# Integrirano geodetsko spremljanje strukturnih deformacij in kopičenja sedimentov na jezu Plovdivtsi (Bolgarija)

# Integrated Geodetic Monitoring of Structural Deformations and Sediment Accumulation at the Plovdivtsi Dam (Bulgaria)

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## IZVLEČEK

*Članek opisuje geodetski pristop za spremljanje strukturnih deformacij in kopičenja sedimentov na jezu Plovdivtsi v Rodopih v južni Bolgariji. Sistem spremljanja vključuje geodetsko mrežo opazovalnih stebrov in reperjev, zasnovanih za zaznavanje horizontalnih in vertikalnih premikov jezu. Horizontalni premiki se določajo z uporabo trigonometričnih meritev, vertikalni premiki pa se spremljajo z metodo geometričnega nivelmana. Kopičenje sedimentov v akumulacijskem jezeru se ocenjuje s periodičnimi geodetskimi in hidrografskimi raziskavami s tehniko profiliranja sedimentov in ehosondiranja. Integrirana metodologija zagotavlja zanesljive geodetske podatke za zaznavanje strukturnih premikov in podporo pri ocenjevanju obnašanja jezu in sprememb v prostornini akumulacijskega jezera. Predlagani pristop podpira zgodnje odkrivanje strukturnih sprememb, izboljšuje oceno dinamike sedimentov ter prispeva k učinkovitemu upravljanju voda in dolgoročni obratovalni varnosti hidravlične infrastrukture.*

## ABSTRACT

*This study presents a geodetic approach for monitoring structural deformations and sediment accumulation at the Plovdivtsi Dam in the Rhodope Mountains, southern Bulgaria. The monitoring system includes a geodetic network of observation pillars and benchmarks designed to detect horizontal and vertical displacements of the dam. Horizontal displacements are determined using trigonometric measurements, while vertical movements are monitored through precise geometric leveling. Sediment accumulation in the reservoir is assessed through periodic geodetic and hydrographic surveys using sediment profiling and echo-sounding techniques. The integrated methodology provides reliable geodetic data for detecting structural displacements and supporting the evaluation of dam behavior and changes in reservoir capacity. The proposed approach supports early detection of structural changes, improves the assessment of sediment dynamics, and contributes to effective water management and the long-term operational safety of hydraulic infrastructure.*

## KLJUČNE BESEDE

geodetski monitoring, premiki jezu, akumulacija sedimentov, hidrografska izmera, sedimentacija v jezeru, varnost jezu

## KEY WORDS

geodetic monitoring, dam deformation, sediment accumulation, hydrographic surveying, reservoir sedimentation, dam safety

## 1 Introduction

Hydraulic engineering structures such as dams play a crucial role in water supply, flood control, irrigation, and energy production. Due to their strategic importance and potential risks associated with structural failure, continuous assessment of their structural integrity and operational conditions is essential. Geodetic measurements provide accurate spatial data that enable the detection of structural displacements and the analysis of deformation processes (Yankov, 2009; Caspary, 1987).

One of the key challenges in dam operation is the detection of structural deformations caused by hydrostatic pressure, temperature variations, seismic activity, and other environmental influences. These factors may lead to gradual displacements or changes in the geometry of the structure. Early detection of such processes is essential for preventing structural damage and ensuring the safety of downstream areas.

Another important aspect of reservoir management is sediment accumulation. Sediment deposition gradually reduces reservoir storage capacity and may affect the operational efficiency of hydraulic facilities. Periodic assessment of sediment deposits enables the evaluation of reservoir capacity changes (Al Fatin and Mustafin, 2019).

Geodetic and hydrographic surveying methods are widely used in deformation monitoring and sediment assessment. Techniques such as precise leveling, trigonometric measurements, GNSS positioning, and echo-sounding allow the acquisition of high-precision spatial data required for monitoring structural behavior and reservoir morphology. Similar approaches have been applied in the monitoring of major hydraulic structures worldwide, including the Xiaolangdi Dam in China (Wang et al., 2023), while satellite radar interferometry techniques such as InSAR are increasingly used for detecting ground and structural deformations.

Similar integrated monitoring approaches combining deformation measurements and hydrographic surveys have been applied in several studies related to the management of hydraulic infrastructure. However, the practical implementation of such integrated monitoring systems for medium-sized reservoirs remains insufficiently documented in the scientific literature. Geodetic and hydrographic surveying techniques therefore represent an essential component of modern engineering monitoring systems used for the safe operation of hydraulic structures.

In this context, the Plovdivtsi Dam, located in the Rhodope Mountains near the Bulgarian–Greek border, is a strategically important hydraulic facility primarily designed for water supply. Due to the complex geological and environmental conditions of the region, continuous geodetic monitoring of the structure and the reservoir is necessary.

The objective of this study is to present a geodetic methodology for monitoring dam wall deformations and assessing sediment accumulation in the Plovdivtsi reservoir. The research focuses on the design of a geodetic monitoring network, the application of precise measurement techniques, and the implementation of sediment profiling methods for long-term observation of reservoir dynamics.

