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UTILISATION OF TERRESTRIAL LASER SCANNING FOR VERIFICATION OF GEOMETRY OF NUMERICAL MODELS OF HYDROTECHNICAL STRUCTURES USING THE EXAMPLE OF A SECTION OF THE CONCRETE BESKO DAM

WYKORZYSTANIE NAZIEMNEGO SKANINGU LASEROWEGO DO WERYFIKACJI GEOMETRII NUMERYCZNYCH MODELI OBIEKTÓW HYDROTECHNICZNYCH NA PRZYKŁADZIE SEKCJI ZAPORY BETONOWEJ BESKO

A b s t r a c t

The paper presents results of utilisation of terrestrial laser scanning for verification of geometry of the numerical model of behaviour of Besko Dam, created on the basis of design data. Results of inventory measurements, performed in the period 2009–2011 with the use of laser scanning techniques are also presented. Changes in geometry of numerical models were introduced on the basis of performed measurements. Analysis, which aimed at determination whether the observed changes in shape influence the forecasting of behaviour of the structure. It has been stated that the applied technology of measurements is a useful tool for verification the model geometry, and, therefore, for checking the model correctness and increasing the reliability of obtained results.

Keywords:

S t r e s z c z e n i e

W pracy przedstawiono wyniki wykorzystania naziemnego skaningu laserowego do weryfikacji geometrii numerycznych modeli zapory betonowej. Porównano geometrię modelu numerycznego zachowania zapory Besko wykonanego na podstawie danych projektowych oraz wyniki przeprowadzonych w latach 2009–2011 pomiarów inwentaryzacyjnych z użyciem techniki skanowania laserowego. Na podstawie wykonanych pomiarów wykonano zmiany w geometrii modeli numerycznych i analizowano czy zaobserwowane zmiany kształtu mają istotny wpływ na prognozowane zachowanie się budowli. Stwierdzono, że wykorzystana technologia pomiaru jest dobrym narzędziem do weryfikacji geometrii modelu, a co za tym idzie, kontroli poprawności jego wykonania i zwiększeniu zaufania do otrzymanych wyników obliczeń.

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1. Introduction

In order to determine displacements of the designed or existing hydrotechnical structure numerical calculations based on the FEM method are often applied [6]. The method assumed for calculations should model, to the required extent, real processes which considerably influence the final result; it should also allow for utilisation of the recent knowledge concerning processes of material parameter changes. Such a method should allow for modelling various variants of construction of the structure, as well as for consideration of basic factors, which influence the analysed process (such as generation of initial tensions, modelling of stages of construction, variations in groundwater level and resulting changes in loads).

FEM allows for estimation of forces and displacements in the foundation and in the designed or existing structure. Depending on the structure geometry, variations in natural conditions and expected accuracy, numerical simulation may be performed using the 2D or the 3D model. Analysis of interactions between the structure and the ground foundation should accompany the entire investment cycle and the structure utilization.

Verification of the developed numerical model, based on measurements of displacements of the real structure, is the most important confirmation that and adequate model has been assumed, which restores the real timetable of implementation (assumption the correct loads) and material parameters. It serves for gaining experiences which improve procedures of verification of material parameters (small deformations range) or modification of parameters determined for another range of deformations. Following the authors' opinion, abandonment of the model verification when measurements of displacements are accessible, should be considered as malpractice. If the model verification concerning the compliance between calculated and real displacements does not allow for confirmation the correctness of values of internal forces which were assumed for the structure dimensioning. As the authors suggest, results of calculations should be the basis for formulating conditions of implementation of the structure monitoring, including the determination of expected values of displacements in particular stages of construction, as well as permissible deviations, considered as alert values. This is extremely important in the course of implementation and exploitation of hydrotechnical structures.

2. Terrestrial laser scanning

Difficult field conditions, which usually occur in places where dams are located, determine the selection of specialised equipment and appropriate technique of surveys. The advantage of the modern technology, such as terrestrial laser scanning, is the possibility to perform many observations in a short time, what, together with the simplicity of maintenance, allows for decreasing the number of a surveying team members. Close proximity of water results in occurrence of local microclimatic conditions, which not always support implementation of observations with the expected accuracy.

