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Research paper

Application of non-contact geodetic measurement techniques in dam monitoring

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Abstract: The maintenance of dams, including the protection of reservoir and flood embankments, requires regular control measurements and assessment of their technical condition. The choice of measurement methods, especially in terms of their speed and reliability, become crucial especially when the facilities are endangered due to a natural disaster. However, despite the enormous rapid development of modern geodetic measurement techniques, measurements at most dams are still conducted using classical techniques, such as angular-linear or leveling measurements which require interference with the measured structure. In addition, they need to be personally performed by employees or require visual inspections of the structure or in its protection zone. This article presents non-contact geodetic measurement techniques, such as terrestrial laser scanning, remote sensing classification of intensity and thermovision images recorded with various measurement sensors, digital image correlation, digital photogrammetry, or UAV. They are presented and compared in terms of their reliability, efficiency and accuracy of the obtained data, and the possibility of their automation and integration. As surveyors and hydraulic and geotechnical engineers are increasingly turning to modern measurement technologies, the aim of this paper is to help in selecting appropriate and effective monitoring tools ensuring fast and safe measurements crucial for the safety and maintenance of concrete structures. It presents examples of research based on the use of the modern measuring techniques carried out in recent years by employees of the Faculty of Geodesy and Cartography at the Warsaw University of Technology.

Keywords: hydraulic engineering, dam, geodetic measurement techniques

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1. Introduction

In the assessment of the safety of hydraulic structures it is necessary to combine different measurement and calculation techniques and experience of specialists from various fields of engineering. Each hydraulic structure is subjected to the action of many internal and external factors, which results in geometric and structural changes, including the properties of materials, in particular the surface properties of construction materials. The data about the state of the structure can be obtained using geodetic measurements of displacements and deformations, which are then used to create a discrete model representing the current state (shape) of the structure. When performed regularly, the measurements bring data that can be used for developing a deformation model. The interpretation of measurement results allows to assess the technical condition and, in case of emergency, help initiate actions to prevent danger to human life and irreversible changes to the natural environment.

The ongoing development of measurement technology has resulted in tools that ever-increase the accuracy, pace and efficiency of measurements of the monitoring of changes in engineering structures. Measurements can bring not only geometric but also spectral data in the form of images (e.g. photographs of structures taken by cameras integrated with surveying instruments and operating in the wavelength range of visible light (video-tacheometry) or thermal radiation), as well additional information recorded for individual points during laser scanning (i.e. the intensity of the returning beam of radiation reflected from the surface of the assessed material). Such multi-criteria analyses provide a more reliable assessment of the condition and safety of hydraulic structures. In addition, the integration of measurements and the use of numerical modeling in the assessment of the structure's behavior and qualitatively diverse data enable a comprehensive assessment of the condition of the hydraulic structure, thus giving a clearer and more transparent picture of the current situation.

2. Non-contact measurement methods

The type of measurement methods used in structural monitoring depends primarily on the external conditions and the state of the structure being assessed. Measurement methods should provide data with a precision and accuracy that enable a correct assessment of the structure's condition [1, 2]. With regard to hydraulic structures, especially structures made of concrete or other dense mixtures, the following three groups of tests can be distinguished:

– destructive testing, which generally involves loading to failure of samples specially prepared or taken from the structure, usually in the form of cylindrical boreholes of varying diameter and length,
– minor destructive testing, which involves a determination of the material performance by pulling or tearing an anchored or adhered component from the near-surface layers of the structure,
– non-destructive testing, consisting of a set of methods allowing to determine the quality of the tested structure without reducing its functional properties, for example non-contact methods, visual (e.g. photography, thermal imaging), sclerometric (e.g. Schmidt hammer test), ultrasonic, seismic (using impact as a factor triggering vibrations) and radar methods, as well as acoustic and radar tomography.

Modern geodetic measurement techniques are based on the acquisition of metric data about the measured structure and its basic properties, i.e. the position and its periodic changes, the shape and its changes, the texture, and spectral properties.

Non-contact surveying methods include control measurements made with total stations in specially designed piecewise angular-linear control networks, in which measurements do not come from measuring instruments located on the structure, but rather from signal targets or characteristic elements of the structure. This tacheometric measurement is a discrete technique that does not provide data for evaluation of a structure's surface. The basic advantage of total station surveys is their high accuracy, allowing the determination of point displacements even at the level of tenths of a millimeter based on observations made from hundreds of meters from the structure. Although classical total station measurements are not the primary focus of this article, they are mentioned here because of their referenceability and similarity (in basic scope) to laser scanning. In laser scanning, a structure is described by a point cloud where the mutual positions of points are determined on the basis of automatic measurement of horizontal and vertical angles and distances to the structure determined during the rotation of a mirror. Specific non-contact measurement techniques – terrestrial laser scanning, spectral data analysis, digital image correlation, and aerial photogrammetry – are described in the following sections. Table 1 summarizes the geodetic measurement methods used in the monitoring of hydraulic structures.

Table 1. Geodetic methods of dam monitoring

Method	Type of structure	Parameters
Tacheometry, periodic inventory measurements	Concrete dams Earth dams Flood embankments	Displacements and deformations of structural elements and indicated control points on the site
Photography	Concrete dams	Visual assessment
Airborne photogrammetry	Concrete dams (only the crest) Earth dams Flood embankments	Visual assessment Image-based metric assessment Data for remote sensing studies Site environment monitoring
UAV (unmanned aerial vehicle) photogrammetry	Concrete dams Earth dam Flood embankments	Visual assessment, Photo-based metric evaluation (including oblique photography) Remote sensing data Site environment monitoring
Terrestrial Laser Scanning (TLS), point cloud	Concrete dams Earth dam Flood embankments	Displacements and deformations of structural elements and indicated control points on the site Identification of surface cracks Deformation of the surface Geometric model of the structure
Terrestrial Laser Scanning (TLS), Spectral analysis Intensity	Concrete dams	Assessment of surface condition: differences in material density, cracks, surface impurities Assessment of filtration
Thermal imaging	Concrete dams Earth dam Flood embankments	Surface condition assessment: cracks, surface impurities Assessment of filtration
2D Digital Image Correlation	Concrete dams	Displacements and quick-changes vibrations of the structure (e.g. due to power plant operation or lowering of the water level)

2.1. Terrestrial laser scanning (TLS)

Measurements in difficult terrain conditions, which are usually associated with dams, require specialist equipment and appropriate geodetic measurement techniques. Surveying instruments which are used to carry out periodical control measurements should be characterized by high precision and accuracy. The close vicinity of the water environment results in the occurrence of local microclimatic conditions which are not always favourable for the performance of observations with the expected accuracy. Terrestrial laser scanners are surveying instruments that can meet these high expectations thanks to the high density of observed points, accuracy, speed, and economics. They allow registration of millions of points representing the measured surface. TLS gives XYZ coordinates of points and the value of the intensity of the reflected radiation in individual places. With the scanned point clouds, it is possible to create quasi-continuous models of concrete structures that can be used in geometric and spectral analyses, as well as obtain information for detailed analytical and computational considerations [3].