The main contribution of this study is the implementation of an integrated engineering–geodetic monitoring framework combining deformation observations of the dam structure with sediment profiling of the reservoir within a unified coordinate and interpretation environment. This approach enables the simultaneous evaluation of structural behavior and reservoir capacity changes under real operational conditions and supports long-term infrastructure monitoring of hydraulic structures located in complex mountainous environments.

The remainder of the paper is organized as follows. Section 2 presents the study area and the main characteristics of the Plovdivtsi Dam. Section 3 describes the geodetic monitoring network and the measurement techniques employed. Section 4 analyzes the accuracy of the monitoring network, while Section 5 presents the methodology for sediment monitoring and volume estimation. Section 6 discusses the integration potential of geodetic monitoring data into digital twin environments, and Section 7 summarizes the study's main conclusions.

## 2 Study area – Plovdivtsi Dam

The Plovdivtsi Dam is located in the Rhodope Mountains in southern Bulgaria, close to the Bulgarian–Greek border (Figure 1). The reservoir was constructed primarily for water supply purposes and plays an important role in providing drinking water for several settlements in the region. Due to its strategic significance and the complex mountainous terrain in which it is situated, continuous observation of the structure and the surrounding environment is essential.




Figure 1: Location of the Plovdivtsi Dam in the Rhodope Mountains, southern Bulgaria.

The dam is an embankment structure with an asphalt-concrete diaphragm serving as the impermeable element. Such dams require careful monitoring during both construction and operational stages because their behavior depends on multiple factors, including hydrostatic pressure, environmental conditions, and geological characteristics of the foundation.

The reservoir basin is characterized by relatively steep valley slopes and active erosion processes, which contribute to sediment transport from the catchment area into the reservoir. Over time, sediment deposition may lead to a reduction in storage capacity and affect the operational efficiency of the hydraulic facility. Therefore, periodic assessment of sediment accumulation is necessary to evaluate long-term changes in the reservoir morphology.

Considering these characteristics, the Plovdivtsi Dam represents a suitable case study for the application of integrated geodetic monitoring approaches that combine deformation measurements of the dam structure with hydrographic surveys for sediment assessment. Some engineering–geodetic investigations carried out during the construction phase of the dam are documented in the literature (Boradzhieva, 2019).

## 3 Geodetic monitoring network for dam deformation analysis

Reliable deformation analysis requires the establishment of a stable and well-defined geodetic reference network in accordance with standard geodetic procedures (Main Directorate of Geodesy, Cartography and Cadastre, 1980). At the Plovdivtsi Dam, a geodetic monitoring network consisting of observation pillars forming the reference network and monitoring points installed on the dam structure was established and constructed to enable long-term observation of structural displacements based on engineering–geodetic investigations conducted during the design and construction stages of the dam (Boradzhieva, 2019; Stefanova and Boradzhieva, 2025a; Stefanova and Boradzhieva, 2025b).

The network includes eight observation pillars (OP1–OP8) positioned around the dam structure (Figure 2). These pillars serve as reference points for determining horizontal displacements of the monitored points located along the dam crest and other characteristic structural elements. The monitoring network was constructed in two stages. The first stage included five observation pillars used during the construction phase of the dam. In the second stage, three additional pillars were installed to complete the monitoring network and ensure adequate geometric stability of the observation system.

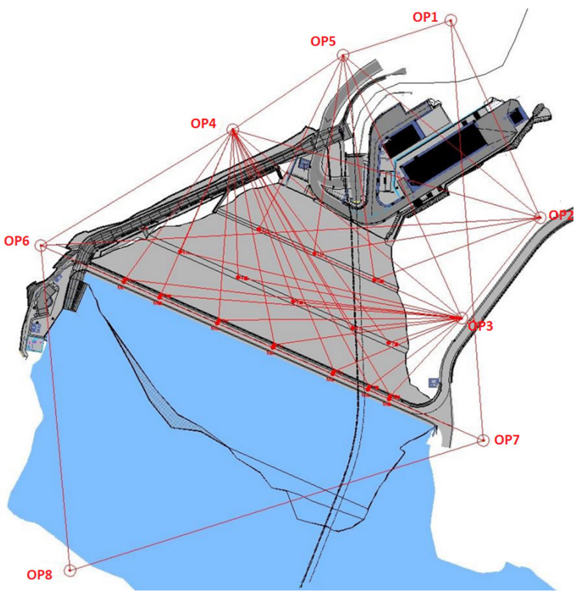


Figure 2: Reference geodetic network for horizontal deformation monitoring at the Plovdivtsi Dam. Observation pillars (OP1–OP8) forming the reference network are shown as circles, while numbered monitoring points installed along the dam crest and berms are shown as solid points. Red lines represent the observation geometry between reference and monitored points.

The observation pillars OP1–OP8 form the reference framework of the monitoring network and are located outside the expected deformation zone of the dam body. The monitored points installed along the dam crest represent object points whose coordinate changes between successive observation cycles are used for deformation analysis.

