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LARGE DAMS IN BOSNIA AND HERZEGOVINA: INTEGRATING GEODETIC TECHNIQUES AND CIVIL ENGINEERING FOR DESIGN, CONSTRUCTION, AND SAFETY

VISOKE BRANE U BOSNI I HERCEGOVINI: INTEGRACIJA GEODETSKIH TEHNIKA I GRAĐEVINARSTVA ZA PROJEKTOVANJE, IZGRADNJU I SIGURNOST

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ABSTRACT

The construction and maintenance of large dams require close integration between geodetic and civil engineering disciplines to ensure structural stability, operational reliability, and long-term safety. This paper reviews the role of geodetic techniques in supporting civil engineering processes throughout the planning, construction, and monitoring phases of dam projects. This paper highlights how continuous monitoring and data interpretation enable early detection of abnormal structural behavior, verification of design assumptions, and implementation of corrective measures.

Keywords: dams, geodesy, civil engineerin, structural health monitoring

SAŽETAK

Izgradnja i održavanje visokih brana zahtijevaju usku suradnju geodezije i građevinarstva kako bi se osigurala stabilnost konstrukcije, operativna pouzdanost i dugoročna sigurnost. Ovaj rad razmatra ulogu geodetskih tehnika u podršci građevinskim procesima tokom planiranja, izgradnje i faze praćenja branskih objekata. Rad također ističe kako kontinuirano praćenje i interpretacija podataka omogućavaju rano otkrivanje anomalija u ponašanju konstrukcije, provjeru projektnih pretpostavki i primjenu korektivnih mjera.

Ključne riječi: brane, geodezija, građevinarstvo, praćenje stanja konstrukcije

1 INTRODUCTION

1.1 Overview of electric power generation sources in Bosnia and Herzegovina

Thermal power plants are the primary source of electricity in Bosnia and Herzegovina, while renewable energy sources account for approximately 40% of total electricity production. Among them, hydropower plants make the most significant contribution, whereas wind and solar power

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plants have a much smaller share. According to the Report on Electricity Flows in the Transmission Network in Bosnia and Herzegovina for 2024 (Independent System Operator in Bosnia and Herzegovina, 2025), the total electricity production in Bosnia and Herzegovina amounted to 13,641 GWh. The distribution of this production by energy source highlights a strong dominance of thermal power plants, which contributed 8,377 GWh, or 61.41% of the total annual production. Hydropower remains the most significant renewable energy source, producing 4,663 GWh, which accounts for 34.18% of the total. This confirms the historical importance of hydropower in the country's energy mix. Other renewable sources such as wind and solar contributed relatively little to the overall production: wind energy: 392 GWh (2.87%), and solar energy: 209 GWh (1.53%). Electricity production by energy source and share of each energy source in total electricity production in Bosnia and Herzegovina in 2024 are presented in Figure 1 and Figure 2.

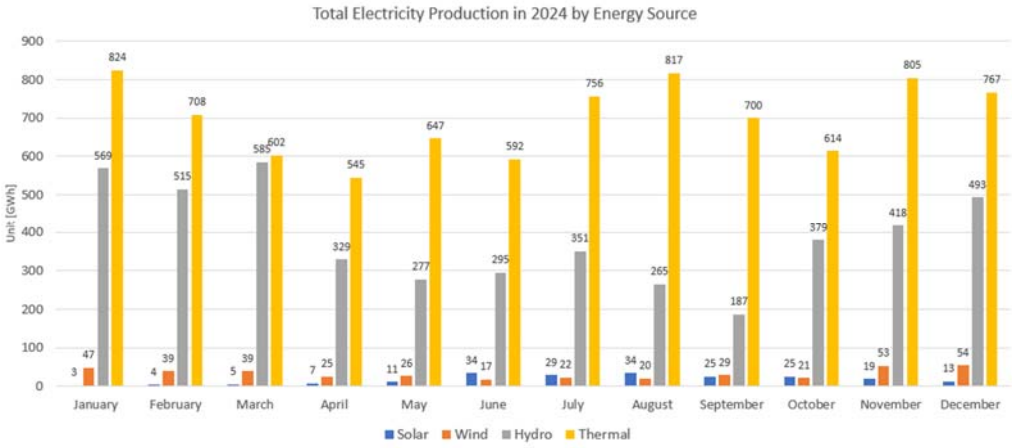

Figure 1. Electricity production in Bosnia and Herzegovina by energy source in 2024 - adapted from Independent System Operator in Bosnia and Herzegovina (2024).

