TECHNICAL TRANSACTIONS | CZASOPISMO TECHNICZNE
ENVIRONMENTAL ENGINEERING | ŚRODOWISKO

2-Ś/2015

PAWEŁ POPIELSKI*, JANINA ZACZEK-PEPLINSKA**, EWA BARTNIK***,
ADAM KASPRZAK**, BŁAŻEJ SMOLIŃSKI**

CONTEMPORARY TECHNIQUES OF DATA ACQUISITION FOR PREPARATION OF NUMERICAL MODELS OF HYDROTECHNICAL STRUCTURES

NOWOCZESNE TECHNOLOGIE POZYSKIWANIA DANYCH DO PRZYGOTOWANIA MODELI NUMERYCZNYCH BETONOWYCH OBIEKTÓW HYDROTECHNICZNYCH

Abstract

This paper presents an analysis of possible uses of contemporary data acquiring methods for elaborating hydrotechnical object numerical models. The subject is considered in two aspects – preparation of a geometrical model based on the results of a geodetic survey of the structure as well as subsoil parameters, and data acquisition for building material characteristics. The results presented for non-invasive measurements of hydrotechnical concrete parameters and geometry of the modelled object are based on the example of Rożnów Dam. The research uses data obtained by terrestrial laser scan and sclerometer tests (taken with a Schmidt hammer).

Keywords: numerical modelling, geodetic survey, laser scanning, sclerometer measurements

Streszczenie

W artykule przedstawiono analizę możliwości wykorzystania współczesnych metod pozyskiwania danych do przygotowania modeli numerycznych obiektów hydrotechnicznych. Zagadnienie rozpatrzono w dwóch aspektach – przygotowanie modelu geometrycznego na podstawie wyników inwentaryzacji geodezyjnej konstrukcji oraz pozyskanie danych o parametrach podłoża i właściwościach materiałów budowlanych. Zaprezentowano wyniki nieinwazyjnych pomiarów parametrów betonów hydrotechnicznych i geometrii modelowanego obiektu na przykładzie zapory Rożnów. Wykorzystano m.in. dane pozyskane za pomocą naziemnego skaningu laserowego oraz dane z pomiarów sklerometrycznych (młotek Schmidta).

Słowa kluczowe: modelowanie numeryczne, pomiary geodezyjne, skaning laserowy, pomiary sklerometryczne

DOI: 10.4467/2353737XCT.15.231.4617

---

* DSc. PhD. Paweł Popielski, Department Hydro-Enginering and Hydraulics, Faculty of Environmental Engineering, Warsaw University of Technology.

** PhD. Janina Zaczek-Peplinska, Chair of Geodesy Engineering and Control-Measuring Systems, Faculty of Geodesy and Cartography, Warsaw University of Technology.

*** Eng. Ewa Bartnik, MSc. Eng. Adam Kasprzak, Eng. Błażej Smoliński, Faculty of Environmental Engineering, Warsaw University of Technology.

1. Introduction

Hydrotechnical objects such as concrete dams are considered to be one of the largest man-made structures. Due to their massive, complicated shapes, long exploitation periods and static and dynamic loads, they are equipped with a number of control and measurement devices. Their condition must be frequently checked and assessed, as in reality failure is often followed by catastrophe and flood downstream. The Problem of dam monitoring relates to the constant observation of dislocations and filtration occurring within the object.

Any phenomenon occurring as a result of hydrotechnical object operation can be researched empirically by observations and sample gathering as well as by using verified numerical models based on researched object surveys. The method adopted for calculations should model, to the necessary extent, the actual processes influencing the final results in a significant way. It should also allow for the use of current knowledge as far as the processes of change in material parameters are concerned. The possibility of modelling various object realisation variants taking into consideration the key determinants for the course of the process factors analysed (generating initial tensions, modelling of phased structure erection, ground water level changes and consequent load changes) is essential [4].

Numerical models allow for the estimation of forces and dislocations within a substructure and within a constructed or operating object. Depending on the object's geometry, variability in natural conditions and expected accuracy numerical simulation can be realized using a 2D or 3D model. An analysis of the interaction between the structure and the substructure should make up a process accompanying the whole investment cycle and further exploitation of the object.

In order to produce a numerical model, current values of material parameters and verified object geometry are essential. While establishing the values of parameters, new bore samples can be obtained, but the cost is high and the process contributes to gradual degradation of the object. An alternative to these problematic methods is offered by non-destructive examination methods such as sclerometry and ultrasound surveys, verified by limited destructive probing tests. The accuracy of results depends on the calculation parameters adopted for the analysis. The correct definition of these parameter values is fundamental for correct numerical modelling.

2. Research subject

The hydrotechnical object which serves as an example for this research is the gravity dam in Rożnów, constructed on 80+000 km of the Dunajec River in Rożnów village, Gródek n/Dunajcem commune, Nowy Sącz County, Lesser Poland province. According to [8], the Rożnów Dam is an object of 1st class importance.

This dam (Fig. 1) is one of the oldest objects of its type in Poland. It was erected between 1935–1941 and remains operational. The reason behind the object's construction was the need to prevent frequent floods occurring in the surrounding areas. The dam is 49 m high and 550 m long, with a 9 m wide crest. The object was fitted with 7 overspill sections with segment locks and 5 bottom outlets located in the western part of the dam. There is a power plant complex located in the middle of the dam, with 4 Kaplan turbines installed. The combined power output of the generators is 56 MW at 29 m head.

