają bezpiecznie drążyć II linię warszawskiego metra [Challenges from the metro – How geodetic technologies allow you to safely drill the second line of the Warsaw metro]. Interview with M. Wiliński," *Geodeta Magazyn Geoinformacyjny*, 9. Available at: https://geoforum.pl/?menu=47064&page=edition2&id=1225&id_article=943&link=rozmawial-jerzy-krolikowski-wyzwan-od-metra-jak-technologie-geodezyjne-pozwalaja-bezpiecznie#edition (Accessed: April 18, 2023).

LEICA GEOMOS (2015) *Are you interested in movements? – technical flyer*. [Leaflet]. Heerbrugg: Sweiz.

LEICA GEOSYSTEMS AG (2018) *Monitoring solutions – Assurance done right, technical flyer*. [Leaflet]. Heerbrugg: Sweiz.

Li, Y. *et al.* (2021) "A comparison method for 3D laser point clouds in displacement change detection for Arch Dams," *ISPRS International Journal of Geo-Information*, 10(3), 184. Available at: https://doi.org/10.3390/ijgi10030184.

Möser, M. *et al.* (2013) *Auswertung geodätischer Überwachungsmessungen [Evaluation of geodetic monitoring measurements]*. 2nd revised and expanded ed. Wichmann-Verlag.

Pasternak, G. *et al.* (2023) "Surface monitoring of an MSW landfill based on linear and angular measurements, TLS, and LIDAR UAV," *Sensors*, 23(4), 1847. Available at: https://doi.org/10.3390/s23041847.

Prószyński, W. and Zaczek-Peplinska, J. (2005) "Kompleksowa modernizacja geodezyjnej sieci kontrolnej środkiem do podniesienia wiarygodności wyników pomiarów przemieszczeń [Comprehensive modernization of the geodetic control network as a means to increase the reliability of displacement measurement results]," *XI Międzynarodowa Konferencja Technicznej Kontroli Zapór*. Zakopane-Polana Zgorzelisko, 8–11 May 2005.

Ramos-Alcázar, L., Marchamalo-Sacristán, M. and Martínez-Marín, R. (2015) "Comparing dam movements obtained with Terrestrial Laser Scanner (TLS) data against direct pendulums records," *Revista Facultad de Ingeniería Universidad de Antioquia*, 76, pp. 99–106. Available at: https://doi.org/10.17533/udea.redin.n76a12.

Rozporządzenie (2007) Rozporządzenie Ministra Środowiska z dnia 20 kwietnia 2007 r. w sprawie warunków technicznych, jakim powinny odpowiadać budowle hydrotechniczne i ich usytuowanie [Regulation of the Minister of the Environment of April 20, 2007 on the technical conditions to be met by hydrotechnical structures and their location]," *Dziennik Ustaw*, 86, poz. 579.

Sanso, F. and Gil, A.J. (2006) *Geodetic deformation monitoring*. Springer-Verlag GmbH.

Sieiński, E. and Śliwiński, P. (2020) *Wytyczne wykonywania badań, pomiarów, ocen stanu technicznego oraz ocen stanu bezpieczeństwa budowli piętrzących wodę [Guidelines for carrying out tests, measurements, technical condition assessments and safety assessments of water damming structures]*. Warszawa: Instytut Meteorologii i Gospodarki Wodnej – PIB.

Spreafico, M.C. *et al.* (2015) "Terrestrial remote sensing techniques to complement conventional geomechanical surveys for the assessment of landslide hazard: The San Leo case study (Italy)," *European Journal of Remote Sensing*, 48, pp. 639–660. Available at: https://doi.org/10.5721/EuJRS20154835.

Stumvoll, M.J., Schmaltz, E.M. and Glade, T. (2021) "Dynamic characterization of a slow-moving landslide system – Assessing the challenges of small process scales utilizing multi-temporal TLS data," *Geomorphology*, 389, 107803. Available at: https://doi.org/10.1016/j.geomorph.2021.107803.