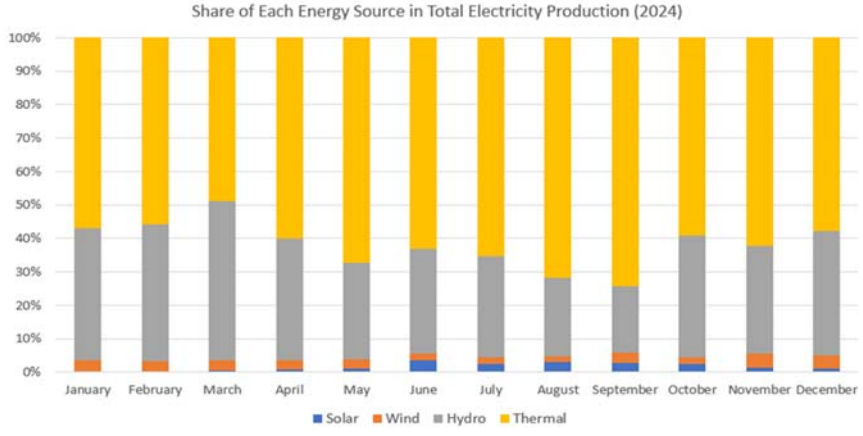

Figure 2. Share of each energy source in total electricity production in Bosnia and Herzegovina in 2024 - adapted from Independent System Operator in Bosnia and Herzegovina (2024).

These figures emphasize the need for further investment in renewable enery sources and especially in wind and solar energy if Bosnia and Herzegovina is to diversify its renewable energy

portfolio and reduce reliance on fossil fuels. This is in line with the targets set out in Directive (EU) 2023/2413, which increases the binding EU-wide renewable energy share to 42.5% by 2030, with an aspirational goal of 45% (European Parliament and Council, 2023). Monthly variations are also notable. January recorded the highest total monthly production with 1443 GWh, while the lowest was in April with 906 GWh, reflecting both seasonal consumption patterns and hydrological conditions.

Given that the most important high dams in Bosnia and Herzegovina were constructed between 1950 and 1990, they are now on average between 35 and 75 years old. From an engineering perspective, this places them in the category of "mature" or "aging" dams, whose operation and stability can no longer be taken for granted (Kovačina and Malović, 2013).

Although many of these structures are still in satisfactory technical condition, their age brings specific risks (material degradation, outdated design standards, environmental changes, and cumulative loading effects). Therefore, regular monitoring can no longer be regarded as a routine formality, but rather as a critical technical requirement (Kovačina and Malović, 2013).

It is thus professionally justified to state that older dams require increased attention and carefully planned monitoring and rehabilitation programs, including:

- precise geodetic measurements of deformations,
- analysis of landslide stability around reservoirs,
- monitoring of sediment accumulation, and
- inspection and reassessment of aging structural elements.

Due to the effects of climate change, Bosnia and Herzegovina has been experiencing a shift from prolonged rainfall to increasingly frequent and intense short-term downpours. These extreme precipitation events often trigger landslides and contribute to large volumes of sediment being washed into hydropower reservoirs. As a result, sedimentation rates are accelerating, which gradually reduces the effective storage capacity of reservoirs and negatively affects both energy production and flood control functions. Precise geodetic measurements of sedimentation in the reservoir allow for a reliable assessment of the available hydropower potential, which directly affects the operational efficiency of the power plant (World Bank, 2023; Ministry of Foreign Trade and Economic Relations of Bosnia and Herzegovina, 2020).

1.2 Timeline of High Dam Development in Bosnia and Herzegovina

Dam construction in Bosnia and Herzegovina has a tradition spanning more than a century. The first large dam in the country was the Klinje Dam, built in 1896 on the Mušnica River near Gacko, in the eastern Herzegovina region (Kovačina and Malović, 2013). More than a century later, the most recently constructed high dam is the Ulog Dam on the Neretva River, located approximately 40 km south of Sarajevo, near Kalinovik. This dam was completed in 2025 (Regulatorna komisija za energeriku Republike Srpske, 2025). Table 1 provides a concise overview of high dams in Bosnia and Herzegovina, including the year of construction, dam type, and primary purpose.

Table 1.
Timeline of High Dam Development in B&H (Kovačina and Malović, 2013; Regulatorna komisija za energeriku Republike Srpske, 2025)

Year	Dam Name	River	Dam Type	Height from Foundation (m)	Primary Purpose
1896	Klinje	Mušnica	Gravity dam	26.4	Water supply
1954	Jablanica	Neretva	Arch dam	85.0	Hydropower
1954	Jajce II	Vrbas	Gravity dam	26.0	Hydropower
1955	Zvornik	Drina	Gravity dam	41.0	Hydropower
1960	Sase	Saska	Earthfill dam	28.0	Other
1962	Alagovac	Alagovci	Earthfill dam	22.8	Water supply, irrigation
1964	Modrac	Spreča	Multiarch dam	33.0	Water supply, recreation, hydropower
1965	Gorica	Trebišnjica	Gravity dam	33.5	Hydropower
1966	Bajina Bašta	Drina	Buttress dam	90.0	Hydropower
1967	Grančarevo	Trebišnjica	Arch dam	123.0	Hydropower, flood control
1967	Hazna	Hazna Stream	Earthfill dam	23.0	Flood control, recreation
1968	Mandak	Mandak	Gravity dam	30.0	Hydropower
1969	Rama	Rama	Rockfill dam	103.0	Hydropower
1972	Vidara	Vidara Stream	Earthfill dam	15.0	Flood control, recreation
1974	Buško Blato	Ričina	Earthfill dam	19.0	Hydropower
1975	Zuna Tomašica	Zuna	Earthfill dam	47.0	Water supply, recreation
1978	Drenova	Drenova	Rockfill dam	15.0	Water supply, flood control
1981	Bočac	Vrbas	Arch dam	66.0	Hydropower
1982	Grabovica	Neretva	Gravity dam	59.0	Hydropower
1982	Salakovac	Neretva	Gravity dam	69.5	Hydropower
1983	Vrba	Vrba	Earthfill dam	31.0	Water supply
1985	Snježnica	Rastošnica	Earthfill dam	58.5	Water supply
1987	Mostar	Neretva	Gravity dam, Earthfill dam	44.0	Hydropower
1989	Višegrad	Drina	Gravity dam	79.5	Hydropower
1990	Tribistovo	Ružićki Stream	Rockfill dam	23.0	Water supply
2025	Ulog	Neretva	Arch dam	53.0	Hydropower