The stability of the observation pillars forming the reference framework was verified for the analysed observation period based on their location outside the expected deformation zone, their stabilization in rock or reinforced concrete foundations, and the consistency of coordinates derived from repeated observation cycles.

The observation pillars are stabilized using forced-centering devices that allow precise positioning of geodetic instruments during repeated measurement cycles. Their structural design depends on the geological conditions of the foundation.

Different structural solutions are applied accordingly. For soil foundations, a specific pillar design is used (Figure 3a), while for rock foundations, a different structural solution ensures the long-term stability of the observation point (Figure 3b).

Each observation pillar is equipped with a platform that allows stable positioning of geodetic instruments during measurement cycles (Figure 3c).

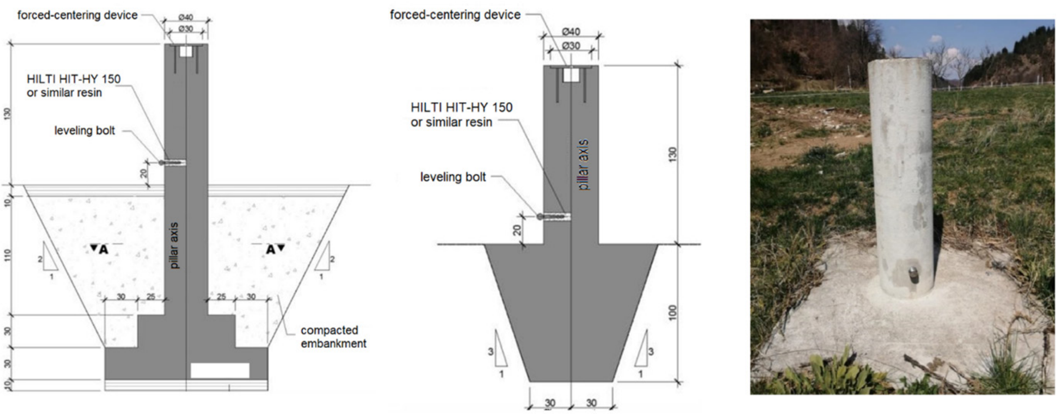


Figure 3: Observation pillars used in the monitoring network:
(a) cross-section of a pillar on a soil foundation;
(b) cross-section of a pillar on a rock foundation;
(c) observation pillar with measurement platform.

The stability of the observation pillars is therefore a key prerequisite for reliable deformation analysis. Accordingly, the pillars are constructed on stable foundations and designed to minimize potential movements caused by environmental influences such as temperature variations, soil settlement, or seismic activity.

After installation, the coordinates of the observation pillars were determined with high precision and adjusted within a local engineering coordinate system established for the deformation monitoring of the dam, allowing the comparison of measurements from different observation cycles and the detection of structural displacements.

A local engineering coordinate system was established for the deformation monitoring network using stable reference points connected to the national geodetic control network. The geometry of the monitoring network follows the elongated configuration of the dam structure, resulting in anisotropic coordinate precision. Consequently, slightly lower positional accuracy was obtained in the y-coordinate component for several monitored points due to the weaker transversal geometric strength of the observation configuration.

The coordinates of the observation pillars were determined using a constrained least-squares adjustment of the geodetic network based on selected stable reference points belonging to the national geodetic control network. The reference datum of the monitoring network was realized using existing triangulation points located outside the expected deformation zone, ensuring the stability of the coordinate framework for repeated observation cycles.

This adjustment strategy preserved the internal geometry of the monitoring network and ensured consistency between successive measurement epochs, allowing reliable detection and interpretation of horizontal displacements of the monitored points installed along the dam crest and other structural elements.

The established reference framework enables coordinate differences between successive observation cycles to be interpreted as deformation vectors derived from repeated geodetic observations.

The configuration of the monitoring network provides sufficient observation redundancy, improving the reliability of displacement determination and increasing the robustness of the deformation analysis results.

Horizontal displacements of the monitored points are determined using trigonometric measurement methods widely applied in deformation studies of engineering structures (Yankov, 2009). The monitoring points installed along the crest of the Plovdivtsi Dam wall are of two types (Figure 4). The first type is located along the axis of the asphalt-concrete diaphragm of the dam wall (Figure 4a), while the second type is positioned in the embankment of the dam wall crest (Figure 4b).