Laser scanners are divided into phase- and pulse-based devices. This division is closely related to the measurement range: phase-based scanning is dedicated to short distances (currently up to 200 m), while pulse-based allow measurements of sites located further from the measurement station (even up to several kilometers). Depending on the mode of distance measurement (phase or pulse) and the type and model of the instrument, the measurement accuracy varies, ranging from a single millimeter to several centimeters. Apart from the method of distance measurement, the accuracy of the results is significantly influenced by atmospheric conditions, point cloud accuracy, the accuracy of referencing to an external coordinate system, etc.

Terrestrial laser scanning is now widely used in various scientific and economic fields i.e. geomorphology [4] hydrology [5], forestry [6, 7], archaeology [8, 9], hydrology and civil engineering [10], glaciology [11], forensic science [12] and many others. We can also observe a growing interest in this method in hydrology, especially in monitoring earth dams e.g. [13–18]. After ten or so years of intensive trials and experiments, terrestrial laser scanning can be considered as another legitimate method, in addition to polar and photogrammetric methods, for measuring the surface of terrain and engineering structures.

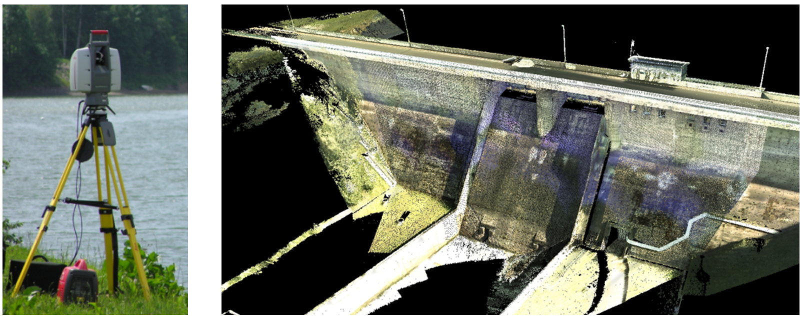
With respect to hydraulic facilities, laser scanning can be used in:

- inventory: inventory of the site at different stages of construction (comparison of completed elements with the design), as-built inventory, inventory after major repairs, periodic measurements during operation,
- verification of the geometry of numerical model of the structure's behavior, e.g. occurrence of dependencies between changes in water level in the reservoir and changes in the structure's geometry,
- assessment of the technical condition of the structure – assessment of the surface condition.

2.1.1. Inventory of a concrete dam body by terrestrial laser scanning

Building inventories are intended to present the actual state the structure and therefore register the occurring changes. Appropriate documentation requires a series of measurements to provide spatial visualization of the measured facility. Thanks to the high speed of terrestrial laser scanners (the latest models of phase-based scanners measure at a speed of one million points per second) and the large amount of data collected, laser scanners have become an indispensable tool used in inventory work. Although the classical measurement technologies guarantee sub-millimeter accuracy of the surveying tasks, they are not able to provide such extensive data coverage.

An example of this type of study can be the inventory of the Besko Dam made in 2009 by a team of employees of the Faculty of Geodesy and Cartography, Warsaw University of Technology (Department of Engineering Geodesy and Detailed Measurements) and Leica Geosystems Poland. The measurements were taken with a Leica ScanStation 2 phase scanner using a green laser. The measurement results for the downstream side of the Besko dam are shown in Fig. 1. The data were acquired from two scanner sites located upstream of the dam and from a site located on the dam crest.



(a) (b)

Fig. 1. Measurements of the Besko dam. (a) Leica Scanstation 2 during the measurement (photo from the author's archive), (b) results of the measurements of the dam from the downstream side [19]

The inventory study prepared with the use of terrestrial laser scanning can be used for various analyses – preparation of vector drawings, numerical models of the structure and its ehavior, the classification of land cover and the management of the structure and its surroundings. Fig. 2 shows the result of modeling the concrete surface of the Besko Dam.

Fig. 2. Results of Besko Dam measurements, model of the external surfaces of the dam [19]

Another example of an inventory study is the 2012 measurement of the Klimkówka earth dam [20, 21]. The object of measurement was the inspection gallery located inside the dam's structure along its entire length (Fig. 3b).

(a) (b) (c)

Fig. 3. Measurement of the Klimkówka dam: (a) Leica Z+F Imager 5010 scanner during the measurement (photo from the author's archive), (b) exit from the left abutment, on the walls are targets for orientation and joining the scans (marked with red circles in the picture), (c) fragment of the inspection gallery scan, on the concrete floor are leveling benchmarks (marked with red circles) and displaced metal covers (prepared by Z+F Laser Control software)

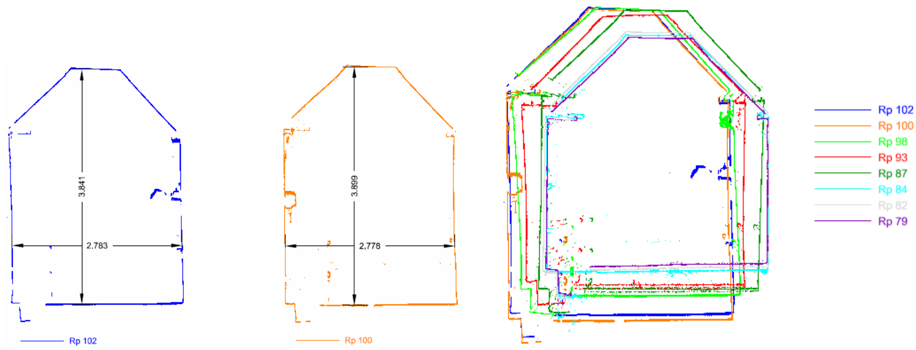
A Z+F Imager 5010 scanner (Fig. 3a) was used to make an inventory inside the inspection gallery. Twenty-three scans were taken with an average resolution of 6 mm at a scanning distance of 10 m. A fragment of the inspection gallery scan is shown in Fig. 3c. The resolution of the scan is closely related to the degree of detail of the model we want to obtain. During the scanning of the inspection gallery the stations were located on the staircase landings at a distance of about 5 m, which provided adequate coverage of the object with laser data and mean error in the height difference between the measured points on the scan at less than 5 mm, expected for this type of measurement. Ascan software (AstraGiS) was used to process the obtained point cloud.