By analysing the data presented in the Table 1 it can be concluded that the majority of high dams in Bosnia and Herzegovina were constructed between the 1950s and 1990s, with the peak of dam-building activity occurring during the 1960s, 1970s, and 1980s. This construction boom was part of a broader development effort in the former Yugoslavia to harness hydropower and manage water resources through large-scale infrastructure. The most commonly used dam types are concrete gravity dams and arch gravity dams, particularly on major rivers such as the Neretva and Drina. Earthfill (rockfill) dams are also present, though in smaller numbers. The primary purpose of these dams is hydropower generation, reflecting the strategic focus on renewable electricity from water resources. However, several dams were also built for water supply, flood control, and recreation. The tallest dam remains the Grančarevo Dam, built in 1967, standing at 123 m and serving both energy and flood protection functions. This historical and structural

diversity highlights the evolving role of dam infrastructure in Bosnia and Herzegovina's development.

This paper examines the role of geodesy and civil engineering across three fundamental phases of dam development: preparatory works, construction, and long-term technical monitoring. As one of the most critical infrastructural components of the hydropower system in Bosnia and Herzegovina, dams demand particular attention, especially in the area of structural health monitoring (SHM). The integration of geodetic precision with Geographic Information Systems (GIS) data management enhances both the safety and efficiency of hydropower operations.

2 GEODESY AND CIVIL ENGINNERING IN PREPARATORY WORKS FOR DAM CONSTRUCTION

Preparatory works for dam construction are critical activities that take place before the actual construction of the dam begins. They ensure that the site is ready, safe, and suitable for the planned structure. These works include a wide range of engineering, geotechnical, logistical, environmental, and legal tasks (U.S. Army Corps of Engineers, 2004; Georgia Environmental Protection Division, 2015; New York State Department of Environmental Conservation, 2020). Key components include:

- feasibility studies and planning,
- site investigations,
- design preparations,
- land acquisition and legal arrangements,
- infrastructure development,
- environmental protection and mitigation, and
- geodetic and monitoring setup.

It is important to note that in practice, some of these phases may overlap or run concurrently, depending on the project timeline and complexity. Additionally, some references merge multiple stages into one, while others break a single phase into several detailed steps, reflecting differences in project management frameworks or national regulations.

Traditional approach of geodetic works during the dam design phase is described by Pašalić (1995). Geodetic works during the dam design phase begin with initial mapping of the river basin using scales from 1:25,000 to 1:200,000. These maps help define the potential dam location, upstream backwater extent, and existing terrain conditions. Once a conceptual solution is formulated, the process proceeds to preliminary and detailed designs, which require more accurate topographic maps, typically at scales between 1:500 and 1:10,000. Dams are generally positioned at the narrowest sections of the river, and multiple location variants are often analyzed. Each candidate site is surveyed to obtain vertical profiles, identify potentially submerged structures, and estimate associated costs - commonly using scales of 1:2000 or 1:2500 (Figure 3). For the selected site, detailed geodetic surveys are then conducted to produce precise situational plans and calculate excavation volumes for the dam foundation.

Traditional geodetic data acquisition relied heavily on manual and optical instruments such as the polar method, orthogonal method, spirit leveling, and tacheometry. These methods were accurate

but labor-intensive and time-consuming, often requiring large field crews and repeated site visits. Analog aerial photogrammetry also played a significant role, using film-based cameras and stereoplotters to create contour maps and topographic models (Wolf and Ghilani, 2012). This is traditional approach of geodetic works for dam construction. Modern approach includes more advanced techniques and methods for data acquisition, analysis and visualization.

Figure 3. Traditional maps used in dam design phase: Analog cadastral map (left) and contour map with elevation data (right) – Scale 1:2 500.