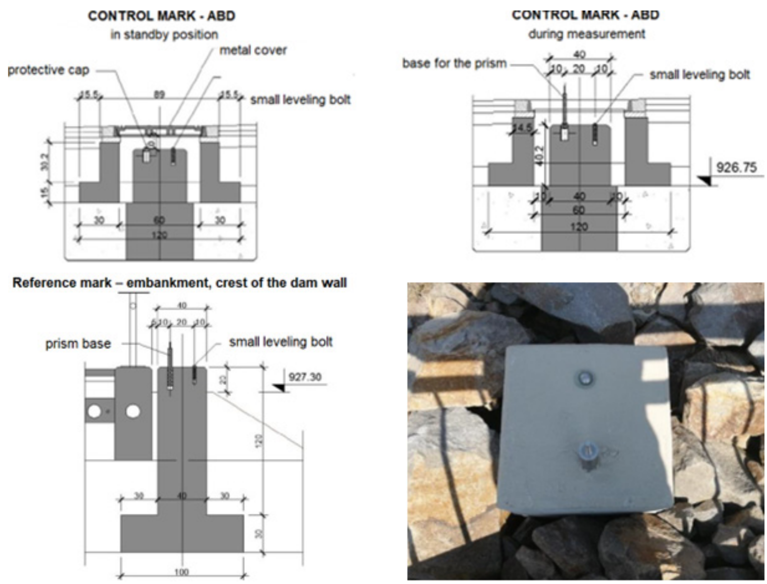


Figure 4: Monitoring points installed along the crest of the dam:
(a) along the axis of the asphalt-concrete diaphragm of the dam wall;
(b) located in the embankment of the dam wall crest.

These measurements are performed from the observation pillars to the monitoring points installed along the dam crest and other structural elements. The trigonometric method allows the determination of precise spatial coordinates of the monitored points and provides reliable information about potential horizontal movements of the structure.

Vertical deformations are monitored using precise geometric leveling. Benchmarks installed along the dam structure serve as reference points for determining height differences between observation cycles. The structural design of the benchmarks depends on the geological conditions of the foundation (Figure 5). The locations of these benchmarks were defined in the design documentation of the hydraulic facility and were selected to ensure reliable monitoring of vertical displacements.

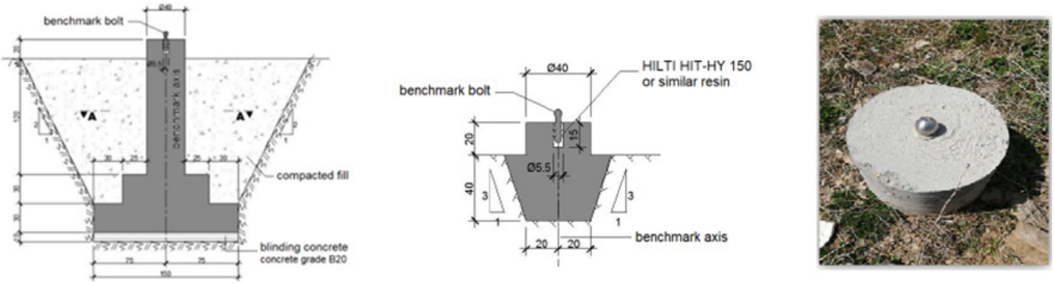


Figure 5: Leveling benchmarks used for vertical deformation monitoring:
(a) cross-section of a benchmark on a soil foundation;
(b) cross-section of a benchmark on a rock foundation;
(c) leveling benchmark.

The spatial distribution of the reference and control benchmarks forming the vertical deformation monitoring network at the Plovdivtsi Dam is presented in Figure 6.

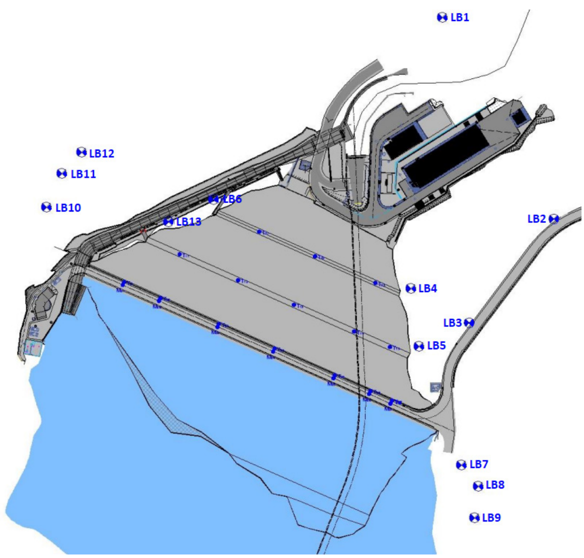


Figure 6: Vertical deformation monitoring network at the Plovdivtsi Dam showing reference leveling benchmarks (LB) and numbered monitored points installed along the dam crest and berms.

The integration of horizontal and vertical deformation measurements provides comprehensive information about the structural behavior of the dam and enables the detection of even small displacements that may indicate developing deformation processes.

## 4 Accuracy analysis of the monitoring network

The reliability of deformation monitoring largely depends on the stability of the reference points and the accuracy of the geodetic measurements. The monitoring network was adjusted using a constrained least-squares adjustment based on selected stable reference points belonging to the national geodetic control network, ensuring a consistent datum for deformation analysis. Therefore, the design of the monitoring network at the Plovdivtsi Dam includes an assessment of the expected measurement accuracy as well as the geometric stability of the network configuration. The expected accuracy of the measurements used in the deformation monitoring system is summarized in Table 1.

Prior to the deformation analysis, the stability of the reference points forming the geodetic control network was assessed. The reference points were selected among observation pillars and existing triangulation points located outside the expected deformation zone of the dam structure.