The feasible analyses for evaluating the condition of the inspection gallery:

- vertical cross-sections of galleries in the locations of benchmarks in the concrete floor,
- comparison of vertical sections to analyze gallery geometry (Fig. 4),
- longitudinal section through the inspection gallery (Fig. 6),
- orthogonal projection of the dam gallery stairwell wall with hypsometric tints (Fig. 6).

It should be noted that the leveling benchmarks of the object's control network are located in special wells about 2–3 cm below the concrete surface in the gallery (surface of the staircase steps, "floor" surface). During measurement with laser scanner these wells were covered with lids (Fig. 3b) – the height of the 3D model was determined using the surface of the lid.

Cross sections were made for the selected parts of the control gallery as shown in Fig. 4a. The locations of the cross-sections coincide with the locations of the control points located at the joints of subsequent sections of the gallery and directly behind subsequent expansion joints. The example cross-sections were dimensioned on the basis of scanning results. The current dimensions can be the basis for monitoring the technical condition of the dam gallery, as the measurements made in subsequent measurement cycles will show possible changes of the structure's geometry – visible on the cross sections of point clouds made at the same spots. The comparison of cross-sections of the gallery (Fig. 4b), especially on its straight section, allows to observe displacements in the successive parts of the structure – changes in the position of sections in relation to each other in successive control periods may indicate destabilization of the gallery's structure and thus a threat to the safety of the object.



(a) (b)

Fig. 4. Diagrams of: (a) cross sections through the dam gallery at selected locations, (b) dam geometry depicted by superimposed cross sections generated at the locations of selected benchmarks

The monitoring of hydraulic structures is not just a geometric inventory of the current state of the structure, but also an assessment of its technical condition. Based on data from the terrestrial laser scanning, it is possible to develop orthogonal projections and supplement them with information on deviations in the form of hypsometric maps which give a comprehensive picture of its condition (e.g. depiction of the wall geometry by indicating its deformation and deformation as a function of deviations from the projected surface). Fig. 5 shows the longitudinal cross-section and Fig. 6 shows the corresponding orthogonal projection on the vertical plane of the gallery wall cross-section showing the shape of the gallery wall (hypsometric tint) – after the superposition of the cross-sections made in subsequent observation cycles it is possible to observe potential changes occurring on the wall surface i.e. changes in the size of cracks, displacements and deformations.

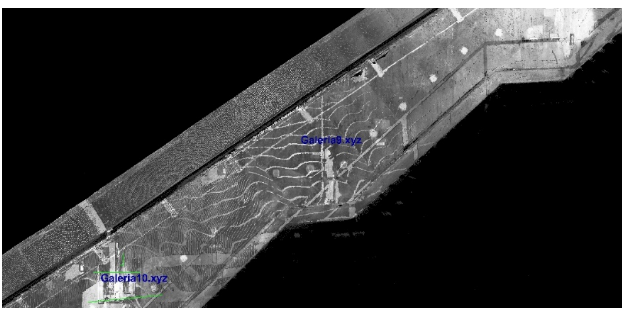


Fig. 5. Longitudinal section through the dam crest (screen shot in Ascan software), blue color indicates scan numbers

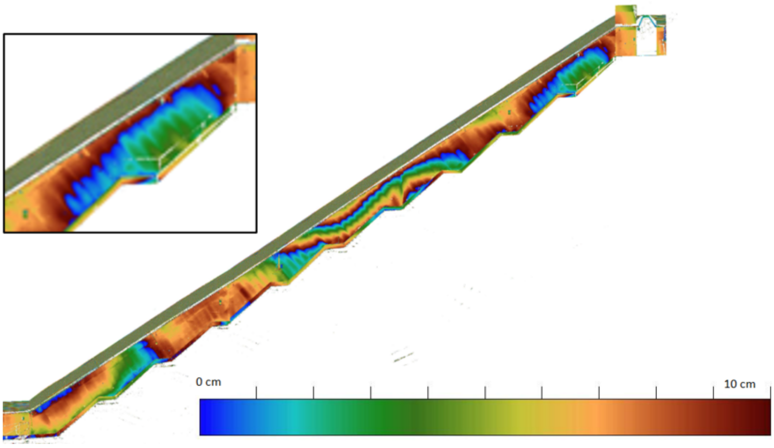


Fig. 6. The figure shows an orthogonal projection of the stairwell wall of the dam control gallery with the hypsometric tints, a section of the gallery shown in Fig. 5 is magnified

2.1.2. Classification based on laser intensity images

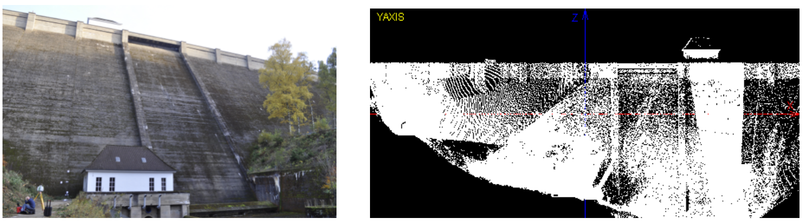
Analysis of the laser ray reflectance intensity has already found numerous applications in various fields and scientific disciplines, especially in relation to airborne laser scanning [22]. Various scientific centers are also conducting research on the use of this type of data obtained from terrestrial laser scanning. Laser reflectance intensity has been taken into account in research in the fields of natural and technical sciences: geology, glacier surfaces [11], open-pit mining, civil engineering [23] and archaeology [24], bringing measurable benefits and a new data resource. Many studies conducted by Polish and foreign centers indicate the legitimacy of using intensity differentiation to diagnose the surface condition of concrete structures. These analyses are performed taking into account various phenomena such as surface color and quality changes resulting from the actions of microorganisms (e.g. algae and lichens), physical and chemical processes (e.g. patina, salinity) and the effects of anthropogenic processes (e.g. soot deposits).

