Journal of Ecological Engineering
Volume 17, Issue 4, Sept. 2016, pages 120–128
DOI: 10.12911/22998993/63887

Review Article

TERRESTRIAL LASER SCANNING IN MONITORING HYDROTECHNICAL OBJECTS

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Received: 2016.06.23
Accepted: 2016.07.26
Published: 2016.09.20

ABSTRACT
Developing Terrestrial Laser Scanning technology is provided by modern measuring instruments, i.e. total stations and laser scanners. Owing to these instruments, periodic control measurements of concrete dams carried out as a part of geodetic surveying provide point models characterised by quasi-continuity. Basing on the results of these surveys, it is possible to conduct a number of geometric analyses, as well as to obtain information for detailed analytic and calculative deliberations. A scanner, similarly to a total station, determines spatial coordinates (X, Y, Z) of the surveyed points by identifying distances and angles. Registration of intensity of the reflected laser beam (Intensity) sent out by the scanner provides additional information on the surveyed object. Thanks to high working speed and a large amount of collected data, scanners have become an essential tool for a geodesist.This paper evaluates the possibility of applying Terrestrial Laser Scanning to test deformations and shifts of flagged points of concrete dam construction based on experimental measurements, including object inventory and evaluation of the dam's concrete structure condition.

Keywords: terrestrial laser scanning (TLS), hydro-engineering, concrete dam, geodetic inventory

INTRODUCTION

The necessity to perform geodetic control measurements and as-built surveys in order to assess the technical and safety condition of a hydrotechnical object stems directly from the Construction Law [Prawo budowlane, 2016], the Water Law [Prawo wodne, 2015] and its consequent regulations – especially the Regulation of the Minister for the Environment on technical conditions which must be fulfilled by hydrotechnical objects and their location [Rozporządzenie, 2007]. It should be stressed that according to the Construction Law, hydrotechnical objects fall into the category of construction works, and as such, they have to observe all of its regulations. Art 5.1 stipulates that a hydrotechnical object must be used and maintained in accordance with the regulations, including technical-structural rules, established Polish norms as well as the principles of technical knowledge, ensuring safety of the object and safety of use.

According to the provisions of Art. 62 of the act, construction works ought to undergo periodic checks at least once a year in order to evaluate the technical efficiency of the used premises. Technical efficiency and value of the whole object ought to be evaluated at least every five years. What is more, in accordance with Article 62.1.4, the safety inspection of the object should be carried out in the event of the following circumstances:

- identification of atypical phenomena occurring in the object during the day-to-day operations,
- passing of a flood wave,
- atypical, intensive ice phenomena.

Additionally, the Water Law clarifies the provisions of the Construction Law with respect to specific types of water structures, to which, under the Act, dam structures intended for use in water resource management or in power industry belong. Owners or managers of such constructions are required to maintain proper technical efficiency and safety of the object and ensure its proper functioning. What is more, they are obliged to carry out surveys and inspections enabling the assessment of the object›s condition and safety, especially in regard to filtration by the object, control gallery and discharge device condition as well as the changes in upper and lower sites of the construction. Depending on the class of the object, various parameters may be monitored i.e.: vertical shifts (settlements and uplifts), horizontal displacements, inclinations to the level, deflections of the object in relation to the vertical, deflections, vibrations as well as linear, angular and shear deformations.

When monitoring the safety of hydrotechnical objects it is necessary to combine various measurement and computational techniques with the experience of specialists from different fields of engineering. The development of surveying technologies provides a wider scope of possibilities for more precise monitoring of changes taking place in engineering works, quickening surveying work, reduction of the number of gross errors as well as for lowering the cost and time required to carry out a survey. As a consequence, it ensures a more reliable evaluation of the hydrotechnical objects' safety and technical efficiency. Integration of surveys, inclusion of numerical modelling of the object›s behaviour and the evaluation of technical efficiency using data of diverse quality in the assessment allow for a more complex evaluation of the structure, hence providing a fuller, clearer and more transparent view.

Periodic measurement and technical inception aims to compare the dam›s geometry with the project parameters in the first years of its operation as well as observation of the changes taking place in the object occurring throughout the lifetime of the object.