The stability assessment was based on the analysis of coordinate consistency between successive observation cycles and on the structural characteristics of the point stabilization. Points stabilized in rock or reinforced concrete foundations were considered suitable for long-term deformation monitoring.

Coordinate differences between observation cycles that remained within the limits of the expected coordinate accuracy were interpreted as an indication of reference point stability and confirmed their suitability for realization of the monitoring network datum.

Table 1: Expected accuracy of geodetic measurements used in deformation monitoring.

| **Measurement type** | **Instrument** | **Expected accuracy** |
|---|---|---|
| Horizontal displacement (trigonometric measurements) | Total station | ±2–3 mm |
| Vertical displacement (precise leveling) | Digital level with invar staff | ±1–2 mm |
| Distance measurements | Electronic distance measurement (EDM) | ±(1–2 mm + 1 ppm) |
| Angular measurements | Total station | ±1" |

The preliminary accuracy assessment of the geodetic monitoring network was performed during the network design stage. Selected results of the estimated coordinate accuracy for several points in the network are presented in Table 2.

The estimated coordinate standard deviations presented in Table 2 provide a quantitative characterization of point accuracy within the monitoring network.

In addition to the preliminary accuracy assessment, the actual accuracy of the network was evaluated after adjustment based on the obtained coordinate standard deviations. The results indicate that the standard deviations of point coordinates are generally within the range of approximately 1–5 mm depending on the geometric configuration of the monitored points and the observation directions. Higher coordinate uncertainties were observed mainly in the y-coordinate component for several monitored points, which is consistent with the elongated geometry of the monitoring network described in Section 3. These values confirm the suitability of the monitoring configuration for millimeter-level deformation detection.

Table 2: Selected coordinate standard deviations obtained from the preliminary accuracy assessment of the monitoring network

| Point | mx [mm] | my [mm] | mp [mm] |
|---|---|---|---|
| 18 | 1.6 | 2.7 | 3.2 |
| 17 | 1.9 | 4.2 | 4.7 |
| 16 | 1.9 | 4.5 | 4.9 |
| 13 | 1.6 | 3.9 | 4.3 |
| 59 | 1.3 | 1.1 | 1.7 |
| 61 | 1.2 | 1.2 | 1.7 |
| 63 | 1.4 | 1.4 | 2.0 |
| 64 | 1.4 | 1.4 | 2.0 |
| 65 | 1.4 | 1.4 | 2.0 |
| 67 | 1.3 | 1.3 | 1.9 |

where:

mx – standard deviation of the x-coordinate component;

my – standard deviation of the y-coordinate component;



mp – positional standard deviation.

The monitoring network configuration includes multiple redundant observations between observation pillars and monitored points, ensuring reliable adjustment results and improving the robustness of displacement detection.

The established monitoring network includes a number of reference and control points whose coordinates were determined within a local coordinate system established for the deformation monitoring of the dam.

The monitoring network established for the Plovdivtsi Dam includes a total of 154 control points stabilized in the field with metal markers and concrete monuments, ensuring the long-term stability of the reference system.

Considering the achieved coordinate precision and observation configuration, the monitoring network enables reliable detection of millimeter-level horizontal and vertical displacements of the dam structure.

Horizontal displacement monitoring is carried out using trigonometric measurements from the observation pillars toward the monitoring points installed along the dam crest. The expected accuracy of coordinate determination depends on the precision of the angle and distance measurements obtained from the total station observations.

Modern electronic total stations provide angular measurement accuracy of approximately 1" and distance measurement accuracy at the millimeter level (Borisova, 2023). Under typical observation conditions, this enables the determination of horizontal displacements with an accuracy of approximately ±2–3 mm per observation cycle.

Vertical deformation monitoring is performed using precise geometric leveling between the installed benchmarks. The leveling network is designed to ensure stable reference points and minimal propagation of systematic errors along the leveling lines. The application of digital leveling instruments and invar leveling rods allows the achievement of vertical displacement accuracy at the level of ±1–2 mm per observation cycle. The vertical deformation monitoring network was referenced to stable leveling benchmarks belonging to the local height reference system established for monitoring purposes at the dam site.

The combined use of trigonometric measurements and precise leveling enables reliable monitoring of both horizontal and vertical structural displacements. The achieved accuracy is sufficient for detecting millimeter-level deformation processes that may occur during the long-term operation of the dam. Repeated observation cycles were carried out during different stages of the monitoring programme. The reference geodetic network was established during the project preparation phase and was subsequently applied during construction monitoring campaigns carried out between 2015 and 2017. The use of a consistent reference framework ensured comparability between observation epochs and allowed coordinate differences to be interpreted as indicators of possible structural displacements of the monitored points. Future integration of GNSS observations may further improve the automation and temporal resolution of deformation monitoring within the existing observation network.

## 5 Sediment monitoring and sediment volume estimation

### 5.1 Sediment survey methodology

Sediment accumulation in reservoirs is a natural process caused by the transport of solid material from the catchment area into the reservoir basin and is widely studied in hydrographic and reservoir management research (Morris and Fan, 1998). Over time, the deposition of sediments may significantly reduce the storage capacity of the reservoir and affect its operational efficiency.