Fig. 1. Rożnów Dam [source: author's own]

3. Establishing object geometry using laser scanning

Terrestrial laser scanning is a relatively new measuring technique situated on the border between classical geodesic surveys, photogrammetry, and computer science.

The scanner operates by emitting a laser beam towards all the objects within the field of view. The scanner uses a mechanism dispersing a laser beam in two directions (vertical and horizontal). The reflected beam returns to the scanner, providing information on the location of the scanned points. The following data is obtained as a result of scanning:

- points collection (cloud) with defined XYZ coordinates,
- intensity of beam reflection from scanned surfaces (additional information),

Scanners can be divided depending on the type of electromagnetic wave emitted. There are two types of instruments: pulse based and phase based scanners. The terrestrial laser scanning survey was conducted by the Geodesy and Cartography Students Society "Geoida" of the Warsaw University of Technology. The surveys conducted [6] [7] were performed using a Riegl VZ-400 laser scanner which is a pulse based scanner using an infrared laser beam. The scanner mechanism is based on a rapidly rotating multi-faced mirror, emitting parallel beams. The frequency of pulses, which is up to 200 kHz, allows 100 scans per second to be taken. The range of the laser is up to 600 m and the accuracy of single point measurement, as per manufacturer's specification, is 3mm. The field of view is 360˚ in the horizontal plane and 100˚ in the vertical plane. As a result of the scanning conducted point clouds were acquired, which were the subject of further processing including: registration, geo-referencing and "combining" in Ascan software made by the Polish manufacturer AstraGIS [7]. The results obtained are presented in Fig. 2.

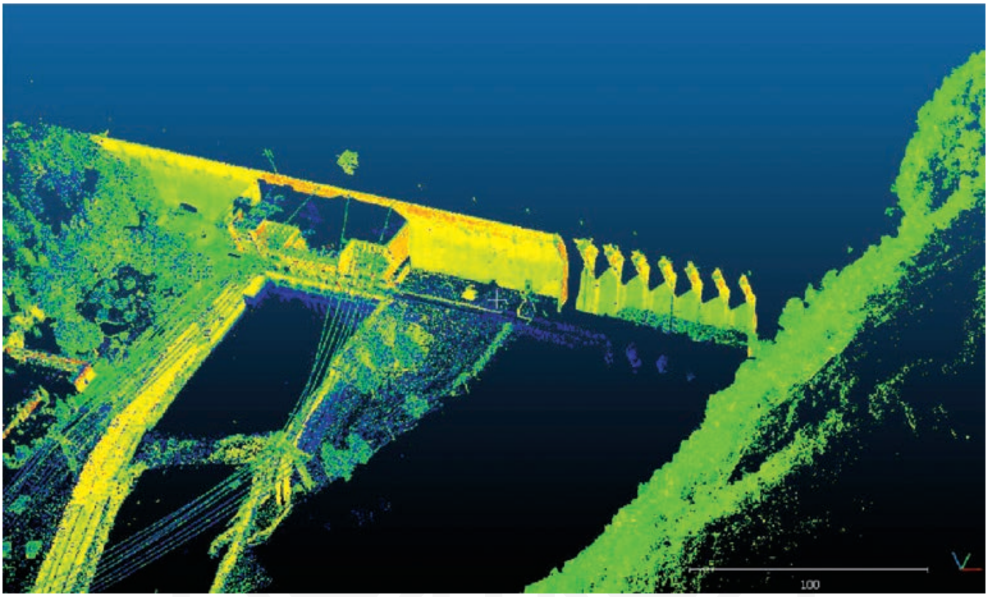


Fig. 2. Scan of Rożnów Dam – point cloud coloured accordingly to the registered intensity values

4. Establishing concrete parameters

4.1. Ultrasound method

Ultrasounds are mechanical oscillations of medium (pressure waves) of frequency at least 20 000 Hz. This frequency is greater than the upper limit of the human hearing range. For concrete constructions, testing waves of frequency between 30 000 Hz and 500 000 Hz are commonly used. Frequency affects the accuracy of measurements. The range of frequencies used for testing allow for higher resolution of the method, but also shortens the effective testing range. A specialist ultrasonic concrete tester is used for testing. The device measures

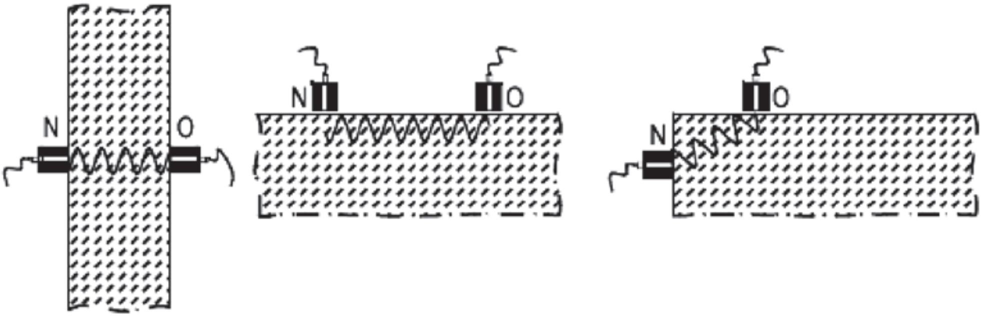


Fig. 3. Head arrangement a) across, b) parallel; c) diagonal N – transmitter head O – receiver head

the time of waves travelling through the medium. In all solid materials longitudinal and transverse waves occur. On the edge of different materials and along the defects waves are partially deflected whereas on the edge of solid material and atmosphere, waves deflect completely. The speed of ultrasound wave propagation in concrete is measured by placing two heads (transmitter and receiver) on the surface of the surveyed object and measuring the time it takes the waves to travel between those devices. The heads can be arranged in different configurations. (Fig 3). It should be noticed that the diagonal setup can cause measurement errors, resulting from angular wave deflection and its impairment.