This paper presents, using selected hydrotechnical objects as examples, the possibilities of using terrestrial laser scanning in taking inventories and carrying out periodic technical efficiency surveys.

MATERIALS AND METHODS

The difficult terrain usually present on the location of a dam determines the selection of specialised equipment and appropriate surveying techniques. Surveying instruments used during periodic control measurements should be characterised by high precision and accuracy of the obtained results. Close proximity of water environment creates local micro-climatic conditions, which not always foster observations with the expected accuracy. Surveying instruments that meet the high expectations (high density of the observed points, accuracy, speed, economics) can be found among terrestrial laser scanners. Terrestrial laser scanners allow for the registration of millions of points representing the surveyed surface. XYZ coordinates and the laser beam's intensity value in particular places are obtained as a result of a survey. Owing to the point clouds registered during a scan, quasi-linear point models of a concrete dam can be created. Using those models as a base, it is possible to perform various geodetic analyses and acquire data for detailed analytical and computational considerations [Popielski et al., 2007].

Scanners can be divided into phase-based and pulse-based instruments. The range of a scan is closely related to this division: phase-based solutions are dedicated to short distances (currently 200m) and pulse-based equipment can be used when surveying objects placed further from the surveying site (up to a few kilometres). Three types of scanners can be distinguished as far as measuring distance is concerned: short, middle and long range scanners. A subsequent characteristic results from this fact, that is, scan accuracy. Those values are in the range from single millimetre up to several centimetres depending on the distance measurement mode (phase or pulse) and the instrument model. Certainly, apart from the distance measuring method, measurement is influenced by other factors i.e.: atmospheric conditions, precision of designation of points connecting single scans (point clouds), precision of reference to an external coordinate system, etc.

Terrestrial laser scanning is widely used by architectural and archaeological communities. This technology has an enormous potential in monitoring where such dense data set can provide an insight into the nature of the structural deformations [Lichti et al., 2000]. An increase in interest in this method can be observed in hydrotechnics, especially in the monitoring of earthfill dams [Tsakiriet et al. 2006, Teskey and Bijoy 2005, Alba et al. 2006, Alba et al. 2008, Ramos-Alcazar et al., 2015].

Taking an inventory of an object aims to present an actual state of an existing structure, and thus register the changes taking place in the object. A number of measurements necessary to create a spatial illustration of the surveyed object is required in order to draw up adequate documentation. Owing to high performance speed of terrestrial lasers (the most modern models of phase scanners measure one million points per second) and large amount of the collected data, scanners became an indispensable tool used in making inventories. Even though the classic measurement technologies guarantee a submillimeter precision of the performed geodetic tasks, they cannot ensure the object data coverage as the laser scanning technology described in the paper.

RESULTS AND DISCUSSION

Taking an inventory of a dam – determining an object's external geometry using terrestrial laser scanning

Possible applications of terrestrial laser scanning in surveying surface deformations and shifts of the flagged points of the concrete dam are numerous. Inventory of a concrete dam in Besko createad in 2009 by a team from Faculty of Geodesy and Cartography, Warsaw University of Technology (Chair of Engineering Geodesy and Detailed Surveys) and Leica Geosystems Polska can serve as an example. The survey was taken using Leica ScanStation2 utilizing a laser working in a green color range. Figure 1 presents the results of a survey of the dam in Besko from the downstream side observable in the Figure 1b.

The data was acquired from two laser sites placed in front of the dam and a site situated at the dam's crown point.

The inventory created using terrestrial laser scanning can be used in many ways, starting form a classification of the land cover, through object construction management, to the creation of numeric terrain models with set accuracy and vertical and horizontal resolution. Based on the results of terrestrial laser scanning, it is easy to countercheck an object's geometry (Figure 3b) – including the differences between the constructed object and the data from an as-built geodetic survey [Zaczek-Peplinska et al., 2011].