To evaluate sediment deposition in the reservoir of the Plovdivtsi Dam, periodic geodetic and hydrographic surveys are carried out using sediment profiles established across the reservoir area.

The sediment profiling method involves the establishment of a series of transverse profiles located at characteristic sections of the reservoir valley. These profiles are stabilized in the field to ensure the repeatability of measurements during subsequent observation cycles.

Each sediment profile is defined by two fixed profile reference points located on opposite banks of the reservoir and stabilized in the field to ensure repeatability of the measurements. These points are stabilized with metal posts and leveling benchmarks positioned above the maximum water level to prevent flooding (Figure 7). This configuration ensures stable reference points for repeated measurements and allows precise positioning of the measurement equipment during each survey. These reference points define the profile axis and ensure consistent positioning of the survey vessel along the predefined measurement line during repeated observation cycles.

The dry land sections of the profiles are surveyed using the polar method with a total station. The submerged parts of the profiles are measured using a single-beam echo sounder integrated with a GNSS receiver mounted on a survey vessel. The echo sounder records water depth along the profile line, while the GNSS receiver provides the spatial coordinates of the measurement points.

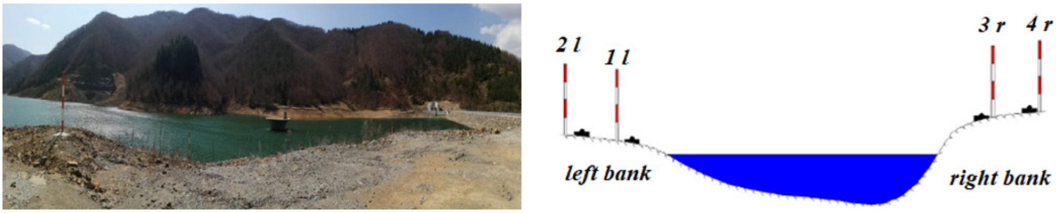


Figure 7: Stabilization and marking of sediment profiles:
(a) field stabilization using metal posts;
(b) schematic diagram of the profile marking system.

During the hydrographic survey, the vessel is guided along the predefined profile axis to ensure that the measurements follow the established profile geometry. In addition, the speed of sound in water is periodically measured using a sound velocity meter to correct the depth measurements obtained from the echo sounder.

After completing the field measurements, the collected data from the total station survey, echo-sounding observations, and GNSS positioning are combined and processed to construct sediment profiles representing the reservoir bottom geometry (Figure 8).

The terrestrial observations obtained from total station measurements were integrated with the hydrographic data derived from echo-sounding and GNSS positioning within a common local engineering coordinate system established for the monitoring of the reservoir. The GNSS receiver mounted on the survey vessel provided planimetric positioning of the echo-sounding measurements, while the depth values recorded by the single-beam echo sounder were reduced to the same vertical reference system as the terrestrial observations. This ensured geometric consistency between the surveyed dry sections of the profiles and the submerged bathymetric measurements and allowed the construction of unified cross-sectional sediment profiles.

The profiles are generated by integrating the surveyed points from the dry sections of the reservoir banks with the bathymetric measurements obtained along the submerged parts of the profiles.



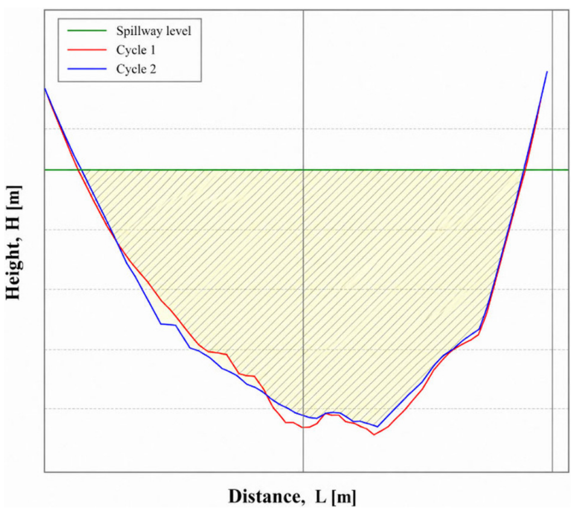


Figure 8: Example of a sediment profile used for sediment volume calculation.

These profiles form the basis for calculating the volume of accumulated sediments by comparing measurements from successive observation cycles.

### 5.2 Calculation of sediment volume

Sediment surveys are performed periodically, with each survey representing a measurement cycle.

Comparison of successive surveys enables the detection of sediment accumulation patterns and long-term morphological changes within the reservoir basin.

In this study, sediment accumulation within the reservoir is determined by comparing sediment profiles obtained in different observation cycles, each representing the state of the reservoir bottom geometry at a given moment in time.

