BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 66, No. 1, 2018
DOI: 10.24425/119062

Reliability of geodetic control measurements of high dams as a guarantee of safety of the construction and the natural environment

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Abstract. In the safety assessment of hydro-technical objects, it is necessary to combine different measurement techniques, calculations and experience of specialists in various fields of engineering. That is possible due to the current development of surveying technology. Undoubtedly, the integration of measurements, including technical assessment as well as object behaviour modelling, makes it possible to perform more comprehensive assessment of objects. Nevertheless, in order to obtain a multidimensional overview of an examined object – especially water dam – it is necessary to know all the possible errors that appear along the "observer-instrument-object" path. In this paper, the authors intended to investigate the influence of atmospheric conditions on the results of geodetic deformation measurements and attempted to consider surface deformation analysis, which is part of obligatory inspections of hydro-technical objects. The study was based on the geometry assessment of the vent wall of Rożnów water dam located within the borders of the South-Polish Protected Landscape Area. The measurements took place in the years 2013–2015 and were performed using Z + F Imager 5010 laser scanner equipped with an integrated thermal camera. Surveying results and analyses based on archival data and forecasts of atmospheric conditions at the location of the hydro-technical facility can be applied while elaborating the rules for a control date selection. The proper definition of a measurement cycle will make it possible to avoid errors of interpretation for those facilities important from the flood protection, recreation and nature perspectives.

Key words: terrestrial laser scanning, technical control of dams, environmental safety.

1. Introduction

Each hydro-technical building is exposed to many internal and external impacts that can influence its geometric and physical changes, especially including its material or – respectively to the topic of this work – surface properties of the materials it was made from. In order to obtain information about the condition of the object, geodetic deformation measurements need to be performed. During measurement, a discrete model is obtained representing the current state (shape) of the object of measurement. With cyclically conducted measurements, it is possible to develop a deformation model [1]. The construction interpretation of the results of the measurements allows for the assessment of its technical condition and, in emergency cases, to commence intervention in order to prevent the risk of human life and often irreversible changes in the natural environment. In order to perform a correct interpretation of the measurement results, it is essential that the data of the analyzed model is obtained with possibly highest accuracy and contains no instrumental or environmental errors. The development of measurement technology has made it possible to monitor continuous changes of an engineering object state. It also accelerates surveying, minimizes gross errors and reduces costs. As a consequence, it provides a more reliable assessment of the technical condition and safety of hydroelectric facilities. Integrating measurements, incorporating numerical modeling of object behavior and assessing the technical condition of a variety of qualitative data ensures the assessment of an object in a more comprehensive and transparent way. However, one should remember that the results of geodetic measurements are error-vulnerable due to the observer's imperfections and changing atmospheric or environmental conditions. Nowadays, many automated measuring systems are produced with instrumental corrections automatically applied to surveying results but, unfortunately, factors affecting the observed object are usually not considered. It is common that the examined object has impact on the natural environment causing long-term changes, which in consequence affects the behavior of the object itself. The impact of hydro-technical structures on the adjacent environment is examined in numerous publications [2, 3].

According to the Water Law [4] and guidelines for carrying out assessments of the health of hydro-technical objects [5], the technical condition of the dams should be checked twice a year and not less than once. The good practice is to perform these measurements annually in the same period each year, e.g. fall (late September to early November), spring (April-May) and by the same surveying team. Owners (users) of hydraulic structures often sign long-term contracts in which the deadlines for follow-up inspections are strictly defined. Land surveyors perform the inspections by measuring horizontal and vertical

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Manuscript submitted 2017-11-06, revised 2017-11-28, initially accepted for publication 2017-11-28, published in February 2018.

displacements of the object. Such measurements are made using precise total-stations equipped with electro-optical distance meters (EDM), taking measurements to the exposed parts of concrete structures. Recently, high-performance laser scanners have also become popular. Their surveying accuracy is strongly influenced by the ambient temperature and the temperature of the examined structure. The next part of the paper presents the influence of temperature changes on the geometry of the dam vent wall in Rożnów (near Nowy Sącz – the municipality of Gródek nad Dunajcem, Southern Poland). The measurements were made between 2013–2015 by using both Z + F Imager 5010 laser scanner equipped with a T-Cam integrated thermal camera and Leica Nova MS50 scanning total station. As a result of laser scanning performed on a selected surface, we obtained a point cloud characterized by point coordinates (X, Y), the intensity of a laser beam reflected from the measured surface as well as the local temperature of test surface measured in the window (0.15×0.15°C). The captured data indicate the correct selection of the surveying date depending on the short-term local meteorological forecasts and not only on the correspondence of calendar dates.