Scanners may be divided into phase and pulse devices. The range of measurements is closely related with this division: phase solutions are dedicated for short distances (at present up to 200 m), whilst pulse devices allow for measuring structures located further from the measuring station (even up to several kilometres). Depending on the measuring distance, close-, medium- and far- range scanners are distinguished. This results in the next characteristic feature, i.e. the measurement accuracy. Depending on the mode of distance measurements (phase or pulse) and the instrument type and model, the accuracy falls within the range between several millimetres and more than ten centimetres.

It is difficult to determine the accuracy of laser scanning since it is influenced, among others, by the following factors:

– distance between scanned objects and the scanner,
– atmospheric conditions,
– accuracy of determination of tie points for particular scans,
– accuracy of connection with the external co-ordinate system,
– angle of incidence of the laser beam onto the surface,
– type and colour of the reflecting surface,
– wavelength,
– object geometry, which may result in the multipath effect,
– ambient illumination,
– instrumental errors.

The final effect of laser scanning are not co-ordinates of specified points, but the geometric model, matched with the obtained cloud of points. Position errors of particular points vary and they include:

– errors in the scanning system (errors in determination of angles),
– distance errors,
– calibration errors.

The final object geometry is created with the use of an algorithm, which is based on the least square method. This results in the accuracy which may be several times higher than in the case of individual measurements and which depends on the appropriate density of measuring on the success of the scanned object.

Resolution is one of the parameters which influence the accuracy. The angular and distance resolution is distinguished. The angular resolution is the ability of the scanner to distinguish two objects, which are located in adjacent measuring directions. It depends on the scanning density and the size of the laser footprint; it decreases together with the increase of the distance between the instrument and the measured object. The scanning density is defined as the distance between two neighbouring, measured points. The higher it is, the higher is also the accuracy of projection of shapes of scanned objects. The size of the laser footprint also influence the measuring accuracy, what may be particularly visible at the edges of scanned objects. The laser beam, when it reaches the edge of the object is partially reflected from its surface; other parts of the beam are reflected by a part of a neighbouring surface or by another object. As a result points which create the discussed edge, will have the incorrectly calculated co-ordinates – it is, so-called, "the edge effect" [4].

With respect to hydrotechnical structures, laser scanning may be applied in such tasks, as [Zaczek-Peplinska, Adamek, Popielski, 2009]:

– the structure inventory – the structure inventory at particular stages of implementation (comparison of constructed elements with the design), post-completion inventory, inventory after overhauls, periodical measurements in the period of exploitation,
– verification of relations existing between variations in water level in the reservoir and variations of the structure geometry,
– evaluation of the structure technical conditions.

The basic limitation concerning utilisation of laser scanning is the high price of devices, which should be increased by the costs of maintenance and adjustment. In the future, the price decrease together with the increase of popularity of laser scanning may be expected due to the increase of the number of scanners available on the market. Probably the technological development will result in widening of the scope of its applications.

3. Geometry of the dam – numerical model versus scanning results

One of the most important elements of the process of creation of the numerical model of behaviour of an engineering structure is the correct projection of its shape. Forecasting its operations, displacements and possible breakdowns and catastrophes is important due to security reasons; this particularly concerns water dams. In the case when spatial information is acquired for a structure of uncomplicated construction, successful utilisation of measurements performed by means of an electronic tacheometer is possible. However, in the case of higher complexity and volumes, such measurements could turn to be too labour-intensive and ineffective. Costs of such measurements and the necessity to involve a several-member team are also the reasons that utilisation of terrestrial laser scanning turns to be much more efficient.

Measurements performed with the use of a laser scanner may be used not only at the stage of the model development, but also in order to verify the model correctness or timeliness.