The sediment profiles established in the Plovdivtsi reservoir are arranged transversely across the river valley at sections where significant sediment deposition is expected. A total of seven sediment profiles were established, covering the main parts of the reservoir area. The spacing between adjacent sediment profiles was not uniform and depended on the geometry of the reservoir basin and the expected zones of sediment accumulation. Shorter distances between profiles were applied in the downstream section near the dam wall, where higher sediment deposition and more complex bottom morphology are expected. Their spatial distribution is shown in Figure 9, while a description of the individual profiles is presented in Table 3. The distances between adjacent profiles were defined during the design of the sediment monitoring scheme and were used in the volume computation according to Equation (2).

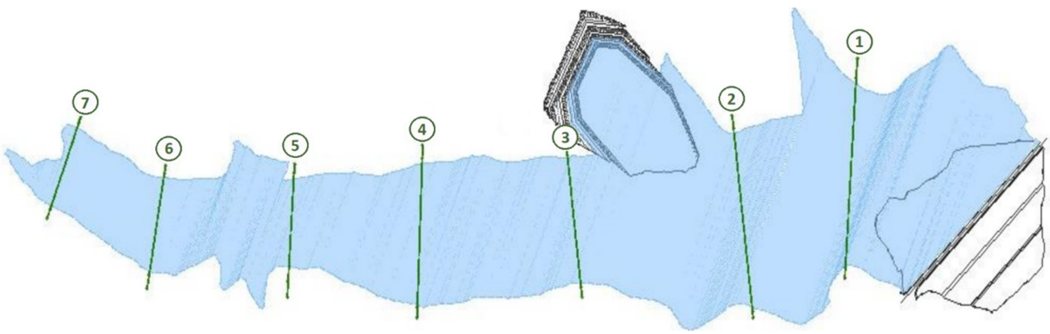


Figure 9: Spatial distribution of sediment profiles (1–7) established across the Plovdivtsi Dam reservoir used for sediment volume estimation.

Table 3: Sediment profiles established in the Plovdivtsi reservoir

| Profile | Description |
|---|---|
| 1 | Upper part of the reservoir |
| 2 | Central section of the reservoir |
| 3 | Central section of the reservoir |
| 4 | Middle reservoir zone |
| 5 | Downstream reservoir section |
| 6 | Near the dam wall |
| 7 | Near the dam wall |

These profiles form the basis for calculating sediment areas and estimating sediment volumes between successive monitoring cycles.

For each profile, the geometry of the reservoir bottom is determined by combining measurements obtained from the dry sections of the profile and the submerged sections measured through hydrographic surveying. The resulting profile represents the cross-section of the reservoir bottom at the time of the survey.

Sediment accumulation is determined by comparing two consecutive measurement cycles. The difference between the reservoir bottom geometry obtained during the reference (zero) cycle and the current measurement cycle represents the accumulated sediment layer.

For each sediment profile, the sediment area is determined as the area enclosed between the two profile lines corresponding to the compared observation cycles. The sediment area is calculated separately for each profile.

To estimate the sediment volume between two adjacent profiles, the average sediment area between them is first calculated. The average sediment area N_{i,j}^{avg} between two neighboring profiles i and j is determined as the arithmetic mean of the sediment areas of the two profiles, as shown in Equation (1).

$$N_{\{i,j\}}^{\{avg\}} = \frac{\left(N_1 + N_j\right)}{2} \tag{1}$$



where:

$N_i$ is the sediment area of profile i,

$N_j$ is the sediment area of profile j.The volume of accumulated sediment between two adjacent profiles is then calculated by multiplying the average sediment area by the distance between the profiles, as shown in Equation (2).

$$V_{\{i,j\}} = N_{\{i,j\}}^{\{avg\}} \cdot S_{\{i,j\}} \tag{2}$$

where:

$S_{\{i,j\}}$ is the distance between two adjacent sediment profiles.The total sediment volume accumulated in the reservoir is obtained by summing the sediment volumes calculated for all pairs of neighboring profiles, as shown in Equation (3).

$$V = \sum V_{\{i,j\}} \tag{3}$$

where:

$V_{\{i,j\}}$ is the sediment volume between two adjacent sediment profiles.

This approach allows the estimation of the total sediment volume within the reservoir and supports the evaluation of long-term changes in reservoir capacity. Periodic repetition of the measurements enables monitoring of sediment dynamics and supports the planning of maintenance activities and sediment management strategies.

The estimated sediment volumes provide important information for reservoir management and support decision-making related to dredging operations, reservoir capacity planning, and long-term water resource management. The accuracy of sediment volume estimation depends primarily on the spacing between sediment profiles and on the accuracy of bathymetric and geodetic measurements obtained using the single-beam echo sounder. Profile-based volume estimation represents a widely applied engineering approach; however, uncertainties may increase in areas between profiles where bottom morphology is not directly measured. The expected uncertainty of sediment volume estimation therefore depends mainly on profile spacing and bathymetric measurement accuracy and remains within the limits typically accepted for profile-based reservoir sediment monitoring. The use of multibeam echo-sounder systems or airborne LiDAR bathymetry could further improve the spatial resolution of the reservoir bottom model and provide a more detailed three-dimensional representation of sediment distribution and may be considered in future monitoring campaigns in order to further enhance the accuracy and efficiency of sediment volume estimation.