2. Purpose and scope of analysis

The aim of the study was to demonstrate that the inclusion of atmospheric variability in the planning and implementation of geodetic control surveying is a factor influencing the reliability of research and the performed analysis. Atmospheric conditions, including temperature, sunlight and humidity, clearly affect the surface properties of the structure. The examined object is a heavy-concrete dam with a height of 49 m and a length of 550 m. It was commissioned in 1943. Currently, it is subject to geodetic control surveying once a year – in autumn.

The location of the dam is significant in relation to the areas of nature protection. The dam itself is situated within the South-Małopolska Protected Landscape Area (Fig. 1) and is only about 1.7 km away from a Natura 2000 site. This site of nature protection – located west of the dam – is named Łososina (PLH120087) and covers the left bank of the Dunajec river. It has been designated for the protection of fish. Due to the characteristic location of the dam and considering its function of preventing floods, the importance for recreation and energy production, it has a great impact on the development of the fauna and flora of the surrounding natural environment – especially in the case of an emergency or structural disaster.

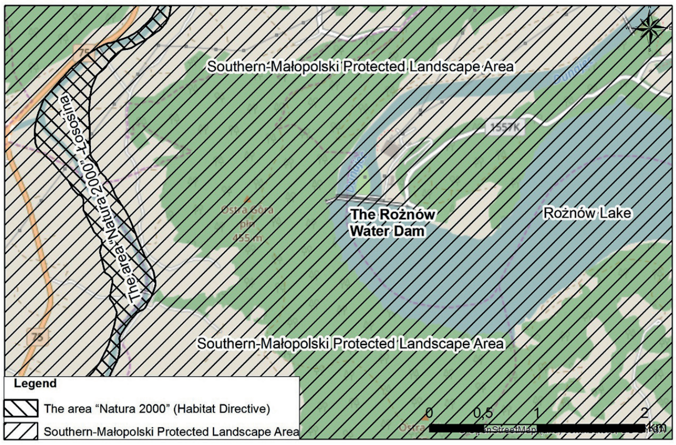


Fig. 1. Location of the examined object in relation to protected areas

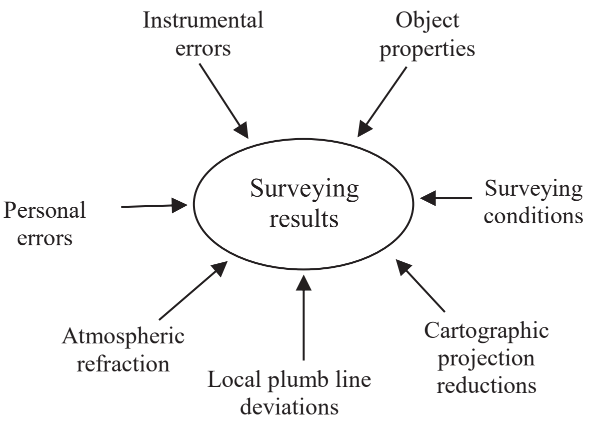


Fig. 2. Factors determining the quality of geodetic measurements

3. The effect of atmospheric factors on geodetic measurements

Regarding the expected high control surveying accuracy, the weather conditions that influence measurements, as well as the temporal effects on the examined structure, should be considered while operating the instrument. Fig. 2 presents a schematic view of different identifiable error sources.