For concrete testing, the following methods are commonly used:

- echo – relies on deflection of the wave from the object surface; the method requires access to the object from one side,
- direct transmission – relies on the weakening of the wave beam by faults; the method requires access from both sides and is used when flaws (cracks) are located relatively shallowly,
- TOFD (time of flight diffraction) – this method is based on the phenomenon of diffraction during wave propagation and dispersion on flaws perpendicular to the direction of the wave. This method is most often used for examining the quality of welds. Aside from cracks, it shows also flaws in medium continuity.

Based on the measured speed of ultrasound waves, concrete compressive strength R can be defined using ultrasound methods. Calculations are conducted following current standards and guidance [13].

4.2. Seismic methods

For assessing the technical condition of hydrotechnical objects geophysical and seismic methods can also be useful. These methods are based on the emission of different types of waves into the tested medium and measuring the parameters of their propagation. Such methods are automated and computerized. This allows the equipment to be adjusted to the specific research conditions. By controlling wave frequencies, different testing depths can be achieved. Depending on the research method, waves can be generated in a different way. Usually this is done mechanically, using hammers of different weights. The emitted wave, depending of the medium properties, propagates with different speed, deflects, or reflects. Using special electronic sensors and computing devices, registration of disturbances can be performed.

Observation of changes in wave propagation allows areas with anomalies to be localised. In the case of large concrete structures such as water dams these anomalies are: fractures, cracks, stratifications, and areas of higher filtration. It should be stressed that most of the phenomena often occur “in depth”, thus making them invisible, and therefore difficult to discover. All the phenomena listed above directly affect the technical condition of hydrotechnical objects. The earlier and more precise the discovery of such occurrence and anomaly, the higher the chances of preventing potential catastrophe. It is worth emphasizing that seismic methods are often the only solution to screening and assessing the object thoroughly. Traditional methods provide data of punctual or superficial character, so results obtained this way are laden with a wide degree of inaccuracy.

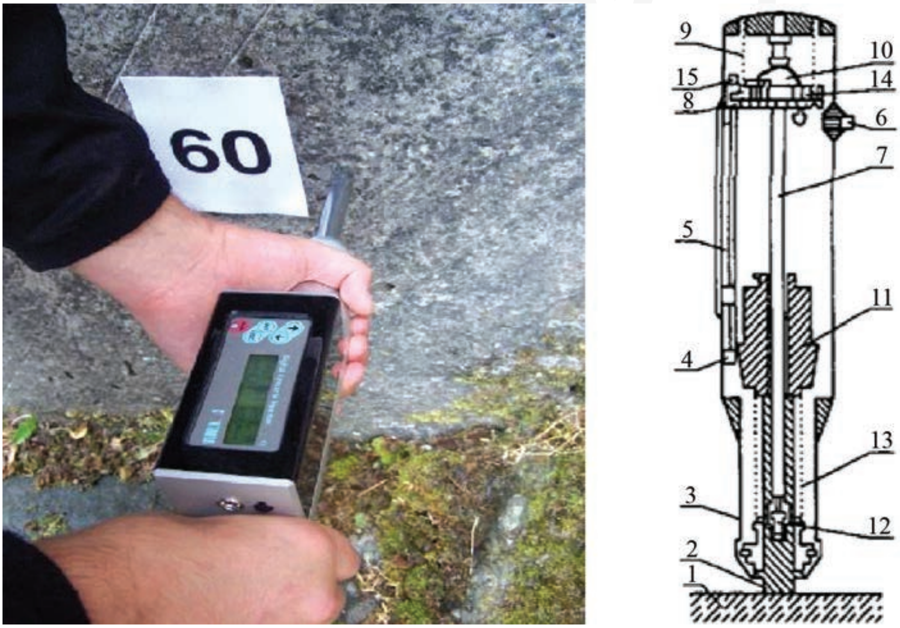
An unquestionable advantage of the seismic method is its non-invasive character, which does not require physical interference with the structure. Such examinations are conducted in a short period of time, usually in an uncomplicated manner. Information about the medium to be tested are obtained relatively quickly, allowing for preliminary assessment of the results while tests are being conducted, or shortly after finishing them.

Research conducted using these methods is usually inexpensive and more effective compared to traditional probing (e.g. drilling), which, on the other hand, is necessary for the calibration of geophysical tests. Thanks to digital registration of data, results can be integrated with numerical models and subsequently detailed analysis based on precise material parameters can be conducted. “Seismic methods are definitely relatively contemporary research methods.” All the advantages and efficiency of seismic methods mean that they are used more frequently in new fields of research.