The usefulness of application of laser scanning results for verification of the geometry of numerical models of behaviour was evaluated on the basis of experimental measurements of the Besko Dam; they were performed on 8–9 June, 2009 by the team of specialists from the Faculty of Geodesy and Cartography of the Warsaw University of Technology (Department of Engineering Geodesy and Topographic Surveys) and Leica Geosystems Polska. Measurements were performed with the use of the Leica ScanStation 2 scanner (Fig. 1a), results of measurements of the Besko Dam are presented in Fig. 1b.

a) b)

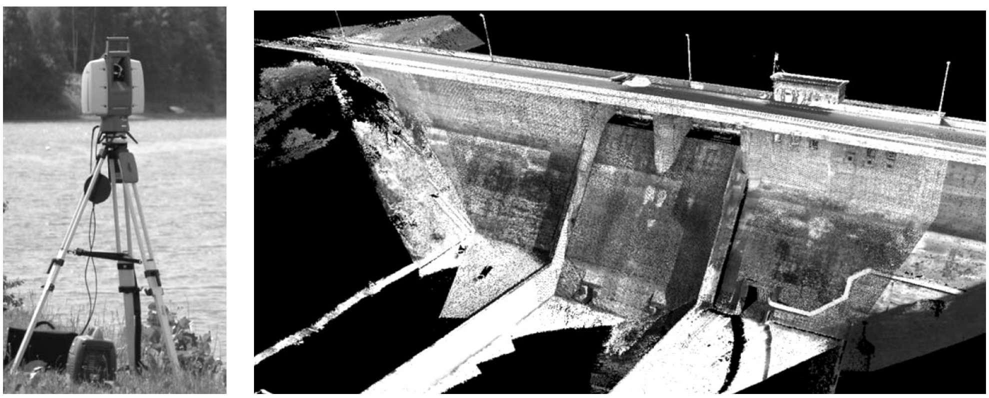

Fig. 1. Measurements of the Besko Dam. a) Leica Scanstation 2 scanner during surveys, b) results of surveys of the dam from the downstream face – results of combination of 5 clouds (about 155 million points)

The geometry of the numerical model [1, 2] of the concrete structure was developed on the basis of intersections originating from the archived design documentation. After completion of the construction of the dam results of post-completion inventory were not attached to the documentation of the post-completion approval and they are not available at the moment. The numerical model considers positions of internal galleries (Fig. 2a) and location of view-finders and benchmarks used for the surveying control of the dam. Using the available software tools the grid of finite elements was generated (Fig. 2b). The controlled points (vie-finders, benchmarks, points of the fixed straight line) correspond to the nodes of the FEM grid. Numerical analyses for the structures de-scribed below were done using the HYDRO-GEO software which is now under development at the Warsaw University of Technology. On the account of the available material parameters, the elastic-plastic soil model was adopted on the basis of the Coulomb-Mohr plasticity criterion. The calculations were performed as a two dimensional task in the plain state of strain. The model was digitized using six-node isoparametric triangular elements of second-order shape function. The analysis was done in the so-called effective stresses. The total number of elements equals to 1213 and the number of nodes – 2566.

The model developed in this way, which considers the dam geometry (developed on the basis of archived documentation) was divided into elements and then it was amended with material parameters and initial, boundary conditions (such as initial tensions and water levels in the reservoir).

The model of the segment 9 of Besko Dam was used for the further elaboration.

a) b)

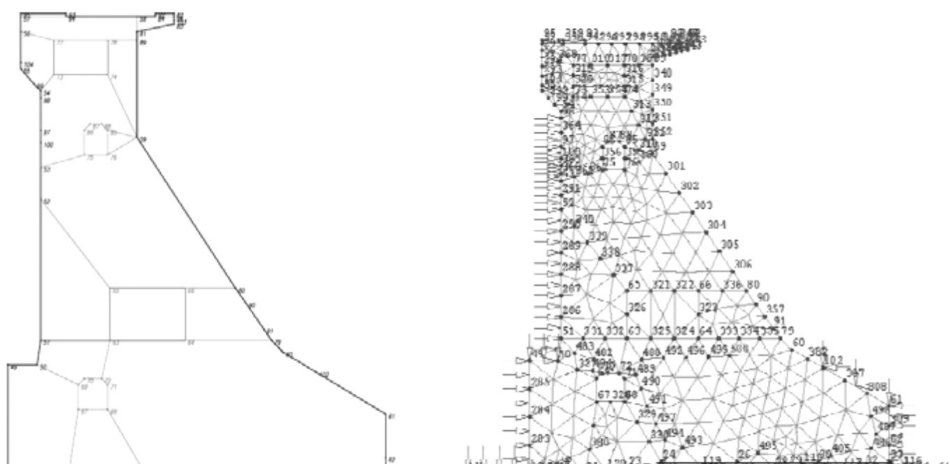

Fig. 2 a) geometry of the section of the dam, assumed for the model (without the background), b) a fragment of a grid of nodes