The error sources related to the measurement conditions, instrument characteristics, the local parameters of the plumb line (the Earth curvature), the observer's experiences or the object properties are so important that during deciding (above all – precise) measurements they have to be considered. Performing a reliable accuracy test (validation of the manufacturer's assumptions) can be performed, among others, by using the procedures included in the ISO standards (in Poland: PN-ISO). According to surveying equipment, these belong to the series ISO 17123.

When validating the operation of surveying instruments according to the above mentioned standards, it should be kept in mind that the results of performed tests show only so called "raw" tolerances (standard deviations) obtained without considering other factors affecting the measurements. It is directly linked with systematic errors and the influence of environmental factors affecting the results of land surveying. Both error-generation groups are the dominant source for real field measurements, so in addition to the ISO test, it is advisable to conduct field accuracy checks examining the impact of field and environmental conditions. That considered, one can assume that the surveying accuracy obtained as a result of carrying out ISO tests can be even several times greater than the actual accuracy of geodetic works determined while their post-processing in the office.

The measurement results are often influenced by the position of the local plumb line [6] – but this factor will be more significant in precision geodetic networks, or wherever the distances exceed at least a few hundred meters. So-called "personal errors" are generally minimized by using robotic total-stations (RTS) equipped with the modules of automatic target recognition (the Swiss manufacturer of geodetic instruments – Leica Geosystems AG names this technology "ATR"). Placed on pillars (forced centering) or on industrial tripods, electronic tacheometers (total-stations) supported by classical servomotors, rotating mechanisms using the piezoelectric effect or electromagnets are able to practically eliminate personal errors. The only significant factor that cannot be overlooked is the ambient refraction characterized by the changing path of a surveying medium (laser beam) while passing through air layers and meeting different meteorological parameters. Regarding that, we can consider here both the influence of local atmosphere as well as holistic climate factors with their variability – observed especially in recent years. The global warming process is gaining in importance, which is mainly due to the progressive changes in the local microclimate. The atmospheric factors directly impacting the results of geodetic measurements in the form of disturbances in the measurement medium – infrared beam (used in older types of electronic totals) or laser (newer generations of total stations and laser scanners). These distortions have different origins and, therefore, are worth to be discussed.

The influence of refractive factors on the beam pattern may be horizontal (lateral refraction) or vertical. In typical engineering geodesy, target distances do not usually exceed several hundred meters. Due to the required accuracy of the positioning of control points, geodetic structural monitoring has a number of recommendations regarding technological aspects. In the case of using smaller prisms, it is advisable that the distances are not shorter than 10 m but not longer than 150 m. This limitation results from the fact that, at distances of less than 10–20 m, there is sometimes considerable ambiguity in the automatic target recognition. In the case of distances greater than 150 m, with the presence of disturbing factors such as variable lighting, haze and dustiness, and with less favorable network geometry, the point positioning accuracy may fall below the industry requirements. Nevertheless, it is often necessary to measure distances longer than 150 meters. In such case, there should be more control points deployed in the particular test area, increased measurement frequency (surveying interval), or more precise reflectors with a larger prism diameter. Despite this fact, it is not advisable to use target distances of more than 400–500 m, which in the case of measuring water dams can be quite challenging for surveyors.

For control measurements or continuous monitoring performed on objects by means of precision electronic total-stations, the correction is usually subjected to the principal distance [7] as shown in Fig. 4. The measured "raw data" is corrected directly by the instrument firmware by executing one of the following procedures:

- automatic distance correction taking into account atmospheric parameters – pressure, temperature and humidity;
- automatic correction of each measured distance, taking into account the current readings from the meteo-sensor,
- automatic distance correction based on the comparison of the currently measured distance with its reference value – in this case, no meteorological parameters are taken into account.

Each of the presented procedures has a set of advantages and disadvantages and is intended for a variety of specific field applications.