Świdziński, W. and Janicki, K. (2016) "Dobrze rozwinięty system monitoringu podstawą bezpiecznej eksploatacji obiektów hydrotechnicznych na przykładzie OUOW Żelazny Most [Well developed monitoring as a basis of safe operation of hydaulic structures based on Żelazny Most tailings pond]," *Czasopismo Inżynierii Lądowej, Środowiska i Architektury Journal of Civil Engineering, Environment and Architecture*, 33, 63(1/II/16), pp. 33–40. Available at: https://doi.org/10.7862/rb.2016.58.

Topcon (no date) *Monitor construction sites and infrastructure for stability and risk*. Topcon Positioning Systems, Inc. Available at: https://www.topconpositioning.com/surveying/monitoring (Accessed: April 18, 2023).

Trimble Geospatial (2023) *Office Software: Trimble 4D Control*. Available at: https://geospatial.trimble.com/en/products/software/trimble-4d-control (Accessed: April 18, 2023).

Ustawa (1994) "Ustawa z dnia 7 lipca 1994 r. Prawo budowlane [Construction law]," *Dziennik Ustaw*, 2023 [consolidated version].

Ustawa (2017) "Ustawa z dnia 20 lipca 2017 r. – Prawo wodne [Water law]," *Dziennik Ustaw*, 2017, poz. 1566 with amendments.

Wilde, K. *et al.* (2017) "Diagnostyka i monitoring nowego przekrycia Opery Leśnej w Sopocie [Diagnostics and monitoring of new textile roof of the Forest Opera in Sopot]," in *XXVI Konferencja „Awarie budowlane" 2013*, pp. 291–298. Available at: http://www.awarie.zut.edu.pl/files/ab2013/referaty/03_Diagnostyka_w_ocenie_bezpieczenstwa_konstrukcji/09_Wilde_K_i_inni_Diagnostyka_i_monitoring_nowego_przekrycia_Opery_Lesnej_w_Sopocie.pdf (Accessed: April 18, 2023).

Wolski, B. (2008) *Monitoring metrologiczny obiektów geotechnicznych [Metrological monitoring of geotechnical objects]*. Kraków: Wydaw. Politechniki Krakowskiej im. Tadeusza Kościuszki.

Woźniak, M. and Odziemczyk, W. (2017) "Investigation of stability of precise geodetic instruments used in deformation monitoring," *Reports on Geodesy and Geoinformatics*, 104, pp. 79–90. Available at: https://doi.org/10.1515/rgg-2017-0017.

Yi, T.H. and Li, H.N. (2012) "Methodology developments in sensor placement for health monitoring of civil infrastructures," *International Journal Distributed Sensors Networks*, 8(8), pp. 612–726. Available at: https://doi.org/10.1155/2012/612726.

Zaczek-Peplinska, J. (2007) *Koncepcja modernizacji klasycznych sieci poziomych do wyznaczania przemieszczeń obiektów hydrotechnicznych [The concept of modernization of classic horizontal networks for determining displacements of hydrotechnical objects]*. PhD Thesis. Warszawa: Politechnika Warszawska.

Zaczek-Peplinska, J. (2018) "Metodyka oceny stanu powierzchni betonowej budowli piętrzącej na podstawie analizy spektralnej wyników naziemnego skanowania laserowego [Methodology for assessing the condition of the surface of a concrete damming structure based on spectral analysis of the results of terrestrial laser scanning]," *Prace Naukowe Politechniki Warszawskiej. Geodezja*. Warszawa: PW.

Zaczek-Peplinska, J. and Kowalska, M. (2022) "Application of non-contact geodetic measurement techniques in dam monitoring," *Archives of Civil Engineering*, 63, pp. 49–70. Available at: https://doi.org/10.24425/ace.2022.141873.

Zaczek-Peplinska, J., Pasik, M. and Popielski, P. (2013) "Geodetic monitoring of objects in the area of impact construction of tunnels and deep excavations – experiences and conclusions," *Acta Scientiarum Polonorum – Architectura*, 12(2), pp. 17–31.