Numeric modelling of a hydrotechnic object's behaviour under the influence of alternating dynamic loads (making a prognosis, object safety assessment in situations when deformations and shifts are detected) may concern changes in large areas being, for example, the result of a change in water relations caused by water damming in the valley area where the object is located or locally selected elements of the construction, ex. overflow sections. In both cases it is necessary to acquire the geometry of the area – a numeric model of the terrain or geometry of the construction. Depending on the model range and the phenomenon being analysed, a different accuracy of the acquired data and a different range of additional information is required. Depending on the expected accuracy, satellite images in various bands, aerial photography and terrestrial laser scanning can be used in order to acquire the data. Among the presented methods, the highest fidelity of the object's representation is obtained using terrestrial laser scanning. Not only does this technology allow for the acquisition of the densest point cloud, but also, owing to the fact that the measurement is performed from the ground level, it makes it possible to survey surfaces not visible from aerial level. Figure 2 presents the result of modelling of Besko dam's concrete surface.

Research done for Rożnów dam in 2013 can serve as another example of an inventory. Riegl VZ-400 impulse scanner equipped with infra-

a) b)

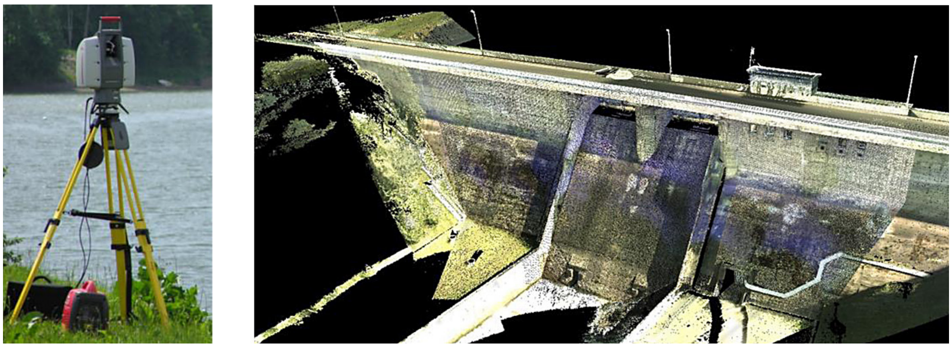

Figure 1. Survey of Besko dam a) Leica Scanstation 2 laser during the scan (author's archive), b) the results of the survey from the downstream side (author's archive)

a)

b)

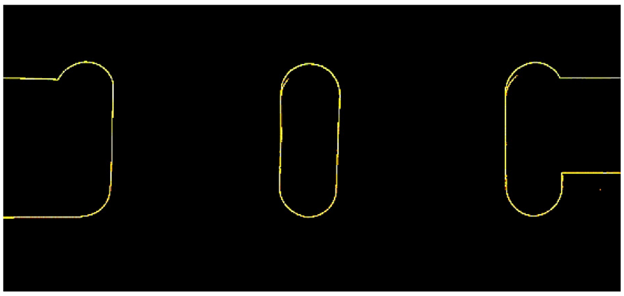

Figure 2. Result of surveying of Besko dam a) Dam's exterior surfaces model, b) horizontal section of the object (above the spillway below the bridge plate in the dam's crown point)obtained using laser scanning (author's archive)

red laser beam was used for surveying purposes [Popielski et al. 2015, Zaczek-Peplinska et al. 2014]. Point clouds were obtained as the result of the scan. Later on, they were processed using Ascan software working with a Bentley MicroStation environment [Zaczek-Peplinska et al. 2014]. The obtained results are presented in Figure 3.

Using the inventory data as reference, a verification of a numerical model of a typical section of the dam nr. XVIII, which is the deepest seated closed section, was performed. For that purpose, Z-Soil engineering calculation software was used. This software uses the finite element method and it can be used to solve problems in the field of geotechnics and hydrotechnics. The section's geometry was adopted on the basis of the archived Polish and German plans. The material parameters were adopted on the basis of the data from the dam's archive, literature and the performed field survey.

In order to compare the archived data with the factual state, the data from the laser scanning was used. Vertical sections (one middle and two extreme ones) of the scanned and modelled sections were compared. The comparison was done in AutoCad (Figure 4). A common element shared by all the sections was the lowest point located on the dam's downstream wall (E). The differences between the respective sections at the bottom of the wall are small. The closer to the dam's crown point thebigger are the registered discrepancies.