While traditional methods such as the polar and orthogonal survey methods relied heavily on manual angle and distance measurements with total stations, modern approaches have embraced digital and automated techniques that increase accuracy, efficiency, and spatial comprehensiveness (Kavanagh and Slattery, 2014). Today, digital tools have fundamentally transformed geodetic workflows by enabling efficient and scalable acquisition of spatial data. Early project stages often rely on lower-resolution datasets such as satellite images or aerial survey data for general site assessment and feasibility studies (Colomina and Molina, 2014; Goff et al., 2021). As the design progresses, accurate, high-resolution data are required for detailed modeling and quality assurance. Technologies such as Unmanned Aerial Vehicle (UAV) photogrammetry, Light Detection and Ranging (LiDAR) scanning, and Global Navigation Satellite System (GNSS) surveying provide dense point clouds and precise geospatial measurements suitable for these later stages of dam design (Tarsha Kurdi et al., 2023). Computer-Aided Design (CAD) and GIS platforms play a central role in processing and visualizing both types of data, enabling semi-automated or fully automated workflows that accelerate design processes and minimize human error while still requiring expert guidance (Figure 4 and 5).

Figure 4. Digital terrain model with contour lines – 3D view.

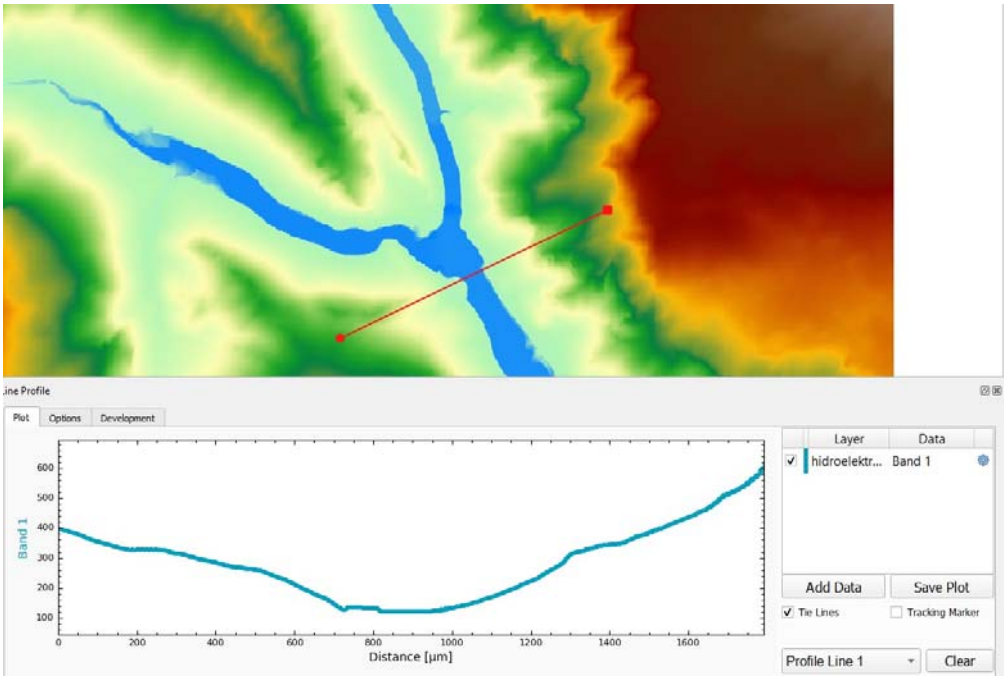

Figure 5. Generation and evaluation of terrain profiles in Quantum GIS software.

From a civil engineering perspective, preparatory works include engineering investigations, site preparation, river diversion, foundation treatment, and the development of access and utility infrastructure. According to Stojić (1997), engineering-geological and hydrogeological studies represent a key component of the preparatory works, providing the necessary understanding of subsurface conditions such as stratification, fault zones, groundwater regimes, karst infiltration processes, and the behavior of geological materials in contact with water. Such investigations are

crucial for assessing site stability and the interaction between geological formations and engineering structures. Comprehensive in-situ and laboratory testing are essential for characterizing soil and rock properties. Typical testing methods include permeability tests, plate load tests, shear strength tests, borehole logging, and geophysical surveys, all of which supply critical data for evaluating the bearing capacity and deformability of the foundation materials (Stojić, 1997; Das and Sobhan, 2018). The integration of engineering geology, hydrogeology, and geotechnical testing allows for the identification of potential geohazards such as slope instability or seepage, which may compromise construction safety and performance. Furthermore, the use of remote sensing techniques and geotechnical monitoring systems offers valuable tools for evaluating slope stability, detecting ground deformations, and anticipating reservoir-induced seismic activity (Stojić, 1997).

A crucial part of preparatory works involves land expropriation, relocation of settlements, and clearance of vegetation within the designated construction zone. Experiences from large dam projects over the past century have demonstrated the importance of addressing social and environmental impacts at an early stage, since inadequate planning of resettlement or environmental mitigation has led to cost overruns, project delays and public resistance (ICOLD, 1997; Wiltshire, 2002; Scudder, 2005). Environmental and ecological considerations must be fully integrated into the preparatory phase of project development. Measures for erosion and sediment control, along with provisions for the protection of fish and wildlife, and other ecological resources, should be regarded as essential components of early planning and design (Bureau of Reclamation, 1976).