### 5.3 Integrated interpretation of deformation monitoring and sediment dynamics

The combined interpretation of deformation monitoring results and sediment accumulation data provides additional information about the interaction between structural behavior of the dam and long-term reservoir processes. While deformation measurements describe the geometric stability of the dam body, sediment accumulation reflects morphological changes within the reservoir basin that may influence hydraulic loading conditions over time.

The integration of these datasets within a unified monitoring framework enables consistent interpretation of structural behavior together with reservoir capacity changes and supports long-term infrastructure management.

Within the presented monitoring framework, sediment accumulation is not interpreted as an isolated reservoir process but as a factor potentially influencing hydraulic loading conditions acting on the dam body. Therefore, the integration of deformation monitoring results with sediment profile evolution supports a more comprehensive interpretation of long-term structural behavior within a unified engineering–geodetic monitoring concept.



## 6 Integration potential of geodetic monitoring data in digital twin environments

In the presented case study, the geodetic monitoring network, sediment profile geometry and displacement measurements provide structured spatial datasets that can be incorporated into a digital twin environment representing the dam structure and reservoir basin. Such integration enables the visualization of displacement vectors together with sediment profile evolution within a unified spatial model of the hydraulic facility. In the present study, the digital twin environment is considered as a conceptual integration framework for monitoring datasets rather than as a fully implemented platform.

Modern infrastructure management increasingly relies on digital models that integrate geospatial and engineering data, commonly referred to as digital twins (Boje et al., 2020; Shahzad et al., 2022). The integration of geodetic monitoring data into digital environments builds upon established principles of engineering deformation analysis, including network adjustment, stability assessment of reference points, and interpretation of coordinate changes between observation epochs (Caspary, 1987; Welsch and Heunecke, 2001). These classical geodetic approaches provide the methodological basis for reliable deformation detection and ensure that monitoring results can be consistently incorporated into modern digital infrastructure management systems.

The geodetic monitoring data obtained from deformation measurements and sediment surveys at the Plovdivtsi Dam may therefore support the development of a digital twin or Building Information Modeling (BIM) environment enabling three-dimensional visualization and the interpretation of structural behavior and reservoir sediment dynamics.

In this context, digital twin platforms should be understood not as independent monitoring systems, but as environments supporting the visualization and interpretation of deformation monitoring results derived from repeated geodetic observations. Within such a digital environment, deformation patterns derived from repeated geodetic observations and sediment distribution obtained from hydrographic surveys can be visualized and analyzed within a unified spatial framework consistent with established deformation monitoring methodologies (Sacks et al., 2020). By combining geodetic measurements, hydrographic surveys, and spatial models, digital twins allow engineers to analyze structural changes, simulate potential scenarios, and improve decision-making processes related to dam maintenance and water management.

Recent studies show that the integration of geodetic, photogrammetric, and hydrographic data significantly improves the observation and management of hydraulic infrastructure (Genchev et al., 2024). Digital twin technology has become an important tool for integrating monitoring data and supporting infrastructure management within the built environment (Mousavi et al., 2024). Applying similar approaches to the Plovdivtsi Dam in future implementations could further enhance the long-term monitoring system and support the sustainable operation of the reservoir.



In this context, the integration of geodetic monitoring data into digital twin environments may facilitate improved visualization, temporal interpretation of deformation processes, and support predictive analysis of dam behavior under varying environmental and operational conditions.

## 7 Conclusion

The long-term safety of hydraulic engineering structures depends on reliable observation of structural behaviour and reservoir conditions. This paper presents a geodetic methodology for monitoring structural deformations and sediment accumulation at the Plovdivtsi Dam in southern Bulgaria.

The established geodetic observation network, consisting of observation pillars and levelling benchmarks, provides a stable reference system for detecting horizontal and vertical displacements of the dam structure. The combined application of trigonometric measurements and precise geometric levelling enables the detection of millimeter-level displacements and ensures reliable deformation monitoring during the operational phase of the dam.

In addition to structural monitoring, sediment accumulation in the reservoir was assessed through periodic geodetic and hydrographic surveys using sediment profiling and echo-sounding techniques. This methodology enables the estimation of sediment volumes and supports the evaluation of long-term changes in reservoir capacity.

Furthermore, the integration of geodetic monitoring results with modern digital modelling environments enhances the potential for comprehensive infrastructure management. By combining deformation monitoring and sediment analysis within a unified geodetic framework, the proposed approach contributes to improved dam safety assessment and sustainable water resource management.

The proposed methodology demonstrates the practical applicability of integrated geodetic and hydrographic surveying methods for monitoring structural deformation and sediment dynamics in reservoir environments. The presented monitoring framework may also be adapted to other hydraulic structures where continuous observation of structural stability and sediment dynamics is required. Future research may focus on the integration of automated monitoring systems and remote sensing techniques for real-time deformation analysis.

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