In conclusion, based on the performed analyses, the methods that provide data for the creation of numeric model were chosen. Figure 5 presents the correlations between data sources and the individual elements of the model:

The data that can be obtained from the project and as-build documentation, like geometry of the individual elements of the object, sitting levels, location of the gallery and other internal installations, modifications of the structure's base introduced during construction. Other material data that can be obtained through various field and laboratory test,

Data that can be obtained through geological and hydrogeological prospecting as well as by using geophysical measurements of the object's foundation,

Object's shape that can be obtained through surveying and laser scanning (ex. geometry of the downstream wall, control and measurement gal-

a)

b)

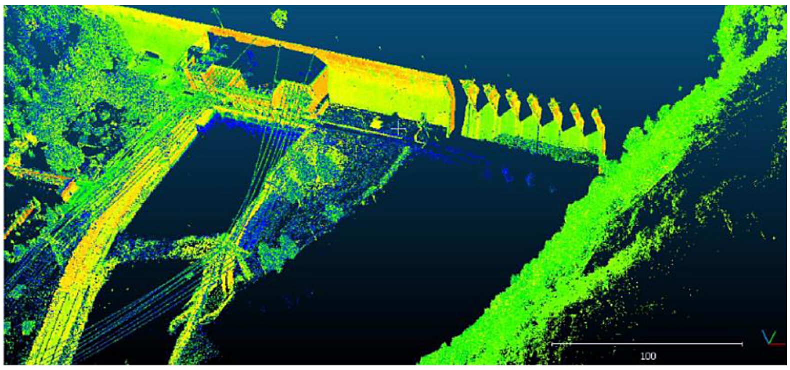

Figure 3. Rożnów dam survey; a) Riegl VZ-400 scanner during the scanning process (picture form author's archive) b) Rożnów water dam's scan

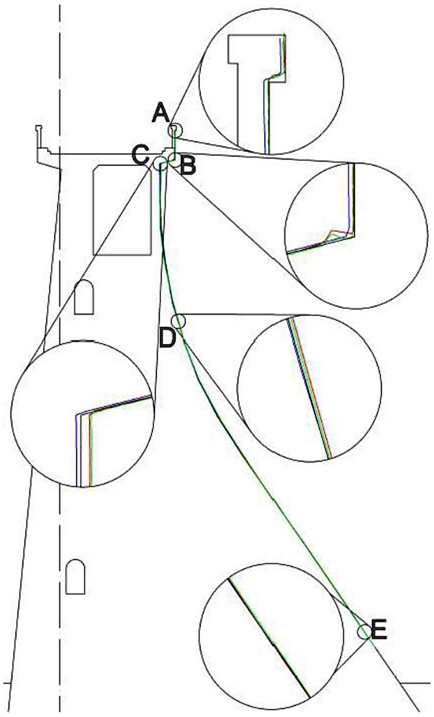

Figure 4. Comparison of sections of XVIII section, section modelled using archived data as reference was compared with three sections acquired using laser scanning [Zaczek-Peplinska et al. 2014]

leries) and readings of control and measurement devices (ex. displacement of the selected points),

The data that can be obtained from the Construction Log Book and from the research concerning the condition of the water reservoir (ex. bathymetry) and readings of control and measurement devices (ex. water level in the reservoir).

Inventory and control measurements inside pump and observation gallery

In 2012, the inventory of the earthfill dam in Klimkówka was taken. Inside the structure of the dam, pump and observation gallery was built along its entire length (Figures 6, 7). Measurements inside the pump and observation gallery

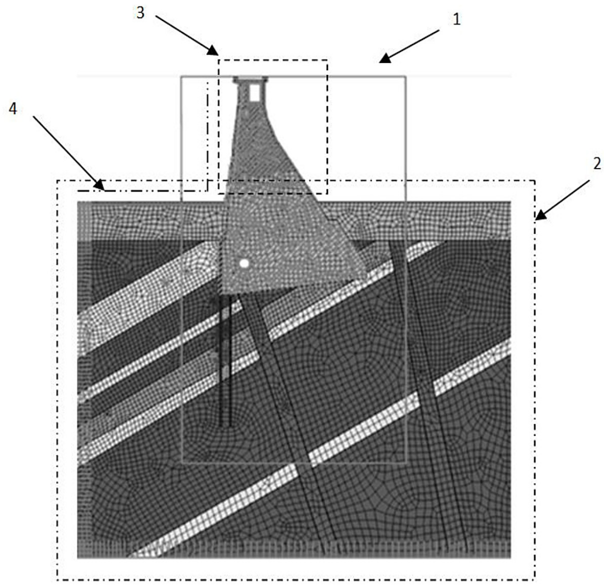

Figure 5. Collation of data sources used in order to generate individual elements of the numeric model scanning [Zaczek-Peplinska et al. 2014]

served the authors as another example of the application of laser scanning in the monitoring of hydrotechnical objects.