Acquisition of measuring data by means of laser scanning is extremely fast and it is performed almost automatically. There is no need to orientate the scanner or to set it over particular, fixed points of the measuring network. However, conventional measurements cover the points which serve for connection and georeference the scans. Therefore, the accuracy of the model obtained from the cloud of points does not depend on technical functionality of a scanning device only, but also on the measurement accuracy and processing of the results of measuring the angular-linear network. The next stage, which influences the accuracy of the final product, is registration (connection) of scanned points and transformation of those points to the common co-ordinate system. The last stages of data processing were performed using the Leica Cyclone 7.0 software package.

Clouds of points, obtained from measurements of the Besko Dam were connected in the process of registration, basing on foxed points of the control geodetic network of the structure. Besides registration of all five clouds of points, they were also georeferenced. The accuracy of performed transformation (the mean absolute error) was equal to 0.003 m. Finally, more than 155 million points were obtained in the common, local co-ordinate system.

4. Verification of the geometric model

A two-dimensional intersection of the segment 9 was analysed in the process of verification of geometry of the numerical model of the Besko Dam. The Leica Cyclone software package allows for creation of intersections of the cloud of points. It is performed by locating the cutting plane (cutplane) in an arbitrary location and setting its thickness (Set Slice Thickness). Before creating verifying intersections, the registered cloud of points was reduced by the function Edit Object –> Reduce Point Cloud, what resulted in the number of points decreased to 25%. For the analysed section 3 intersections were created – in the centre and at the edges; then they were averaged (Fig. 3), the width of cutting was equal to 0.10 m.

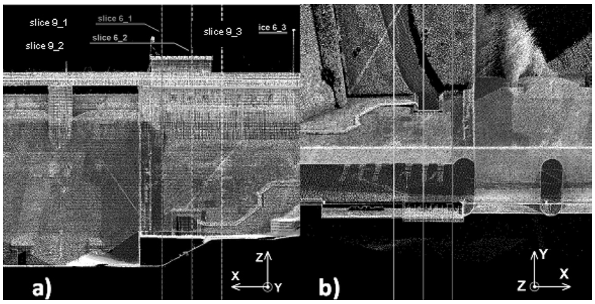

Fig. 3. Location of performed intersections: a) view from the downstream face, b) view from the top

As a result, 3 two-dimensional clouds of points were obtained, which presented the intersections – from the downstream face to the ground level and from the upstream face to the water mirror level, covering the crown – which described the external shape of the dam outline.

In order to verify the geometry applied for creation of the numerical model of the behaviour of the dam, the best fitting straight lines should be matched with points obtained as a result of the intersection. The number of those lines was assumed in accordance with the outline presented in Fig. 2a.

Matching was performed using the least square method for each of three intersections. 12 straight lines were matched into each intersection; their crossings pointed to location of corner points of a figure which described the shape of the intersection of the segment 9 (Fig. 4).

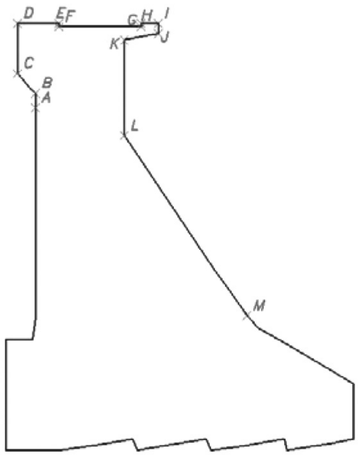

Fig. 4. Characteristic points of geometry of the segment 9 of the dam

In order to achieve the most representative shape for the entire section of the dam, co-ordinates of characteristic points, obtained from three intersections, were averaged. Table 1 presents co-ordinates of the common points and their differences.