Among the most critical preparatory tasks is river diversion, which ensures a dry and stable foundation area for subsequent construction. Several methods can be used to divert river flow, including diversion tunnels excavated through abutments, conduits constructed through the dam foundation (commonly used in staged construction), flumes or open channels for surface diversion, and cofferdams to enclose the working area. The selection of an appropriate diversion method depends on factors such as river discharge characteristics, geological conditions, and the overall construction schedule. In large-scale projects, multi-stage diversion schemes are often required. In parallel, dewatering measures, such as pumping installations and drainage galleries, are implemented to maintain dry and stable conditions within the foundation pit (Bureau of Reclamation, 1976).

The dam foundation requires thorough treatment to ensure sufficient strength, impermeability, and long-term stability. Typical foundation improvement measures include the excavation and reshaping of weak or weathered zones, removal of loose or unstable rock, implementation of grouting programs to minimize seepage, and installation of drainage systems to reduce uplift pressures (Stojić, 1997; Bureau of Reclamation, 1976). Historical experiences have demonstrated that inadequate or improper foundation preparation has frequently been a critical factor contributing to dam failures (Wiltshire, 2002).

Prior to the commencement of principal construction works, access roads, temporary bridges, and construction camps are constructed to ensure the efficient transportation, handling, and storage of construction materials, machinery, and equipment. Construction camps provide accommodation, administrative offices, and operational spaces for the workforce, thereby supporting effective site management. Additionally, ancillary works, such as the installation of

temporary power and water supply systems and the construction of workshops, storage areas, and service facilities, are carried out to support the continuous and organized execution of construction operations.

3 DAM CONSTRUCTION PHASE: GEODETIC AND CIVIL ENGINEERING PERSPECTIVE

Stake-out may be understood as a set of surveying actions with the goal to determine geometric system created by interconnected points, lines, and planes, which enables to indicate the location and height of a structure and its elements (Pawlowski and Abbas, 2009). In other words, geodetic stakeout is a surveying process that involves transferring planned coordinate points from a design (drawings, models, or maps) to physical positions in the field (Figure 6).

Traditional geodetic stakeout methods include orthogonal method, polar method, angular intersection and resection (i.e. backward intersection). With the advent of total stations that allowed fast and reliable distance measurements the polar method became especially popular due to its ease and efficiency (Sestras, 2021). In the modern era, GNSS method have largely taken precedence, because even in challenging environments like urban or forested areas it is possible to achieve accuracy adequate for most civil engineering projects. When GNSS is unavailable or unreliable, the polar method remains the standard fallback. Advancements in robotisation of geodetic instruments created hybrid methods that combine total station with GNSS – this approach mitigates limittaions of GNSS method in the areas where sky view is highly obstructed. Modern robotic total stations allow one-person operation of polar method stakeout with prism tracking.

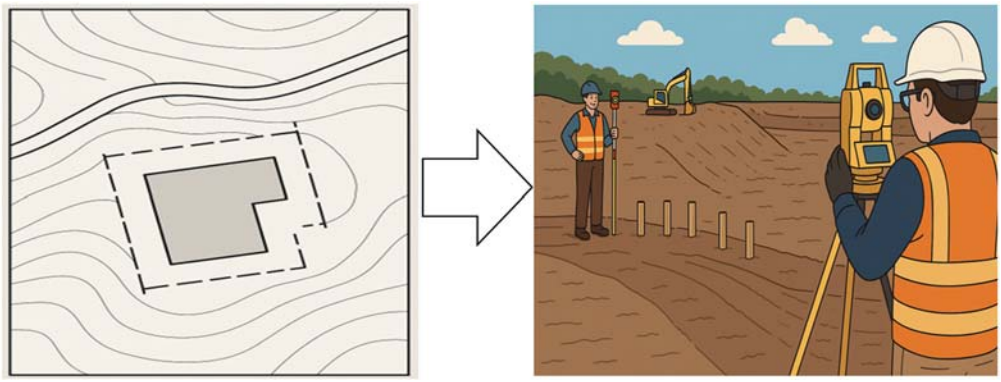

Figure 6. Plan view and field stakeout of an object outline by geodetic survey (author's illustration, created from original sketch and improved with the assistance of ChatGPT, 2025).

In modern dam stakeout operations, GNSS methods can be highly effective provided terrain conditions meet geodetic standards. In relatively flat and open environments, GNSS offers efficient and reliable positioning suitable for many surveying tasks (Scaioni et al., 2018). However, in narrow canyons or gorge-like settings, GNSS performance can deteriorate due to restricted sky visibility, few visible satellites, and extensive multipath errors, rendering GNSS unsuitable for precise staking (Hussain et al., 2021).

For staking out larger and more complex structures such as dams, it is essential to establish an adequate geodetic control network, ideally adjusted as a free network. Because construction sites often lack complete organizational plans, this network must be adapted throughout the construction process, as certain points may be destroyed, displaced, or obstructed. In such cases, the triangulation network, commonly used in these projects, can be supplemented with a polygonal network to ensure accuracy and continuity. For vertical control, a levelling network is established, measured with precise levelling methods and typically adjusted as a free network tied to a benchmark (Pašalić, 1995).