In order to take an inventory inside the pump and observation gallery, Z+F Imager 5010 laser was used (Figure 8). 23 scans with average resolution of 6 mm × 10 m were performed. The scan resolution is closely connected to the desired detail level on the model that will be obtained. Nevertheless, one has to remember that in these types of tasks it is not advisable to aim for resolutions that are too high and rather focus on good point cloud coverage of the object, which in turn requires a larger number of scanning sites. During the scan of the gallery the sites were placed on platforms at the spacing of 5 m, which ensured the previously mentioned proper coverage of the object with laser data. Such placement of the scanner ensures that the average accuracy of the

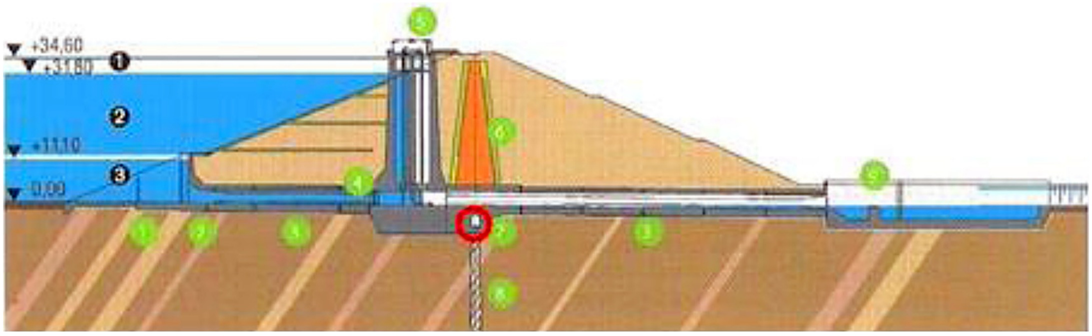

Figure 6. Cross-section of the dam in Klimkówka, pump and observation gallery described in the article marked with a red ring [Zbiornik wodny Klimkówka (information flyer), RZGW Kraków]

a) b)

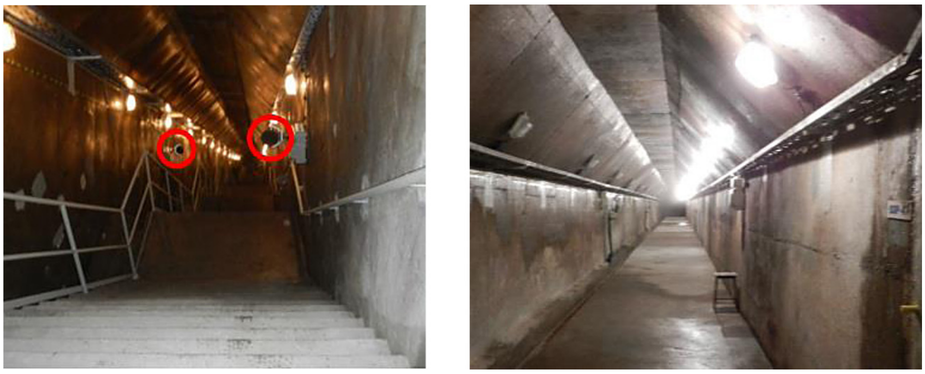

Figure 7. Pump and observation gallery a) descent from the side of the left gable, targets on the walls used for orientation and scan joining (marked in the picture with red rings), b) central corridor

a) b)

Figure 8. Klimkówka dam survey: a) Leica Z+F Imager 5010 scanner during the measurement (author's archive), b) a section of the observation gallery, levelling benchmarks visible on the floor (marked with red rings) and the removed metal covers (processing: Z+F Laser Control software)

difference in height between the measured points on the scan is above 5 mm, which is expected from this type of measurement. Ascan software was used to analyse the obtained point cloud.