Multispectral classification is one of the more commonly used methods for thematic information extraction. Given that the value of laser reflectance intensity allows to diagnose the condition of concrete structures [3], automatic image recognition techniques such as the Iterative Self-Organizing Data Analysis Technique (ISODATA) are used in the unsupervised classification of remote sensed multispectral images [25, 26]. This technique allows obtaining classes (groups) of pixels with similar reflectance properties similarly to supervised classification.

In supervised classification, the identification and location of particular surface types (in the case of concrete surfaces these may be cracked areas, vegetated areas, clean areas, areas subject to leaching, wet areas, or areas of increased filtration) are known *a priori* as a result of field work, visual assessments, or examination of samples taken from the structure's surface. Analysis is limited to locating specific sites that represent homogeneous patterns of known surface types for remote sensing data. These areas are called training fields because the spectral characteristics of these samples will be used to train a classification algorithm to produce a map of surface types from the intensity image. Each pixel both inside and outside the training field area is evaluated and assigned to the class it is closest to or most likely to be a member of. Supervised classification can be performed using parallel piped, minimum distance, and maximum likelihood algorithms, etc.

A maximum likelihood algorithm is used in the assessment of the condition of a concrete surface using the supervised classification method. All digital processing described in this section of the paper was performed using ERDAS Imagine software.

An example of a study using intensity values for analyses can be measurements by terrestrial laser scanning made in 2013–2014 at the Ecker Dam (Fig. 7) located in the Harz Mountains (Germany) [3]. During the measurement period, the downstream wall of the dam needed to be cleaned of overgrowing vegetation (lichens, mosses, and incidentally in the small seedlings of trees (mainly birches) and shrubs) and surface defects of concrete needed to be filled. During earlier conservation work in the 1970s, the object was cleaned and some restorations were made using material with different surface properties; some of the walls were protected by a thin layer of cement coating, the remnants of which can be seen in the upper part of the wall.



(a) (b)

Fig. 7. Ecker Dam: (a) view from the downstream side, (b) fragment of a point cloud recorded using a Leica ScanStation C10 scanner

Based on the color visualization of the registered point clouds, raster images of laser reflectance intensity were prepared and the following processing of the registered images was performed:

1. ISODATA unsupervised classification – 10 classes for each data type, for a 5×5 mm pixel,
2. Unsupervised classification using the ISODATA method for integrated data (two different images of the same homogeneous area were classified simultaneously) – data recorded with two different scanners – 10 classes. As only those surface changes that were greater than 5 cm were assumed significant for the hydraulic structure, it was decided to perform processing for degraded (averaged) data to a pixel size of 5×5 cm and 10×10 cm. After analysis of the results, it was concluded that the pixel size of 10×10 cm allows optimal indication of changes on the structure's surface.
3. Define reference fields for surfaces with different properties and analyze the distribution of reflectance intensity values over the separated areas.
4. Aggregation of test areas – determination of training areas for supervised classification. The areas were grouped into classes defined *a priori*: clean concrete, concrete

with little moss growth, concrete with significant moss growth, concrete with impurities, restorations with material of other properties (e.g. cement), and significant surface erosion.

5. Supervised classification of intensity images using the maximum likelihood method.

Integrated intensity images resulting from scanning the surface with two scanners at the same time were used for classification. The purpose of carrying out this classification was to indicate areas on the concrete surface belonging to predefined classes, with analysis performed for intensity images with different pixel sizes – 5×5 mm, 5×5 cm, 10×10 cm. The results of the supervised classification of the intensity image for one of the observation stations are shown in Fig. 8.

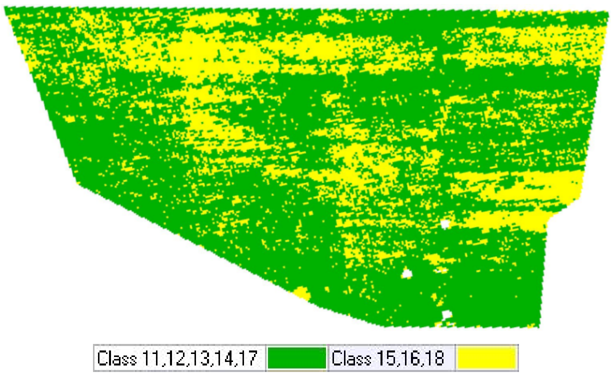
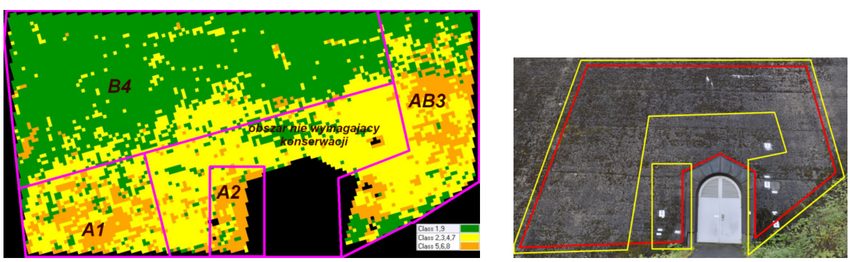


Fig. 8. Result of supervised classification using the method of highest similarity, both recorded intensity images were classified (for Leica ScanStation C10 and Z+F Imager 5006h scanners), pixel size 5×5 cm, classes are labeled in the following manner: Class 11, 12, 13, 14, 17 – moss covered concrete, Class 15, 16, 18 – clean concrete

The practical result of the study is the indication of areas on the surveyed concrete surface that should be filled, cleaned or protected in order to avoid or halt surface erosion. Fig. 9 shows the areas indicated for cleaning on the selected fragment of the downstream



(a) (b)

Fig. 9. Areas indicated for protection, classes are marked accordingly: Classes 1, 9 – concrete overgrown with moss, Classes 2, 3, 4, 7 – concrete slightly overgrown with moss, Classes 5, 6, 8 – replacements with material of other properties, significant surface erosion, (b) area to be protected marked in the visible range photo (yellow)

wall; the areas A1 and A2 – for securing and filling in holes, ca. 14.3 m^2 (A1: 11.2 m^2, A2: 3.1 m^2), area B4 – for cleaning the surface from overgrowing vegetation – ca. 75.3 m^2, area AB3 – for securing, cleaning (especially in the upper part of the area) and filling in holes – ca. 25.4 m^2.