4.3. Scleromertic method

For the purpose of this paper, sclerometer tests of the Rożnow dam’s concrete surface layer on the downstream face were conducted using a Schmidt sclerometer, commonly called a Schmidt hammer (Fig. 4.). Tests were conducted by the Scientific Circle of Civil Engineering Students.

The Schmidt sclerometer was developed in 1950 by Ernst O. Schmidt and has undergone further modifications and new applications.



1 – examined concrete, 2 – impact plunger, 3 – housing, 4 – indicator, 5 – scale, 6 – spring release button, 7 – hammer guide bar, 8 – disk, 9 – compression spring, 10 – trigger regulation, 11 – hammer mass, 12 – guide, 13 – impact spring

Fig. 4. Schmidt hammer construction scheme [12]

The measurement is conducted based on the assumption of direct relations between strength of concrete and its hardiness. It is defined by the distance the rod rebounds after putting it against the wall with a defined force triggered by a system of springs (Fig. 5). Assessment of concrete strength is possible thanks to the rebound value obtained after each measurement, and regression curves are prepared for a specific type of concrete. Based on these readings, the compressive strength of the concrete can be determined. Generalising, for concretes of the same type and parameters, the higher the rebound value the greater the compression strength of the material. For the purposes of this survey, a Controls Digital Concrete Hammer type N with a digital meter and data register Schmidt hammer has been used. Its characteristics are standard impact energy at 2.207 Nm and it is designed for analysing objects and elements above 100mm thick and strong in structure.

65 test areas were designated on the downstream face of the non-overflow sections of the object on different levels, along the joint of the wall, in the middle of section and next to the observed cracks (Fig. 5).

The results of conducted measurements obtained for selected points are presented in Table 1. For result elaboration, a statistical method was applied. For each of the test series, the average rebound was defined, as well as standard deviation. Data was verified based on the conditions defined in [11]. Based on this analysis, the results obtained can be recognized as correct. In order to determine concrete strength, the method of hypothetical regression curve matching for adequate content, construction technology and age of concrete was adopted. To determine strength [8] was used. According to the above guidance, it is advised to assume a relation between concrete strength and rebound value in the form:

$$R = aL^2 + bL + C \text{ [MPa]} \tag{1}$$

where:
R – compressive strength of concrete [MPa],
L – rebound value [-],
$a, b, c,$ – regression curve empiric values [–].

Missing factor values and corrective factors should be assigned based on a strength analysis of actual samples collected on the object. Taking into consideration the absence of such samples, the following relation has been used:

$$R = 0.0356\mathrm{L}^2 - 0.795\mathrm{L} + 6.4 \text{ [MPa]} \tag{2}$$

According to [12], the above formula is true for concretes (of analogous origin to the Rożnów dam concretes) where:

- Concrete/water ratio: 1–3,
- Cement content: 250 kg/m^3 and 350 kg/m^3,
- Aggregate: river gravel,
- Compaction: mechanical,
- Curing: natural.

The results of the calculations obtained during research average rebound values with respect to the above formula, and values of concrete compressive strength for control points were derived. The results are presented in Table 2.

Table 1

Results of sclerometer tests. Obtained rebound values

Measurement point number	Rebound value L [–]																Average Rebound value L [–]
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
1	31.7	31.9	32.3	32.6	33.1	33.3	33.3	34.8	34.9	35.0	35.7	35.8	36.0	36.1	37.2	37.3	34.41
2	26.0	28.0	28.6	29.1	30.4	30.6	31.4	32.2	33.1	33.2	33.9	34.1	34.6	34.7	34.7	35.3	32.16
3	23.6	23.7	24.0	25.3	27.6	28.4	29.0	29.0	29.1	30.3	31.7	32.4	32.9	32.9	33.2	33.5	29.38
4	20.1	21.4	22.1	22.5	22.8	24.1	24.9	25.0	25.2	25.6	27.7	28.6	29.0	29.6	30.8	31.3	25.59
5	20.6	20.6	20.6	21.4	21.9	23.3	23.6	24.3	25.9	26.3	26.5	26.6	27.4	28.0	33.2	39.0	26.28
6	20.9	24.2	24.4	24.6	25.1	26.1	26.4	26.6	26.9	27.0	28.8	29.8	30.4	30.5	32.3	33.4	27.22
7	28.7	28.8	30.1	30.7	31.0	32.1	32.5	32.7	32.9	33.2	34.3	34.4	34.5	34.8	35.8	36.0	32.77
8	24.7	25.9	27.8	28.9	29.6	30.5	31.7	31.9	31.9	32.2	32.7	33.5	36.5	36.6	37.5	38.6	31.98
9	24.2	24.3	26.7	27.1	27.4	28.1	28.1	28.2	28.5	28.7	28.8	30.6	30.9	30.9	32.5	36.3	28.67

Table 2

Concrete compressive strength R

Control point number	Average rebound value *L* [–]	Concrete compressive strength *R* [MPa]
1	34.41	21.20
2	32.16	17.65
3	29.38	13.77
4	25.59	9.37
5	26.28	10.09
6	27.22	11.14
7	32.77	18.58
8	31.98	17.38
9	28.67	12.87

Fig. 5. Taking tests and control points

The results obtained were related to average strength values acquired from barrel samples, researched during the construction of the Rożnów dam, which were determined at 350 kg/cm^2 [2]. The results acquired during the calculations are significantly lower, and certainly do not reflect the actual technical condition of the surveyed structure. Decreases in strength reaching even 50% are very unlikely. The results were in accordance with initial anticipations. The occurrence of the lowest concrete strength values for control points were located close to scratches and cracks.