A number of studies were performed on the oriented and aligned point cloud. The studies focused on presenting the feasible analyses of technical efficiency of the observation gallery. Results of the studies included, among others:

- vertical sections of the gallery in places were levelling benchmarks were located on the floor,
- orthogonal projection of the wall of the gallery's stairwell with superimposed hypsometry (Figure 10),
- comparison of vertical sections for the purpose of analysis of the gallery's geometry (Figure 11).

Benchmarks of the levelling lines belonging to the object's control network are located in special wells approximately 2–3 cm below the concrete surface (surface of the steps, surface of the "floor") in the gallery's corridor. During the measurement performed with the use of a laser scanner, those wells were covered (Figure 8) – the height of the 3D model was determined on the surface of the cover.

Monitoring hydrotechnical objects is not limited only to taking geometric inventories of the actual condition of the structure, but also encompasses the evaluation of its technical efficiency. On the basis of the data acquired through terrestrial laser scanning, it is possible to develop orthogonal projections and supplement them with information on the deviations in the form of so-called "hypsometric sketches", which provide a comprehensive view of the object's condition (ex. wall geometry – deformations and warps, deviations from the designed surface). Pictures 9 and 10 present longitudinal sections of the observation gallery. Picture 9 presents a longitudinal section and picture 10 presents its corresponding orthogonal projection on a vertical plane of the gallery wall, which visualizes the shape of the gallery wall (hypsometric sketch). By superimposing the sections created in subsequent observation cycles, one can notice the possible changes taking place on the wall surface, that is, changes in the size of cracks, wraps or deformations.

For the selected sections of the observation gallery, cross-sections seen in Figure 11 were prepared. The places where the cross-sections were made match the location of the control benchmarks placed next to splices of the consecutive sections of the gallery and directly after each subsequent dilatation. The edges of a section are weaker structural points and are subject to greater loads resulting from changes of the water level in the reservoir. Those places are observed not only in order to diagnose the condition of the gallery, but also to monitor the geometry and the sealing structures of the object. Example sections were dimensioned based on the scan results. Current measurements may become the basis for future technical efficiency monitoring of the dam's gallery, as the measurements carried out in the consecutive surveying cycles will visualize possible changes in the object's geometry – they will be visible on the sections of point clouds taken in the same places. Comparison of cross-sections of the gallery (Figure 11), especially in the straight portion, makes it possible to identify shifts of each consecutive structure section – changes in section placement in relation to one another in subsequent control periods may suggest destabilization of the gallery's structure and therefore warn of possible object safety risk.

CONCLUSIONS

Works on various hydrotechnical objects with the use of terrestrial laser scanners have already started both in Poland and worldwide. However, laser technology plays only a supplemen-

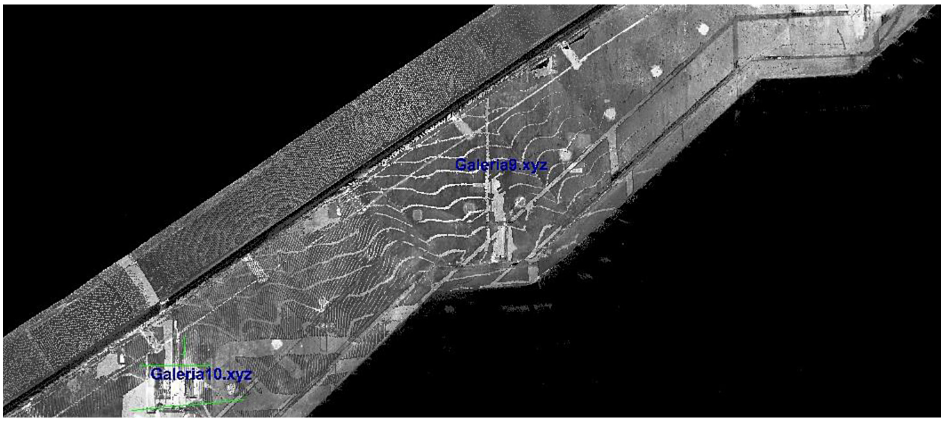

Figure 9. Longitudinal section of the dam's crown (screenshot form Ascan software), scan numbers marked in blue