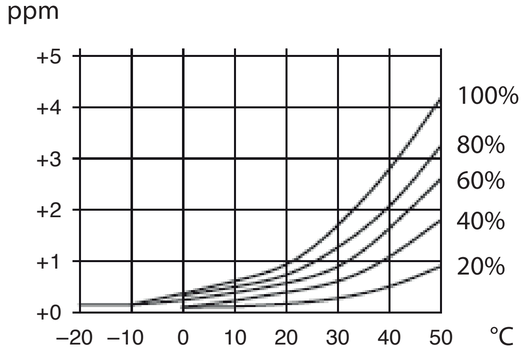


Fig. 3. Graph of atmospheric correction of atmospheric pressure and humidity (source: Technical Reference Manual MS50, Leica Geosystems AG)

Entering meteorological parameters at the beginning of measurement and their subsequent verification at the end does not take into account the variability during the entire measurement cycle. It is only a generalized value, which can lead to errors. However, this approach will be sufficient when surveying under constant conditions – especially indoor [8]. Using the meteo-sensor introduces to the control system another element that has to be managed in terms of IT. Therefore, it is necessary to provide additional power supply and a transmission module. In addition, the sensor measures the atmospheric parameters at their location and does not take into account their variability along the entire distance. Moreover, there is a danger of introducing erroneous corrections when the sensor stays in sunlight or in the shade while the condition of the object is quite different. The use of meteo-sensor, however, provides current atmospheric parameters, which, with a large amount of collected data, is a solution that facilitates the proper functioning of the system. In many cases, several meteo-sensors are used on the site, which significantly improves the reliability of the monitoring, but – in the meantime – generates significant costs and requires increased IT support. Determining distance corrections for the reference base may seem to be the simplest solution but in the case of multiple error sources occurring at the same time, the displacement of the control points will be subject to high uncertainty and ambiguity. It will lead to so-called data peaks – difficult to interpret and, when using monitoring systems, generating false alarms. Each approach, therefore, requires case studies and use of the observer's expertise. In recent years, the use of thermography is also of great importance. Thermal imaging provides additional information about the exact temperature distribution on the object as well as in its near surrounding, which completes the current model of the studied structure.

For example, in Leica Geosystems precise total-stations, distance correction is based on functional dependency [7]:

$$\Delta D = 286{,}34 - \\ - \left[\frac{0{,}29525\,p}{(1+\alpha\cdot t)} - \frac{4{,}126\cdot 10^{-4}}{(1+\alpha\cdot t)}\cdot 10^{\left(7{,}5\cdot\frac{t}{(237{,}3+t)}+0{,}7857\right)}\right] \quad (1)$$

where:

ΔD – atmospheric correction [ppm],
p – atmospheric pressure,
t – air temperature [°C],
h – relative humidity [%],
α – coefficient equal 1/273.15.

This formula applies to air humidity not exceeding 60%. In case this value is exceeded, a generalized atmospheric correction of 2 ppm (2 mm/km) is usually assumed.

In the case of measurements carried out by scanning total stations or laser scanners, except the refraction influences, atmospheric parameters can also influence beam intensity [9].

For instruments using the impulse measurement principle, the correction for distance measurement can be determined from the equation [10]:

$$D = \frac{C_0}{2\cdot n}\cdot t_l + K_0 \quad (2)$$

where:

n – coefficient of atmospheric refraction,
C_0 – light speed in vacuum,
t_1 – double-run time of laser beam (impulse),
K_0 – correction coefficient of a null-place in EDM.

For phase instruments, this relationship will take the form:

$$D = N\cdot\frac{C_0}{2\cdot n\cdot f} + R + K_0 \quad (3)$$

where:

f – modulation frequency of a bearing beam
N – full amount of phase cycles
R – the rest from establishing a full value of phase cycles.

On the basis of these formulas, different refraction models have been developed, later used by manufacturers of geodetic instruments.

4. Changeability of atmospheric-environmental conditions

For many years the climate or its variability has been the subject of interdisciplinary research. In Poland, such studies are conducted within the framework of the European projects [11] or university analyses [12–15].

Considering the analysed geodetic survey problems, the authors focused on presenting changes in environmental conditions understood as the state of atmospheric parameters in particular time and place. It was assumed that changes in weather conditions objectively reflecting the meteorological condition of the research area will be based on the values recorded at Nowy Sącz station, due to its proximity to the objects located in Rożnów. Archival studies unequivocally confirm that the variability of thermal characteristics in Nowy Sącz is consistent with the trends observed in more general spatial scales, but in some periods the effects of local factors are evident (Fig. 4).