Table 1

Coordinates of common points and their differences

Archived model			Averaged intersection			Difference		Distance between points [m]
Nr	**X [m]**	**Y [m]**	**Nr**	**X [m]**	**Y [m]**	**dX [m]**	**dY [m]**	
A	97.852	18.000	**A**	98.270	18.000	0.418	0.000	0.418
54	97.852	18.900	**B**	98.295	19.778	0.443	0.878	0.984
55	96.152	20.700	**C**	97.005	20.967	0.853	0.267	0.894
95	96.152	25.200	**D**	97.081	25.398	0.929	0.198	0.950
93	100.002	25.200	**E**	100.259	25.334	0.257	0.134	0.290
94	100.002	24.900	**F**	100.373	25.220	0.371	0.320	0.490
84	107.622	24.900	**G**	107.339	25.215	–0.283	0.315	0.423
92	107.622	25.200	**H**	107.445	25.322	–0.177	0.122	0.215
82	109.202	25.200	**I**	108.854	25.366	–0.348	0.166	0.385
83	109.202	24.300	**J**	108.828	24.274	–0.374	–0.026	0.375
81	106.052	23.700	**K**	105.950	23.777	–0.102	0.077	0.128
59	**106.052**	**15.130**	**L**	**106.052**	**15.130**	**0.000**	**0.000**	**0.000**
M	117.294	–1.000	**M**	117.436	–1.000	0.142	0.000	0.142
A’	97.852	–1.000	**A’**	98.003	–1.000	0.151	0.000	0.151

The calculated standard errors of position of points not still exceeded 2.5 mm (2.5 cm) having regard the following steps: measuring angles and distances (scanning), the registration of scans, the transformation to the local co-ordinate system of object model, approximation of characteristics straights which obtained from the intersection of clouds of points.

5. Correction of geometry of the numerical model

Changes concerning the shape of the modelled intersection of the dam were introduced according to three variants, with diversified methods of matching points into the scanned model, and, as a result, with differences in distribution of nodal points and small differences in the final geometry. In the variant I the intersection area was decreased by 1.2%, what resulted in the decrease of the volume of this segment of the dam and its mass – by approximately 208 tones. In the case of variants II and III this reduction equalled to 1.8%, i.e. approximately 309 tones, from the initial mass of the segment equalled to 17578 tones. The volume was calculated on the basis of the intersection area and the designed width of the segment 9. This paper discusses results for the variant III, for which the biggest corrections were introduced, comparing to the archived (the primary) model. Figure 5 presents visualisation of changes introduced to the model.

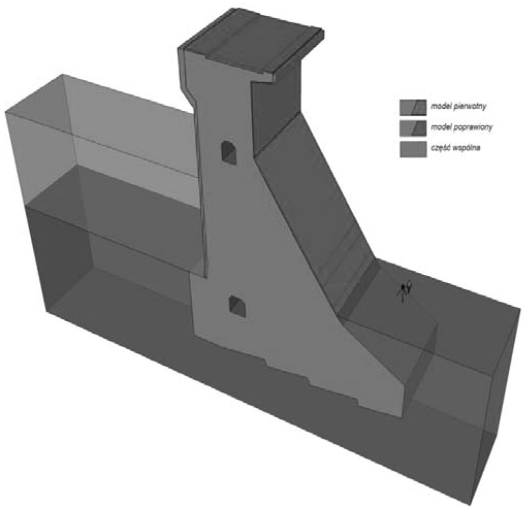

Fig. 5. Visualization of the segment 9 of the dam with differences between the model based on designed data and the model based on laser scanning results

Matching the nodal points to the new model of the intersection geometry consisted of shifting breaking points to new locations, determined on the basis of data from scanning; the node 59 corresponding to point *L* was assumed as the “fixing point”. It was justified by the best matching the shape of the downstream wall of both intersections. Nodes located between breaking points were projected on the straight lines, which created the intersections; proportional distances between them were maintained.

Corrected co-ordinates of points were reintroduced to the HYDRO-GEO package. Computations were performed similarly to computations performed for the archived model [Popielski, Zaczek-Peplinska 2007], i.e. in three stages: stage I – generation of initial stresses in the subsoil, stage II – modelling the dam construction (“the dry reservoir stage”), stage III introduction of loads resulting from filling the reservoir with water. Recalculation of the model was to answer the question whether performed correction of the geometry and reduction of the mass of the segment (Table 2) would result in considerable changes in displacements of selected nodes.