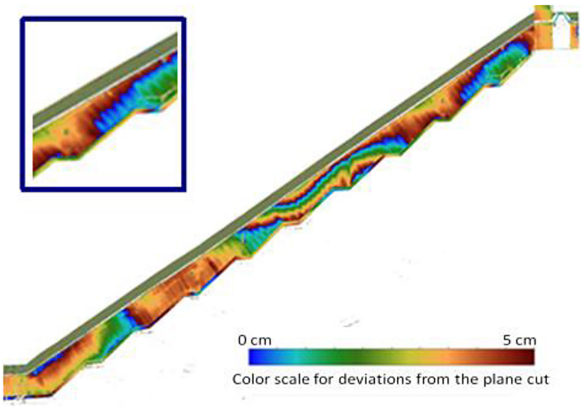

Figure 10. The picture presents an orthogonal projection of the stairwell wall belonging to the dam's gallery with superimposed hypsometry; fragment presented in Figure 11 was distinguished

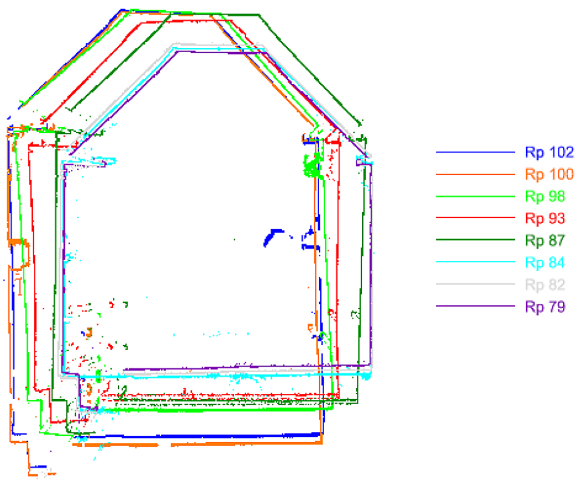

Figure 11. Dam's geometry presented as superimposed sections generated in the location of the selected benchmarks

tary role to classic and photogrammetrical measurement methods, and it is not the main method used in order to realize geodetic tasks that concern the technical inspection of dams. There is a need to conduct further research and development of the mentioned technology in this direction. Terrestrial laser scanning carried out with the right measurement resolution is well suited for secondary analysis of the object's condition – splits, cracks, damp patches and filtration as well as forquick creation of an object's geometric inventory. Evaluation of dampness levels in an observation gallery is particularly important from the perspective of the object's safety – filtration through the main body of the dam due to plants overgrowing on the embankments is often noticed late as compared to the moment the phenomenon begins.

This paper presents example analyses and studies that can be carried out using the data obtained through the laser scanning of Besko, Rożnów and Klimkówka dams as a basis. It can be said that terrestrial laser scanning may be a reliable supplement to classic surveys, and in the future might even replace them. One has to remember that the specificity of hydrotechnical objects requires application of particular procedures and development of separate surveying methodology focused on laser technology. It is essential to pay particular attention to the selection of the scanner and to the object's structure when attempting to apply laser scanning.

Reproducibility of the obtained results, and in consequence, the usefulness of terrestrial laser scanning in periodic object control enables the results to be recognized as reliable and an important supplement to the hitherto used surveying techniques.

To summarize, it has to be stressed that the presented studies are an introduction to further research on methodology concerning the application of terrestrial laser scanning during periodic control measurements of hydrotechnical objects.

Test measurements on water dams carried outboth in Poland – Besko, Solina, Klimkówka, Rożnów as well as abroad: Eckertalsperre (Germany) and cooperation with object users: Tauron Ekoserwis Sp. z o.o., Regional Water Managements Authority in Cracow, PGE Energia Odnawialna S.A., Harzwasserwerke Ltd. indicate a need to implement new methods of hydrotechnical object control in order to increase operational safety, prevent malfunctions and catastrophes and bring about a faster and effective warning system for object users and people living in its vicinity.

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