In geodetic practice, for large and complex construction projects, the control network is typically structured in several hierarchical levels. It generally consists of (Pawlowski and Abbas, 2009):

- first-order network – established in geodetic framework with GNSS and classic measurements,
- second-order network – serving as the reference framework for realizing specific structures or groups of structures and their interconnections, and
- detailed points – marking the positions of selected structural elements, such as pillars or walls.

The foundation staking is carried out based on the dam design plan, with the dam axis marked and stabilized on site using permanent markers, which are incorporated into the triangulation system. The dam axis is usually aligned with one of the coordinate axes of an independent local system, simplifying further calculations. Foundation depth is initially approximate in the design, refined during excavation, after which surveying is used to determine excavation volumes and concrete requirements (Pašalić, 1995).

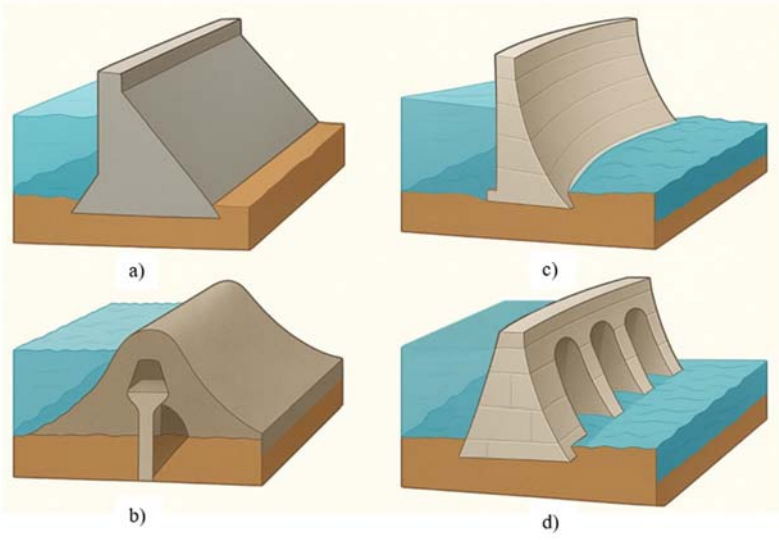

Figure 7. Schematic Representation of four dam types: gravity, arch, embankment, and buttress (author's illustration, created from original sketch and improved with the assistance of ChatGPT, 2025).

For different dam types (Figure 7) the stakeout procedure may vary in detail. However, the core of every dam stakeout remains the same: the establishment of a high-quality geodetic control network and application of adequate geodetic method.

The methods of dam construction vary substantially depending on the type of the dam. Embankment dams, including earthfill and rockfill types, are built in successive layers of compacted material. Developments in soil mechanics and geotechnical engineering throughout the 20th century have transformed embankment dam design from simple, homogeneous embankments into zoned structures incorporating impermeable cores, drainage filters, and rockfill shells to enhance stability and seepage control (Wiltshire, 2002; U.S. Army Corps of Engineers, 2004; Novak et al., 2007). Concrete gravity dams are typically constructed in staged concrete blocks, requiring strict regulation of temperature variations and shrinkage effects. Detailed guidelines for batching, mixing, placing, curing, and for the management of thermal stresses through pre-cooling and post-cooling systems are provided in standard dam construction manuals (Bureau of Reclamation, 1976; Novak et al., 2007). Arch and buttress dams, on the other hand, require precise geometry and continuous monitoring of stresses and deformations during construction. The use of numerical analyses in conjunction with field instrumentation and observations is essential to verify the structural behavior throughout the construction process (Figure 8) (Stojić, 1997; Hadzalic and Ibrahimbegovic, 2025).

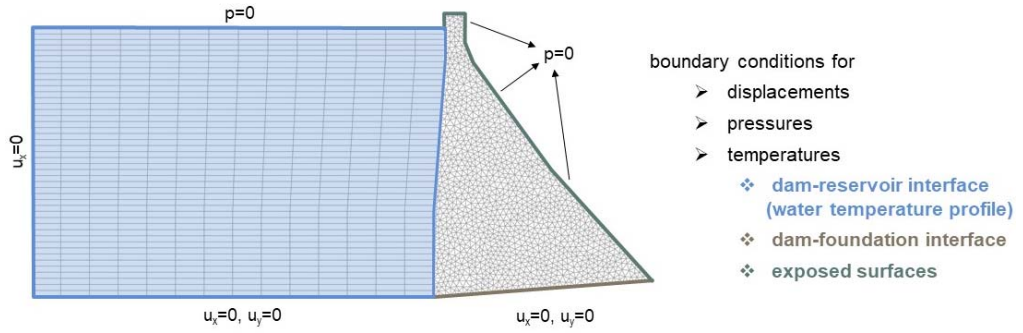

Figure 8. Finite element-based numerical model of the dam–reservoir system with boundary conditions illustrated.

Concurrently with dam body construction, the spillways, outlet works, diversion tunnels, intake towers, and power conduits are built, which are essential for ensuring hydraulic safety, flood routing, and controlled water releases. Spillways are designed and constructed to safely pass the design flood inflow, while outlet works provide flexibility for water supply, irrigation, and power generation. In addition, civil engineering practice involves the construction of galleries and adits within the dam body, which serve for drainage, grouting, inspection, and instrumentation (Bureau of Reclamation, 1976; Fell et al., 2014).