By examining the multi-annual variations in the mean values of minimum and maximum temperatures, it was found that the minimum and maximum temperatures show a statistically sig-

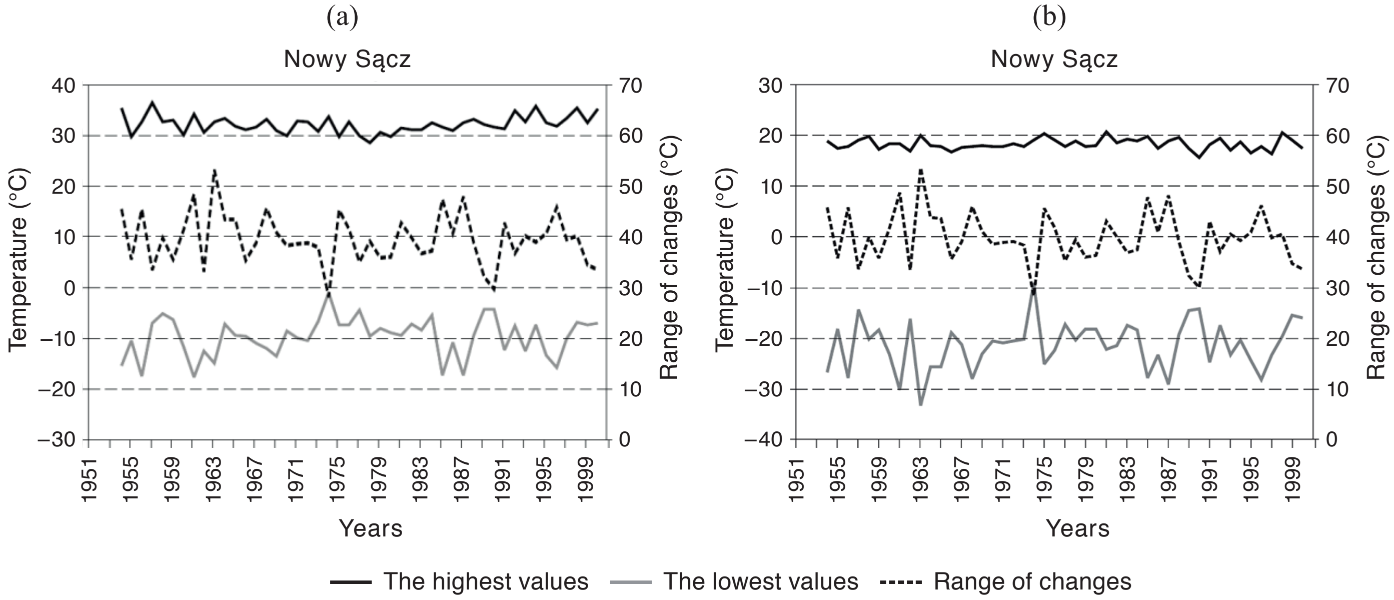


Fig. 4. Variability of maximum and minimum temperatures in the period 1951–2000 at Nowy Sącz station, a) maximum temperatures b) minimum temperatures [16]

nificant upward trend ($p < 0.05$). Extreme temperatures over 50 years – the highest of 36.7°C and 20.5°C, and the lowest –17.8°C and –33.5°C [16] show how the weather conditions were uneven in different years.