Errors and inaccuracies might arise as a result of the regression curve selection based on the literature, caused by the inability to acquire and test actual samples. It should also be kept in mind that the range of tests conducted was rather short and develop from the characteristics of the method used. Only the surface layers of the structure were examined. During 70 years of service period, the surface has been exposed to adverse factors including changes in working conditions, humidity changes, and freezing.

For these reasons, the results cannot be regarded as wholly reliable without verification using other research methods.

It should be emphasized that the Rożnów dam is continuously operating and undergoes frequent inspections regarding technical condition and further service. Research involving the Schmidt hammer tests does not require complex methodology, and results can be obtained quickly. Data elaboration causes no difficulty and interpretation of the results is relatively easy. All these aspects support this method.

Without doubt, a major disadvantage of the sclerometer method is its range – limited only to the surface layers of concrete. It is accepted that the Schmidt hammer provides reliable information on concrete strength up to 20 cm depth (40 cm access from both sides). There is a considerate insufficiency of this method related to the inability to research the material characteristics of layers of concrete located more deeply. In that respect, this method can serve as demonstrative and cannot be regarded as wholly conclusive with reference to the structure as a whole, especially for hydrotechnical objects and water dams.

In order to acquire more accurate information and results, it is necessary to obtain samples using traditional boring methods and conduct destructive testing in order to determine the regression curve values. Seismic screening of at least some sections of the structure would also be very helpful in the course of correct assessment of its technical condition. This would allow results to be compared against other methods.

5. Numerical modelling

The numerical model was prepared for a typical section of the dam, number 18. It is the deepest founded non-overflow section of the object. The engineering software Z-Soil was used for the calculations. The software applies the finite elements method for calculations and can be used to solve geo- and hydrotechnical problems. Section geometry was established based on archival Polish and German plans. Due to the lack of geological documentation, the stratigraphic arrangement of geological layers was adopted based on studies published in the 1930's and scientific articles regarding dam foundations [1] (Fig. 6). Modelling the anti-filtration sealing layers was challenging, as they have been implemented in the form of injections, as there were also no reliable surveys documenting faults in the rock formations. It was decided to represent consolidation grouting as two "slurry walls".

The geometry of the object was modelled in AutoCAD software as a 2D section. After importing a two dimensional model into Z-Soil, it was developed into a 3D model. Material parameters were adopted from dam archives sources, the literature, and material tests conducted on site.

In the next step, boundary values were applied (Fig. 7). High and low water levels were taken into consideration in the form of surface loads. Water levels were determined based on literature data. [8, 9]. On the lower model plane, unmovable supports were located whereas towards the sides, supports allowing only for vertical movements were located.