Selection was performed based on the results of the supervised classification performed using the maximum likelihood method on the integrated intensity images acquired from both scanners.

The assessment of the surface condition allowed us to estimate the necessary scope of works, their type and cost. Determination of the scope of works translated directly not only into economic savings, but also into better selection of maintenance techniques and appropriate protection of people working at great heights during repair works.

2.2. Thermal imaging measurements

For many years, thermal imaging has been widely used in road building, construction, spatial planning [27] and in natural studies [28,29]. Recent years have witnessed a dynamic development in terrestrial laser scanning technology. One of the most recent propositions introduced by Zoller + Fröhlich company is an integration of a thermal camera with a terrestrial laser scanner. This solution allows the acquisition of geometric and spectral data on the surveyed structure and also provides information on the surface's temperature at the selected points.

An example of the use of thermal imaging measurements in control measurements is assessment of the surface condition, including the identification of concrete cracks of a fragment of the vent wall of the Rożnów dam (Fig. 10) performed in September–October in 2013 and 2015. The Rożnów dam is a heavy concrete dam with a height of 49 m and a length of 550 m, and was put into operation in 1943. Measurements were made with a Z+F Imager 5010 scanner with an integrated T-cam thermal camera.

Fig. 10. View of the tested downstream wall of the Rożnów dam with the measured fragment of the wall marked with a red rectangle

The integration of the data from terrestrial laser scanning with thermal data makes it possible to directly, without any distortions, compare thermal and intensity images. Fig. 11 clearly shows that both images contain information which can supplement one another. Using only intensity image, it would be impossible to notice that the area around point 1 possesses locally different surface thermal properties which can indicate the existence of a crevice, crack or increased filtration. Using thermal data it is also possible to note that the leakages present in the vicinity of point 2 and 3 heat up much slower than the rest of the surface, which significantly changes the way the material works and in turn may result in increased surface erosion. One can observe how thermal dilatation between closed sections of the dam work. With appropriate selection of the analyzed temperature and colour range one can highlight the analyzed aspects. Thanks to a geometrically uniform data layout it is possible to compare the registered data and analyze it in a differential aspect.

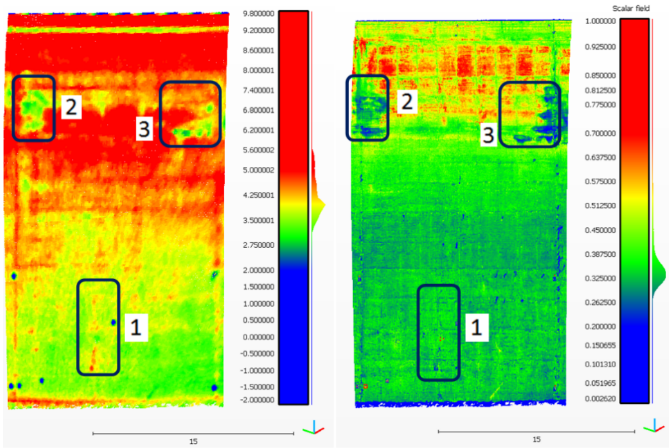
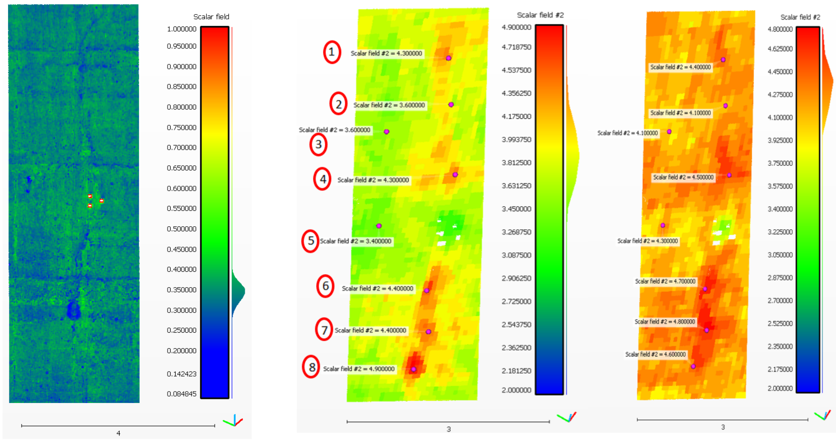


Fig. 11. Juxtaposition of a thermal image (on the left) and intensity image (on the right) for a selected fragment of the downstream wall of a dam in Rożnów

Thermal data can also be used in order to study nalyzin of crevices and cracks. Using data from the second measurement site a comparison of thermal data registered at 14:00 and 18:00 in area 1 of Fig. 11 was made. Fig. 12a presents a point cloud coloured with intensities corresponding to the analysed crevice. Fig. 12b, in turn, presents the same fragment of the clouds registered at two times of day coloured using temperature values. For the purposes of thermal data analysis 8 XYZ points were selected where the temperature was measured for both clouds.

Points 1, 2, 4, 6, 7 and 8 were placed in the area where cracks were located – in the immediate range of the analysed crack, whereas point 3 and 5 were selected as reference points located outside the cracked area. By nalyzing the calculated temperature differences in Table 2, a faster increase in temperature can be noticed on the surface surrounding the crack than in the crack itself (changes equal to 0.9°C and 0.5°C accordingly). A temperature drop was registered for point 8. This may result from the resolution of the thermal image. For the selected fragment of the thermal image the pixel size equals 5×5 cm. In the case of points selected on the edges of the crack the obtained temperature will be a mean value for an area of 25 cm^2.

Point clouds acquired through terrestrial laser scanning may be used for, apart from thermal analysis, geometric analysis of the selected crack. One can determine geometric characteristics of the crack, like width or depth, in the selected sections by fitting appropriate planes into the selected fragment of the point cloud.