Table 2

Differences between the archived model and the corrected model

Variant	Area. [m^2]	Difference	Difference [%]
Archived	647.3	–	–
Updated	635.9	11.4	1.8
	Volume [m^3]	**Difference**	**Difference [%]**
Archived	7767.4	–	–
Updated	7631.0	136.4	1.8
	Mass [t]	**Difference**	**Difference [%]**
Archived	17578	–	–
updated	17269	309	1.8

6. Changes of displacements of common points as a result of introduced correction of the geometric model

Five points were selected to compare changes of displacements of nodal points. Two of them – points 89 and 90 – are the points, which locations are identical with the location of view finders, used for control surveys. Remaining three points: 301, 302 and 303 result from the division of the intersection into elements; for those points the highest increments of displacements per the dam height unit were stated for various upper water mirror levels [Zaczek-Peplinska, Popielski, 2008]. It was to allow for achieving the possibly biggest displacements and their differences.

For the stage III of computations the upper water mirror level was assumed as 336.99 m above the sea level. The level of 310.00 m above the sea was assumed on the downstream face as the ordinate of the water mirror level. Displacements resulting from changes in water level in the reservoir, for the archived and updated models were computed. Computed horizontal displacements of the models and their differences are presented in Table 3.

Table 3

Horizontal displacements of the model and their differences with pointing to the maximum values

Horizontal displacements

Point	Stage	Archived [m]	Corrected [m]	Differences [mm]
89	I	0.0000	0.0000	0.0
	II	–0.0032	–0.0029	–0.3
	III	**0.0032**	**0.0039**	**–0.7**
90	I	0.0000	0.0000	0.0
	II	–0.0006	–0.0005	–0.1
	III	0.0041	0.0043	–0.2
301	I	0.0000	0.0000	0.0
	II	–0.0019	–0.0017	–0.2
	III	0.0037	0.0041	–0.4
302	I	0.0000	0.0000	0.0
	II	–0.0017	–0.0015	–0.2
	III	0.0037	0.0041	–0.4
303	I	0.0000	0.0000	0.0
	II	–0.0015	–0.0013	–0.2
	III	0.0038	0.0042	–0.4

7. Final remarks

During the backward analysis, high differences (from surveying perspective) in the shapes of intersection of the segment 9, between the geometry of the archived model and the model obtained from laser scanning were observed. The computed difference of the mass between these models seems to be important. However, it should be considered that the model was created on the basis of the archived, primary design of the dam, which differs from the real conditions. The mass difference of the segment equalled to approximately 2% (309 tones), for the total mass of the segment equal to 17578 tones.

Differences in computed displacements of control nodes between the archived and updated model were close to 1mm in one case only, what is equal to 20% of the displacement forecasted for that node.

On the basis of performed research works, it may be stated that:

- The type and accuracy of the final product, obtained in the process of processing data from laser scanning are appropriate for verification and support of creation the geometry of numerical models of behaviour of building structures. The obtained differences between models are important – in the case of the mass of the structure, it corresponds to approximately 309 tones. The model created on the basis of archived materials may not correspond to the real shape of the structure.
- Measurements performed by means of the laser scanner are economically justified and require less involvement of an operator than in the case of utilisation of other methods, what results in limited risk of mistakes.
- Laser scanning may be successfully utilised for verification of models of behaviour, in particular in the case of structures of complicated shapes, or which are difficult for measurements with the use of conventional methods.
- Data acquired from laser scanning measurements better restore the real geometry of the measured objects. The obtained cloud of points may be the basis for further analyses, creation of three– and two-dimensional models, creation animated images and visualisation.
- The obtained results proved, that in the case of massive, concrete hydrotechnical structures and analyses of displacements caused variations in water level in the reservoir, the accuracy of determination of the dam geometry of 1% approximately, is sufficient.
- It should be analysed, how the measured differences in the dam geometry influence the computed values if displacements caused by thermal loads.

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