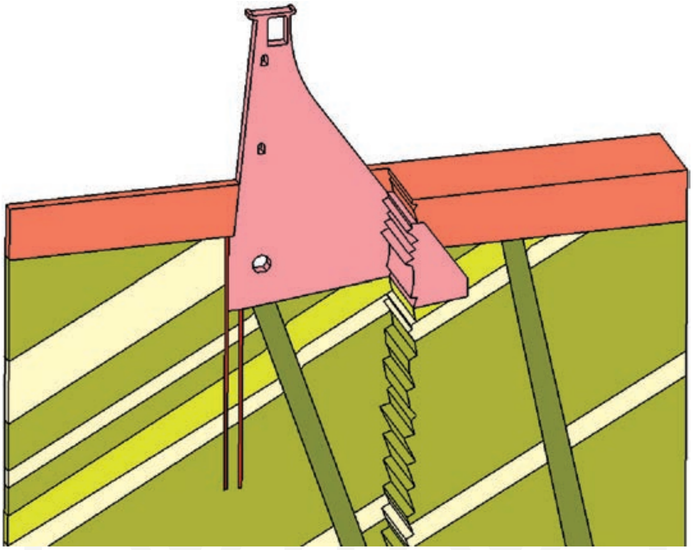


Fig. 6. Layout of subsoil layers

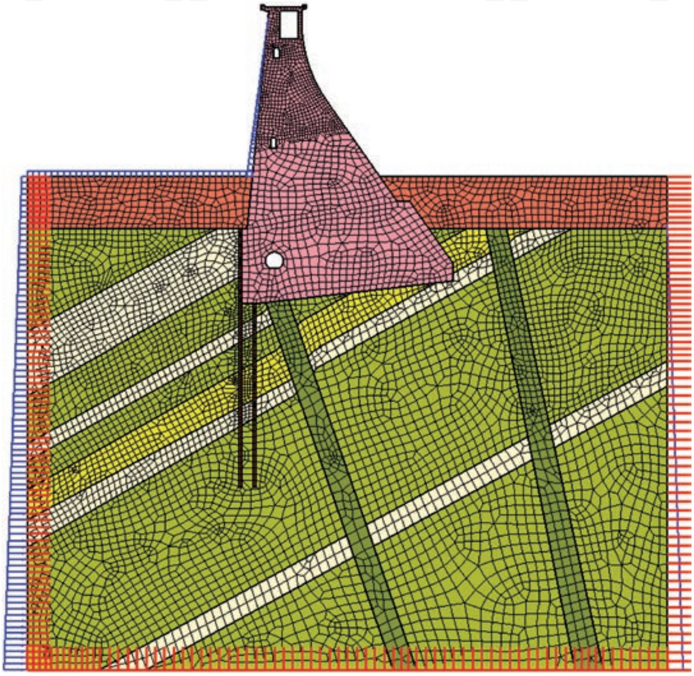


Fig. 7. Boundary conditions

During numerical analysis, calculations for “empty reservoir” and water damming structure were conducted. Fig. 8 shows the displacements in the form of a deformed mesh for the case when water is dammed by the object. The values for maximal displacement and the directions in which they occur are shown in the window on the right. The highest displacements, of .035 mm, were observed along the Y axis. Deformations are scaled-up because they should indicate the direction of the determined displacements. If the scale of the displacement was the same as the model scale, they would not be noticeable.

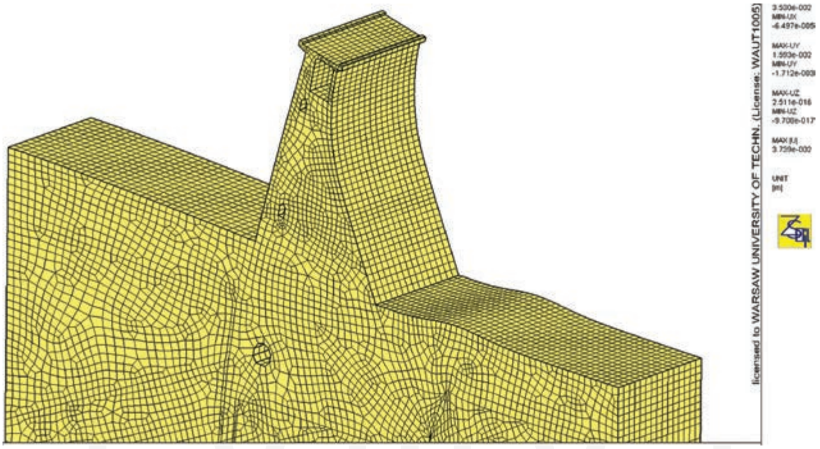


Fig. 8. Finite elements mesh displacement for damming structure

Displacements were visualized also as an isolinear map. Fig. 9 shows the absolute values of displacement for the dam damming up water.

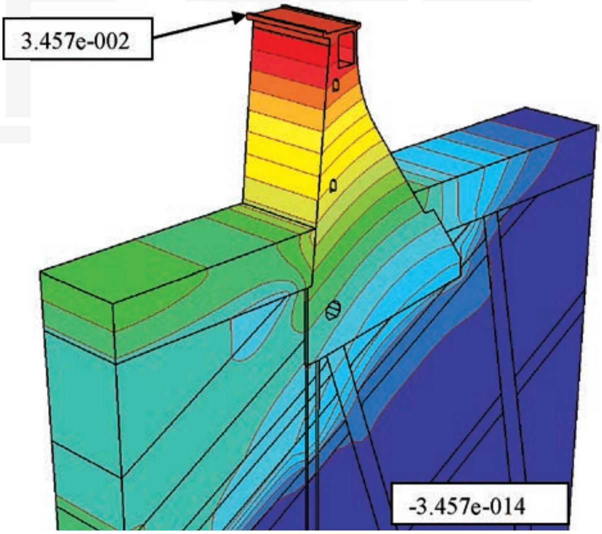


Fig. 9. Absolute displacements

The software used for model handling allows the methods of presenting the results to be combined. Fig. 10. shows an isolinear map that is a combination of the displacement diagram and the determined 2D model sections deformations. The projection of displacements within a given section can be applied in order to show displacements in a legible way in comparison with two adjacent dam sections with different foundation conditions.