(a) (b)

Fig. 12. (a) Registered intensity values for the selected fragment, (b) Registered thermal values at 14:00 (on the left) and at 18:00 (on the right) for a selected fragment of the downstream wall of the water dam in Rożnów

Table 2. Juxtaposition of temperature values in points 1 to 8 at 14:00 and 18:00 and their differences

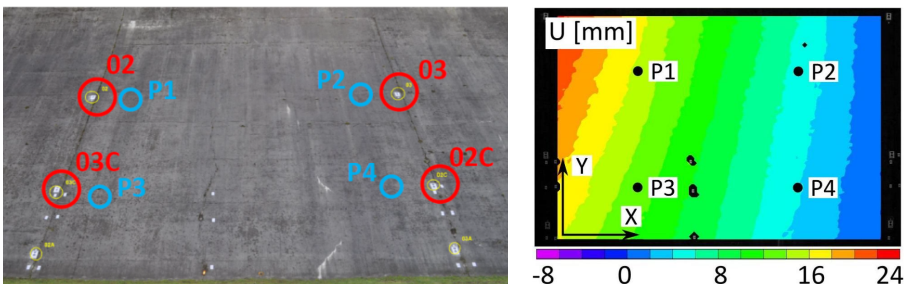
Point number	Temperature [°C] time 14.00	Temperature [°C] time 18.00	Temperature difference [°C]
1	4.3	4.4	0.1
2	3.6	4.1	0.5
3	3.6	4.1	0.5
4	4.3	4.5	0.2
5	3.4	4.3	0.9
6	4.4	4.7	0.3
7	4.4	4.8	0.4
8	4.9	4.6	–0.3

2.3. 2D Digital Image Correlation

Another non-contact and non-invasive measurement method is 2D Digital Image Correlation, which can be used to study dynamic deformation of structures. 2D DIC is not strictly a surveying method, but a method from the group of image analysis which, due to the dynamic development and miniaturization of photographic technologies, are becoming cheaper and possible to use in diagnostic measurements. Thanks to the DIC method it is possible to continuously record displacements, elastic deformations and vibrations of the structure without the limitations related to the signaling of control points or localization of point vibration sensors (accelerometers) on the structure.

An example of the use of the 2D DIC method is the measurements made at the Rożnów dam: during periodic geodetic control measurements of the dam in August 2013, a phenomenon of elastic deformation of the dam sections adjacent to the power plant was observed. Starting the power plant causes dynamic loading, which results in varying movement of the adjacent sections and a clear return to the initial state after the loads are balanced. The described analyses were performed for the dead sections of the facility marked in Fig. 10.

In order to study the behavior of dam section XVIII adjacent to the power plant during turbine operation, measurements were made using two methods: tacheometric and 2D DIC. The latter enables the measurement and monitoring of displacements and deformations of the observed structure in the whole field of view of the camera. The measurement system consists of just one camera which captures a series of images, one of which is the reference image. The tested surface must be prepared by applying a stochastic speckle pattern (in special cases, the speckle pattern may be the natural texture of the tested object). The reference image is divided into small rectangular regions (called subsets) containing $N \times N$ pixels. The dimensions of the sub-sets depend on the quality and speckle size of the speckle pattern. The CKO algorithm tracks the position of each subset from the reference image in all other images of the measurement series. U and V displacement vectors are calculated for each subset. By using advanced interpolation methods, sub-pixel accuracy is achieved [30]. Measurement results are obtained in pixels, then scaled to mm using an object of known length (registered in the measurement image). The output is a set of displacement maps, which can then be used to calculate deformation maps. Four points located in the center of the section were used for the study (Fig. 13a).



(a) (b)

Fig. 13. (a) Location of control points – displacements of points 02, 02C, 03, 03C were determined by geodetic method, deformations of points P1, P2, P3, P4 were determined by 2D Digital Image Correlation method, (b) Map of maximum values of deformation U (in X axis direction), with indicated points (P1–P4)

Tacheometric measurements showed distinct displacements of the section in the direction towards the power plant. The determined horizontal displacements, especially their components perpendicular to the axis of the structure's crest, indicated a periodical slight inclination of the section towards the upstream water, which was confirmed by the values of vertical displacements: points located higher up (O2, O3) had dropped, while those located in the lower part of the wall (O3C and O2C) were uplifted. All the observed displacements were suppressed and returned to the state before the power plant start-up about an hour after the hydroelectric set started operating.

Simultaneously with the tacheometric measurements, observations were made in continuous recording mode, every 10 seconds, using the 2D Digital Image Correlation method. An AVT Pike 16 Mpx camera (Allied Vision Tech) with a 28 mm fixed focal length lens was used. Based on the recorded and transformed images, deformation maps in two directions were developed. Deformations in the *X*-axis direction expressed as *u* [pixels] were rescaled and expressed as *U* [mm] and similarly deformations in the *y*-axis direction expressed as *v* [pixels] and then *V* [mm]. Fig. 13b shows a map of the maximum values of U deformations, expressed by color scale, oriented according to the mathematical coordinate system and the marked points (P1–P4). The data recorded for the marked points were used for quantitative analysis (Fig. 14). The graphs show the deformations (*U*) of the surface with respect to the length (*X*) (Fig. 14) of the measured wall section from the downstream side. Deformations (*U*) are specified in millimeters per meter [mm/m] of wall length/height.

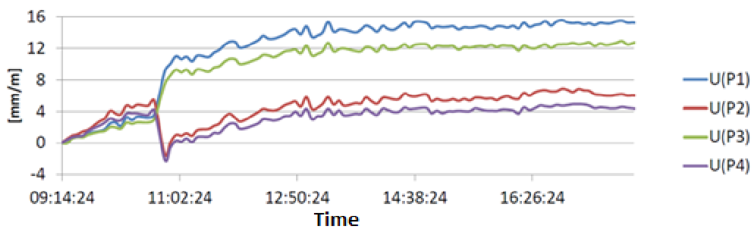


Fig. 14. An example of U deformation in the X-axis observed using 2D Digital Image Correlation

Based on the experiment, it was concluded that both methods are suitable, and this type of testing can add to the evaluation of the effects of variable loading on the structure's condition when water starts flowing through turbines.

2D Digital Image Correlation (2D DIC) is a method based on a continuous surface; it is not discrete and so it is possible to observe continuous deformation of the surface, which is not possible in case of tacheometric measurements. However, 2D DIC lacks unambiguous assessment of the accuracy and significance of displacements, which is important in technical control of massive engineering objects. It should also be noted that the tacheometric method of measurement is on the one hand more reliable, but at the same time more labor intensive. This shows that each of the presented methods has its advantages and disadvantages, and when used together they can be a rich source of information about the structure.