Material quality control represents a fundamental aspect of the dam construction phase. The quality of concrete is maintained through strict specifications governing aggregate grading, water–cement ratio, admixture use, and curing methods. Particular emphasis is placed on temperature control, which involves pre-cooling of aggregates, post-cooling through embedded pipe systems, and careful sequencing of lifts to minimize the risk of thermal cracking (Bureau of Reclamation, 1976). For embankment dams, equal importance is assigned to the selection and

control of fill materials, adherence to compaction standards, and maintenance of optimum moisture content (U.S. Army Corps of Engineers, 2004).

Monitoring during dam construction is essential. Alongside geodetic monitoring, comprehensive instrumentation systems are implemented to measure temperature variations, deformations, pore-water pressures, seepage flows, uplift pressures, and stresses within both the foundation and dam body (Stojić, 1997; Bureau of Reclamation, 1976). Continuous monitoring and data analysis enable the early detection of abnormal behavior, support the verification of design assumptions, and provide a basis for timely maintenance or corrective measures.

4 INSTRUMENTS AND METHODS FOR STRUCTURAL HEALTH MONITORING OF LARGE DAMS

Structural health monitoring of large dams begins immediately upon completion of construction, with baseline measurements (usually referred to as the "zero series of measurements") conducted before reservoir filling. Monitoring continues during the filling stage and is then maintained throughout the entire service life of the dam. After impoundment, geodetic observations are typically carried out at relatively short intervals (weekly or monthly) depending on the type of structure and safety requirements (Institut za vodoprivredu „Jaroslav Černi", 1982). In the modern era, the process has become easier to automate: physical measurements can be recorded continuously, and in some cases geodetic methods are integrated through the use of permanent GNSS stations. Nevertheless, each case is highly site-specific, since terrain conditions, dam type, and environmental influences determine the configuration of the geodetic control network and the choice of monitoring methods and instruments.

The geodetic network established for preparatory works and dam construction can later be used, either fully or partially, for dam monitoring. In many cases, this network requires additional points located in stable areas, while points placed directly on the dam are installed in such a way that they represent the entire structure. From a finite number of strategically positioned points, it is thus possible to infer the overall behavior of the dam (Hamzić, Avdagić and Bešić, 2020).

Stable reference points are typically positioned both downstream and upstream of the structure. For monitoring vertical displacements, the network often takes the form of the letter "H", since the dam is frequently the only connection between the two riverbanks. Networks for monitoring horizontal displacements are usually configured as geodetic triangles or rectangles, owing to the high accuracy requirements in the structural health monitoring of dams (Hamzić, 2022).

The results of geodetic observations provide both vertical and horizontal displacements of the dam structure and its surrounding area. When combined with physical measurements, these data deliver a comprehensive understanding of the dam's behavior. By considering all factors influencing dam movements, experts can assess whether the structure remains stable. Furthermore, through the application of predictive models (statistical, numerical, artificial intelligence, or hybrid approaches) it is possible to forecast future structural behavior.

Monitoring and safety control are essential to ensure the structural stability and operational reliability of dams throughout both the construction and service life. From a civil engineering perspective, these processes form a continuous loop of measurement, evaluation, and

intervention, aimed at verifying design assumptions, detecting anomalies, and preventing potential failures. The primary objective of dam monitoring is to record and interpret the actual behavior of the structure and its foundation, and to compare it with the predicted performance derived from design analyses. Historically, insufficient observation of hydrogeological conditions and structural responses has been identified as a major contributing factor in several dam failures (Stojić, 1997).