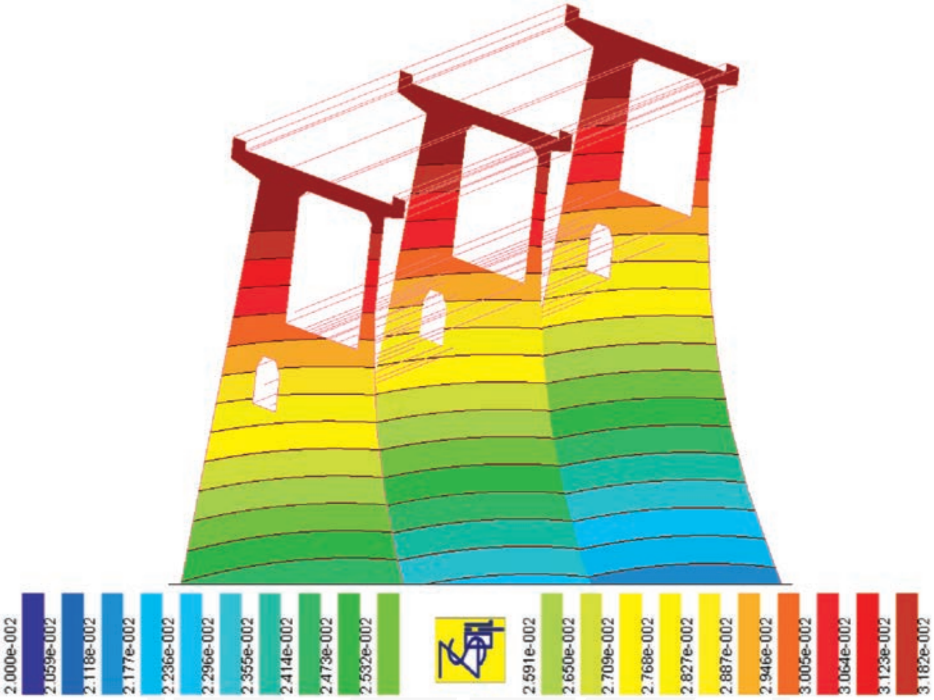


Fig. 10. Combination of graphs presenting displacement and model deformations of determined flat cross sections cut at 7.5 meters. Non-uniform scale.

5.1. Comparison of geometrical data with laser scanning results

In order to verify geometrical model accuracy, the results of the survey utilizing laser scanning method were compared with the entered archival data [3]. The data were compared in the form of vertical cross-sections of surveyed (generated in ASCAN application) and modelled sections. The comparison was executed in AutoCAD (Fig. 11). Diagrams include sections acquired based on data acquired from different sources. The common element for all cross-sections was the lowest point located at the bottom of the downstream face of the dam (E). At the base of the downstream face differences between the cross-sections are slight. Closer to the crest of the dam (further away from the base station of survey) the differences were increasing. They are visible around point D and equal 2.5 cm. The highest disparity reaching 6.2 cm was recorded at the crest of the dam around area A. This might result from the inaccuracy of the scanning method or local concrete dwindling.

In the case of massive, large scale objects such differences are insignificant in the scale of the whole structure, and their influence on the calculation results are insignificant [3]. A comparable error is made by simplifying the geometry during model elaboration using archival data.

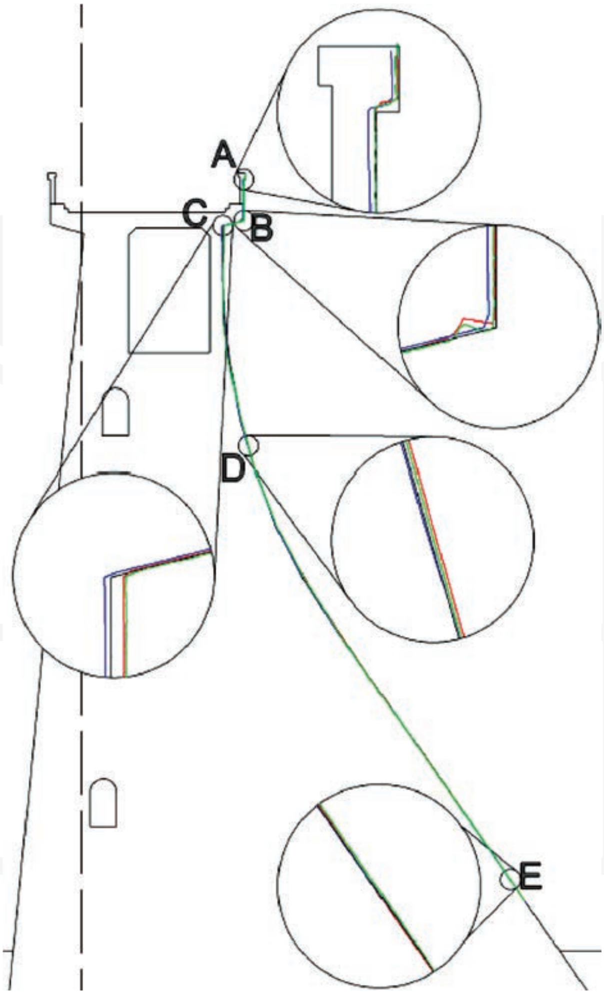


Fig. 11. Comparison of 18 section geometry with laser scanning

The methods allowing data to be obtained for preparing the numerical model were chosen based on the analysis conducted. Fig. 12. shows the relationships between data sources and specific model elements which could be generated using this information:

1. Data likely to be obtained from design and construction documentation, such as the geometry of particular object elements, foundation levels, internal galleries and other internal installation localizations, structure sub-base modifications realized during construction. Other material parameter data which can be obtained result from field and laboratory research.

2. Data likely to be obtained using geological and hydrogeological reconnaissance and using geophysical tests of subsoil.
3. Structure shape that can be acquired using geodesic surveys and laser scanning (e.g. geometry of downstream face and inspection galleries) and indications of control measurement devices (e.g. dislocations of selected points).
4. Data that can be obtained from the Building Log and from reservoir water level studies (e.g. barymetric measurements), indications of control-measuring devices (e.g. reservoir water levels).