2.4. Remote sensing in monitoring earth dams and flood embankments

In analyzing literature, one can find examples of various remote sensing technologies, such as radar interferometry, GNSS satellite measurements, optical and microwave (radar) satellite imaging, airborne laser scanning, aerial photography and UAV data, in the monitoring of flood embankments. This short chapter introduces and briefly presents the possibilities of these techniques.

2.4.1. Airborne monitoring of hydraulic structures

Satellite data used in global analyses can be applied to flood embankment monitoring, including radar [31–33] and optical [34] data. The advances in this technology result in a steady increase in spatial resolution (ever smaller pixel) and temporal resolution (ever higher frequency of images) for most of our planet. However, the satellite data is only used to monitor and pinpoint locations for more accurate measurements. A tool using satellite data can be used for large-area analysis of imagery to preselect areas dedicated for measurement from airborne and unmanned platforms (UAF). Aerial orthophotos, numerical elevation models derived from Airborne Laser Scanning (ALS) data, and topographic databases can also be used in systems monitoring hydraulic objects. A multi-temporal analysis tool using time series processing and observation can indicate – through uncomplicated analyses based on vegetation indices – areas of flooding, leakage, occurrence of illegal objects, anthropopressure, and animal influence.

2.4.2. Unmanned aerial vehicles (UAV)

Aerial laser scanning in a quasi-continuous manner (discrete but relatively high-density data) is typically effective for capturing the shape of flood embankments [35]. An example of data development in the form of an elevation model visualized using a color palette and a shaded model is shown in Fig. 15, depicting a section of a flood embankment. A big problem with ALS data in flood embankment monitoring is the low frequency of laser scanning programs at the scale of entire regions, hence airborne scanning cannot serve as a data source for permanent monitoring of objects. Stationary scanning with terrestrial scanners, which are already a popular tool for surveyors, is in turn low efficiency. In order to scan flood embankments from both sides (from the side of the watercourse and from the

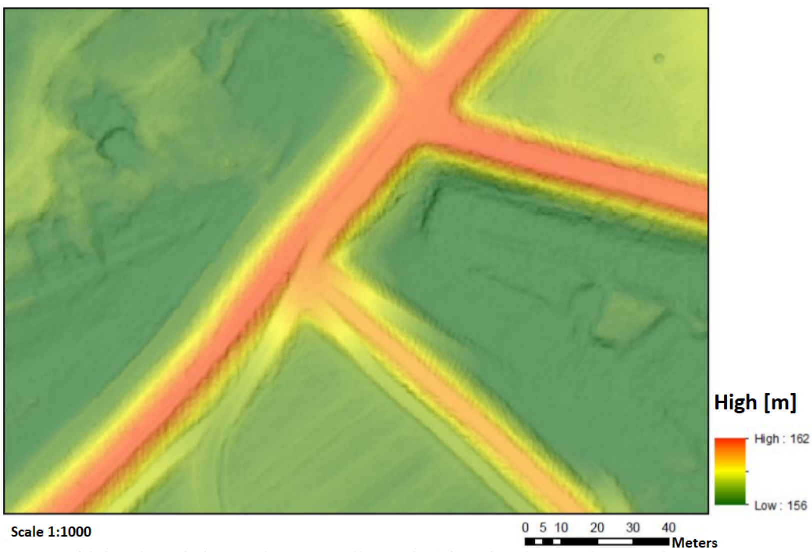


Fig. 15. Hypsometric tints of the floodbank (m. a.s.l.; Kronsztadt 86 elevation system) and the shaded model presenting the floodbank topography (ISOK data source) [36]

side of the protected area), the scanner would have to be placed repeatedly on both sides of the embankment (which reduces its efficiency) or on the embankment (which limits the scope of recorded data).

The solution is the use of unmanned aerial vehicles (UAVs), which have been used for several years in many high accuracy measurement tasks performed in short time intervals without significant financial cost, also in the monitoring of flood embankments [37]. In the last decade or so, we have also seen a tremendous development of airborne laser scanning technology, although UAVs started to be used relatively recently to this purpose, about 5 years ago [38]. An example is presented in Fig. 16 with a section of a point cloud representing a section of a flood embankment and nearby vegetation, obtained using the Yellowscan Mapper scanner. This data presents data density of up to several tens of points per square meter, was acquired from a height of 30 meters, with a relative accuracy of a few centimeters [39]. These platforms typically use low-altitude stereoscopic photography to acquire a point cloud using photogrammetric methods. The use of an aerial scanner on a UAV platform has an advantage over the traditional method capturing only digital images, by modeling the shape of the terrain without vegetation – thanks to the penetration of vegetation by the laser beam. UAVs are highly mobile – they can take measurements very quickly on both sides of the river, and even simultaneously when a river is narrow. The scanning range of a UAV flying above a linear object is much better than measurements on the ground, and far less time-consuming as terrestrial scanners need to change position or have to be placed on mobile platforms located next to the embankment (surrounding roads, scanning from water platforms).

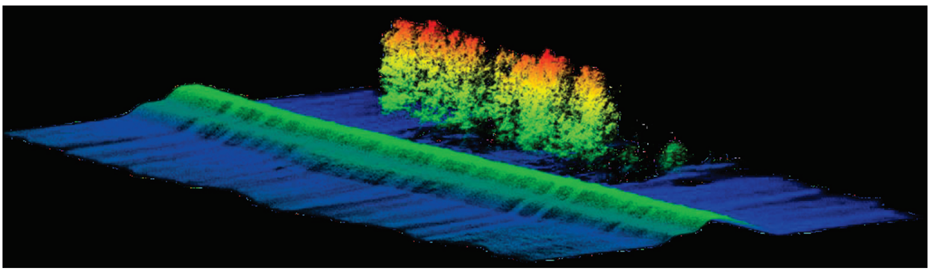


Fig. 16. Isometric view of ALS data presented as a color elevation map based on data acquired from a UAV platform with a Yellowscan Mapper scanner [36]

In addition to the use of an ultralight airborne laser scanner on UAV platforms, optical cameras that provide data to create orthomosaics are also used in flood embankment monitoring. A multispectral camera can provide particularly important information, with photogrammetric images recorded in several spectral channels (blue, green, red and near infrared), giving the possibility to assess the condition of a flood embankment by detecting changes in vegetation cover, condition of uncovered soil, presence of water, or condition of vegetation growing on the soil. Especially in this context, near infrared (NIR) spectroscopy is particularly important, as this radiation is almost completely absorbed by water and significantly reflected by vegetation – depending on its state and species. These relationships give a chance to detect soil devoid of vegetation cover, characteristic for most types of flood embankment damage.