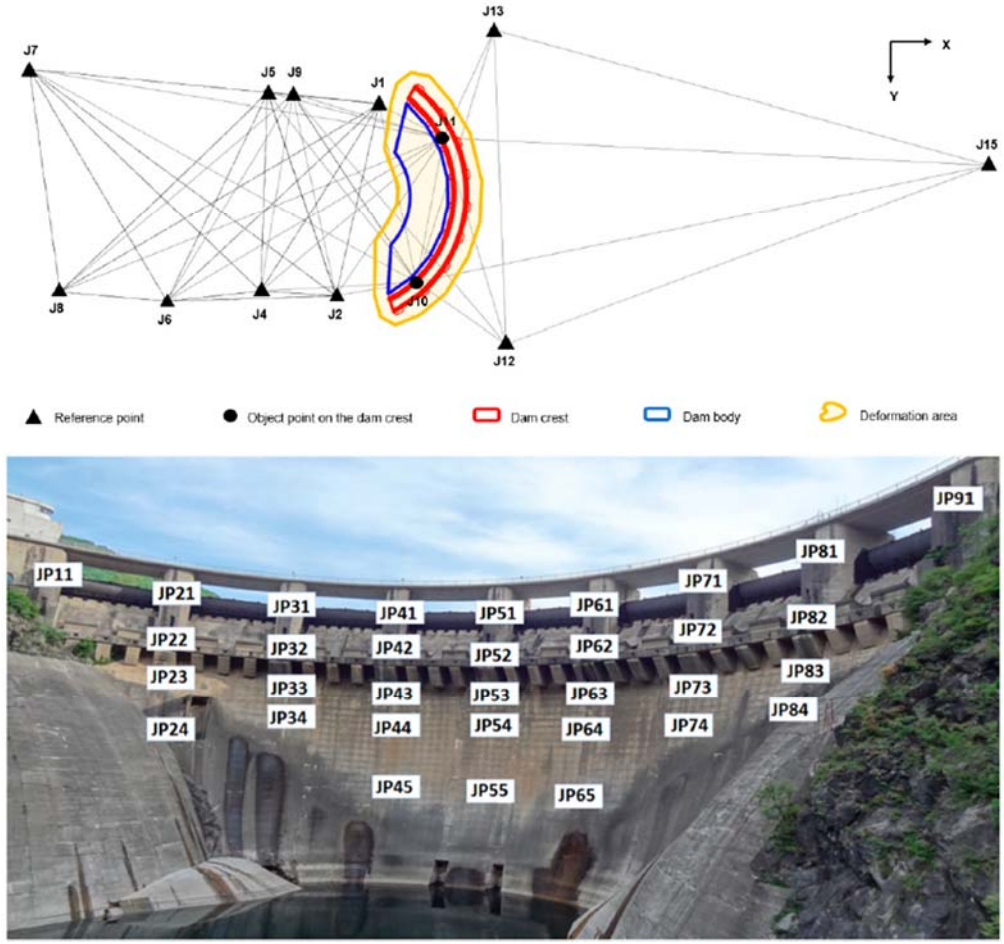

Figure 9. Reference point network (top) and distribution of object points on the downstream side of the HPP Jablanica dam body (bottom) (Hamzić, Avdagić and Bešić, 2020).

A comprehensive monitoring system incorporates both geodetic instruments and specialized sensors. Geodetic methods involve precise surveying of crest displacements, abutment movements, and embankment settlements, while mechanical instruments, such as extensometers, inclinometers, and joint meters, record deformations within the structure. Electrical and electronic sensors include piezometers (for measuring pore-water and uplift pressures), strain gauges (for stress monitoring), and temperature sensors (for temperature variations monitoring). Additionally, hydraulic monitoring through drainage galleries equipped with measuring weirs

and flow meters enables the assessment of seepage quantity and quality, supporting early detection of changes in hydraulic behavior (Wiltshire, 2002).

Monitoring begins during the construction phase, where it serves to verify foundation performance, control uplift pressures, and identify potential seepage paths. Instrumentation data provide crucial feedback for construction management, guiding decisions such as the implementation of additional grouting, drainage measures, or slope stabilization works. Once the dam enters operation, monitoring becomes an integral part of long-term safety management.

According to the Bureau of Reclamation (1976), monitoring programs should encompass measurements of structural deformations (including settlements, horizontal displacements, and rotations), hydrostatic effects (uplift pressures, seepage, and drainage flows), and stress–strain behavior within both the dam body and foundation. Continuous observation over extended periods enables trend analysis, facilitating the early detection of abnormal behavior such as accelerated settlement, increased seepage, or progressive cracking.

The collected data are analyzed through technical diagnostics, wherein observed values are compared with allowable limits prescribed by design specifications and safety standards. When deviations are identified, appropriate corrective measures may include foundation treatment (e.g., supplementary grouting or drainage), structural rehabilitation (reinforcement or crack sealing), or hydraulic interventions (such as relief wells or spillway modifications). Modern dam safety assessments integrate instrumental data, visual inspections, and numerical modeling, providing a comprehensive basis for evaluating residual service life, resilience to extreme events, and compliance with regulatory safety requirements (Wiltshire, 2002; Hadzalic and Ibrahimbegovic, 2025).

5 CONCLUSIONS

The construction and long-term operation of large dams requires a high level of coordination between geodetic measurements and civil engineering practices. From the preparatory phase to the operational stage, each step demands precise data acquisition, reliable interpretation, and continuous verification of structural behavior. The integration of modern geodetic technologies, such as GNSS surveying, LiDAR, and UAV photogrammetry, with civil engineering methods enhances the accuracy of design, ensures precise construction control, and provides a robust framework for structural health monitoring.

The review of historical and contemporary practices demonstrates that the safety and performance of dams depend not only on engineering design and material quality but also on systematic monitoring and timely maintenance. Geodetic measurements, combined with physical measurements, form the foundation of an integrated monitoring system capable of detecting early signs of structural instability or degradation. This multidisciplinary approach allows for the early identification of risks, supports predictive modeling, and enables informed decision-making in dam management.

In the context of Bosnia and Herzegovina's aging dam infrastructure, adopting modern geodetic and monitoring technologies is vital for maintaining operational safety, optimizing hydropower production, and ensuring compliance with international standards. Strengthening collaboration

between geodesists and civil engineers will be essential for developing adaptive, data-driven systems that enhance the resilience and sustainability of dam structures under evolving environmental and climatic conditions.

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