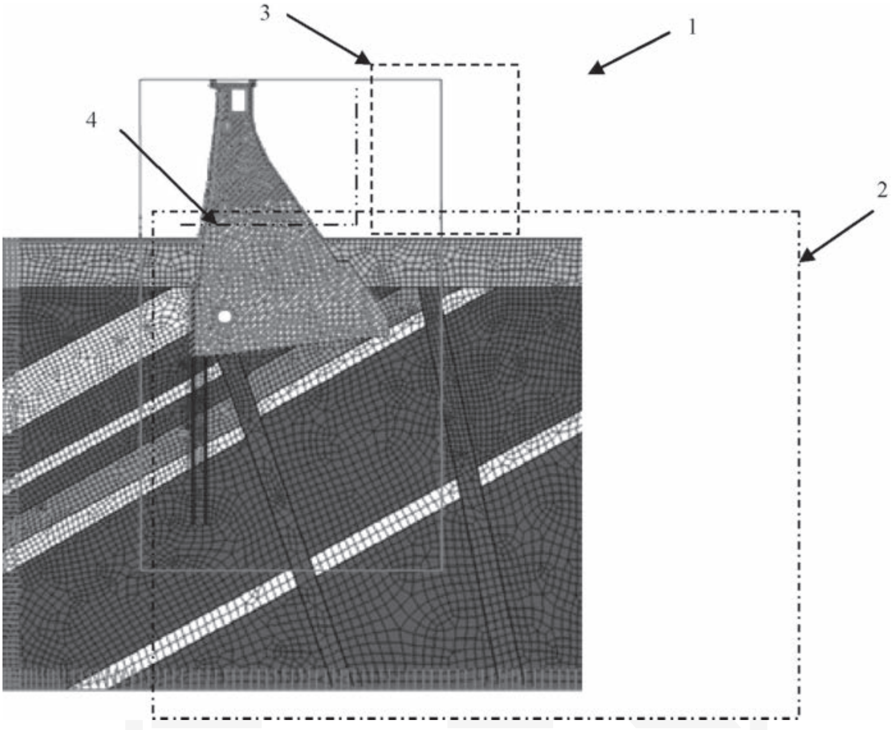


Fig. 12. Combination of data sources for generating specific elements of the numerical model

6. Conclusions

- Acquiring data for the preparation of water dam numerical models is an interdisciplinary problem and requires cooperation from many specialists.
- Information and data from different realms such as object geometry, sub base, material parameters, geology, hydrogeology and object operation conditions are necessary.
- Geometry can be established based on archival information as well as geodesic surveys.
- The laser scanning method can be very useful as a source of data for objects lacking complete technical project documentation as well as for assessing geometry changes, for example documentation of the development of scratches and cracks, etc.

Bibliography

[1] Balcerski W., *Problemy statyczne fundowania zakładu wodno-elektrycznego w Rożnowie*, Gospodarka Wodna, Warszawa 1938.

[2] Jarząbek S., *Laboratorium betonowe w Rożnowie*, Życie Techniczne, Nr 9, 1937.

[3] Kollis W., *Studja dla projektu zbiornika wodnego w Rożnowie na Dunajcu*, Warszawa 1935.

[4] Popielski P., Zaczek-Peplinska J., *Wykorzystanie modeli numerycznych w eksploatacji budowli pietrzących*, Materiały XII Międzynarodowej Konferencji Technicznej Kontroli Zapór, Stare Jabłonki 2007, 241–255.

[5] Zaczek-Peplinska J., Popielski P., *Wykorzystanie naziemnego skaningu laserowego do weryfikacji geometrii numerycznych modeli obiektów hydrotechnicznych na przykładzie sekcji zapory betonowej Besko,* Czasopismo Techniczne 1-Ś/2013, Wydawnictwo Politechniki Krakowskiej, Kraków 2013.

[6] Grant Rektorski PW, *Analiza możliwości wykorzystania geofizycznych metod sejsmiki powierzchniowej do oceny stanu technicznego wałów przeciwpowodziowych*, Koło Naukowe Inżynierii Wodnej Politechniki Warszawskiej, Warszawa 2013.

[7] Grant Rektorski PW, *Opracowanie modelu numerycznego zachowania się zapory betonowej i jego weryfikacja na podstawie geodezyjnych pomiarów okresowych z uwzględnieniem okresu wezbrań sezonowych,* Stowarzyszenie Studentów Wydziału Geodezji i Kartografii Politechniki Warszawskiej "Geoida", Warszawa 2013.

[8] OTKZ IMGW, *Ocena stanu technicznego i bezpieczeństwa zapór w Rożnowie i Czchowie – zapora Rożnów*, marzec 2012.

[9] OTKZ IMGW, *Zapora w Rożnowie – Wyznaczenie przemieszczeń*, marzec 2012.

[10] Rozporządzenie Ministra Środowiska z dnia 20 kwietnia 2007 r. w sprawie warunków technicznych, jakim powinny odpowiadać budowle hydrotechniczne i ich usytuowanie (Dz.U.2007.86.579).

[11] Norma PN-EN-12504-2:2002, Badania betonu w konstrukcjach. Część 2. Badania nieniszczące. Oznaczenie liczby odbicia.

[12] Instrukcja ITB 210/1977, *Instrukcja stosowania młotków Schmidta do nieniszczącej kontroli jakości betonu.*

[13] Instrukcja ITB 209/1977, *Instrukcja stosowania metody ultradźwiękowej do nieniszczącej kontroli jakości betonu.*

[14] Drobiek Ł., Jasiński R., Piekarczyk A., *Metody lokalizacji wad konstrukcji betonowych – metoda ultradźwiękowa*, Przegląd Budowlany, 9, 2007.