3. Summary

Selection of a technique in measuring hydraulic structures is usually preceded by an analysis of their effectiveness. Also significant are factors such as access to appropriate measuring instruments, software for data processing and analysis, required precision and accuracy, time needed to perform a given study, and available funds. There are also studies that need to take into account access to the inventoried object – distance, lack of visibility (shadows, lack of lighting), or safety considerations (live wires, the structure is in operation).

The specific character of dam structures requires particularly careful monitoring, and the data obtained during the control measurements should be used for the assessment of the structure's safety, technical condition, and adequate maintenance of the structure. The assessment of the technical condition of dams is of particular importance nowadays as the majority of Polish dams have already exceeded their operational life. Their safety risk significantly increases and, at the same time, the growing threats are neglected by their owners and users. The condition of many flood embankments in Poland is also insufficient.

Table 3 lists and compares the discussed non-contact measurement methods in terms of their advantages, limitations, accuracy, and cost.

Geodetic surveys and numerical analyses performed for hydraulic structures can be divided into several basic groups with dedicated non-contact surveying techniques (summarized in Table 3):

- as-built surveys of structures, geodetic periodic measurements of displacements and deformations – due to the accuracy of measurements the best measurement methods are total station and terrestrial laser scanning,
- inventories for the purpose of making numerical models of a structure's behaviour – terrestrial laser scanning and terrestrial photogrammetry and measurements from UAV platforms are recommended,
- recording the behavior of structures during short-term variable loads – terrestrial photogrammetry and methods of digital image correlation, total station for observation of changes in the position of single points,
- surface condition assessment – depending on the required accuracy and scope of the assessment: cracks, impurities, moisture – ground laser scanning, ground photogrammetry, spectral analyses, thermal imaging
- technical condition assessment of the object – the choice of methods depends on the scope of the assessment; in order to obtain data for the assessments under the provisions of the Construction Law and the Water Law Prawa budowlanego [40] i Prawa wodnego [41], tacheometry and terrestrial laser scanning should be used, mainly for the sake of the accuracy of the measurement.

Due to the high cost of measurement of a single hydraulic structure, it is not recommended to use regular photogrammetric measurements from an aeroplane; for the preparation of environmental analysis and the so-called backward analysis in relation to previous periods it is recommended to use archival data from the state's geodetic and cartographic resource.

Currently, due to the development of measurement technology and software for data processing, terrestrial laser scanning is considered a universal technique, allowing the performance of complex studies and analysis, which were not previously available for any

Table 3. Non-invasive geodetic methods for monitoring hydraulic structures

Method	Advantages	Limitations	Accuracy	Measurement time/cost
Tacheometry, inventory measurements	Monitoring can cover a large area, inventory limited to the course of individual cracks and fractures	Discrete measurement, time-consuming, high cost	Depending on the instruments used: 0.1–10 cm	Long duration of measurement / high labour costs of the measurement team
Photography	Fast inventory of the surface	Often difficult to access the facility, low accuracy, limited area	Low	Fast measurement, low cost
Airborne photogrammetry	Monitoring provides complete and detailed data, can cover a large area	Limited accuracy, requires photopoints on the monitored surface	5–10 cm	Moderately time-consuming / very high costs of the plane flight
UAV (unmanned aerial vehicle, drone) photogrammetry	Monitoring provides full and detailed data, measurement of elements that are difficult to access and high, can cover a large area	Limited accuracy depending on many factors including flight stability and requires high coverage of adjacent areas, large situational limitations	5–10 cm	Fast measurement and development using dedicated software / low cost
Terrestrial Laser Scanning (TLS), point cloud	Quasi-continuous measurement, Short measurement time, full inventory of the structure, Provides data for the model of the structure and behavior prediction	Requires connecting / datum points on the monitored surface	Depends on adopted measurement resolution (point cloud density): 0.2–1 cm	Fast single station measurement, real-time data processing possible with dedicated software / Moderate processing cost (depends on expected displacement)
Terrestrial Laser Scanning (TLS), Intensity spectral analysis	Short measurement time, classification and evaluation of technical condition and surface, Detection of filtration areas	requires connecting / datum oints on the monitored surface	Depends on the adopted measurement resolution and the dimension of the image classification window: from 0.5×0.5 cm	Fast single station measurement / Moderate development cost
Thermal imaging	Short measurement time, evaluation of surface, Detection of filtration areas	Large influence of uneven insolation and varying weather conditions on the measurement results	Low accuracy depending on thermal camera sensitivity and resolution	Fast measurement and data processing using dedicated software / low cost
2D Digital Image Correlation (2D DIC)	monitoring vibration and displacement, high accuracy	Range limited to single sites, requires stable measuring stations in close proximity to tested structure elements, requires specialized software, requires calibration of each measurement	High accuracy, quasi-continuous measurement 0.1–1 cm	Measurement time equal to the operating time of the structure under test, short data processing time (automation) / medium costs

of the measurement techniques used in construction and hydraulic engineering. Terrestrial laser scanning allows the preparation of tests of almost any part of the object without additional field work or direct contact with the structure. This is made possible by the method of data registration which results in a point cloud representing the geometry of the scanned objects. The method also provides additional radiometric information on the intensity of reflection of the laser beam from the surface of the measured object. Particularly important advantages of the laser scanning method include the speed of registration of a vast amount of data and a low cost of measurement.

All non-invasive non-contact measurement methods make it possible perform analyses for any site in the structure as the need arises, increase safety by reducing work at heights to a necessary minimum, for some techniques (total station, laser scanning with the acquisition of integrated data, photogrammetry) measurements can be easily repeated, compared, and presented provided that appropriate methods of data processing are used.

It is important to remember that only geodetic surveying allows for the acquisition of fully metric data on the behavior of a structure (displacements and deformations) and its condition (location with respect to the locally used coordinate system of the locations of disturbances, discontinuities and surface impurities).

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