In general, the climate of Poland is characterized by high variability of weather and significant variation of the seasons in successive years (average annual air temperature values range from slightly above 5°C to nearly 9°C). Unfortunately, in recent years we can observe a number of deviations from the expected weather variations, such as the first half of May 2017. Large variations in average daily and monthly temperatures are confirmed by the Polish Institute of Meteorology and Water Resources (IMGW). Therefore, trying to determine optimal periods of geodetic surveys, we should take into account not only average, annual or maximum-annual temperatures but daily or even hourly conditions as well (Table 1). The significance of

Table 1
Long–term averages from 2001–2016 for the city of Nowy Sącz, compiled for September and October, when the most common control measurements of hydro–technical objects are performed [based on IMGW data]

Year	**Month**	**Average monthly air temperature (°C)**	**Absolute maximum of daily temperature (°C)**		**Absolute minimum daily temperature (°C)**		**Average humidity (%)**	**Absolute maximum of humidity (%)**		**Absolute minimum of humidity (%)**	
			max	data	min	date		max	date	min	date
1986	September	12.4	27.8	16.09.86	–0.7	26.09.86	79.4	97	10.09.86	62	20.09.86
	October	8.5	26.7	02.10.86	–3.1	25.10.86	74.4	94	10.10.86	49	19.10.86
1987	September	14.4	27.7	13.09.87	0.8	29.09.87	78.4	95	30.09.87	67	01.09.87
	October	10	23.1	19.09.87	–4.9	30.10.87	75.3	96	24.10.87	38	06.10.87
1988	September	13.8	26.9	01.09.88	6.5	04.09.88	80.1	92	21.09.88	67	24.09.88
	October	8.4	25.5	13.10.88	–5.3	26.10.88	74.5	88	31.10.88	46	27.10.88
1989	September	14	27.9	19.09.89	1.5	30.09.89	83.9	97	04.09.89	71	13.09.89
	October	10.1	24.6	23.10.89	1.6	14.10.89	81.6	97	09.10.89	70	12.10.89
2001	September	12.8	21.3	21.09.01	1.5	28.09.01	82.7	97	24–25.09.01	59	10.09.01
	October	12	26.6	03.10.01	–5.2	25.10.01	82.3	95	17.10.01	61	31.10.01
2003	September	13.8	30.9	21.09.03	1.1	26.09.03	74.6	96	12.09.03	48	23.09.03
	October	6.4	20.3	02.10.03	–8.3	25.10.03 28.10.03	79.5	93	04.10.03 27.10.03	57	29.10.03
2004	September	13.1	26.2	14.09.04	2.1	18.09.04	75.5	87	25–27.09.04	58	12.09.04
	October	10.9	23.7	06.10.04	–2.9	13.10.04	76.8	95	09.10.04	55	14.10.04
2006	September	15.6	27.6	07.09.06	5	10.09.06	71.5	92	20.09.06	61	05–06.09.06 13–14.09.06
	October	11	25.4	03.09.06	–5.4	31.10.06	72.2	92	14.10.06	40	19.10.06
2007	September	12.4	25.7	17.09.07	1.1	21.09.07	75.4	58	29.09.07	94	05.09.07
	October	7.8	22.1	01.10.07	–2.5	15.10.07	85.5	100	24.10.07	64	16.10.07
2008	September	12.7	32.2	07.09.08	3	28.09.08	82.2	95	16–17.09.08 20–21.09.08	62	04.09.08
	October	10.2	21.5	14.10.08	0.5	06.10.08	82	96	03–04.10.08	61	31.10.08
2009	September	15.1	28.9	03.09.09	4.3	30.09.09	78.8	92	13.09.09	65	01.09.09
	October	8.1	24.9	08.10.09	–1.6	22.10.09	83.2	94	11.10.09	63	04.10.09
2010	September	12.4	22.5	23.09.10	3.9	20.09.10	83.7	96	11.09.10	59	25.09.10
	October	6	19.3	31.10.10	–4.2	28.10.10	79.5	99	18.10.10	47	31.10.10
2011	September	15.7	30.8	05.09.11	3.7	25.09.11	76.6	96	21.09.11	58	05.09.11
	October	8.5	24.4	04.10.11	–2.9	18.10.11	81.2	94	07.10.11 22.10.11	59	19.10.11
2012	September	14.9	29.6	11.09.12	1.9	22.09.12	77.1	97	20.09.12	59	11.09.12
	October	9.3	24.3	06.10.12	–1.6	12.10.12	80.6	95	02–03.10.12 23.10.12	61	06.10.12
2013	September	12.1	24.4	08.09.13	0.7	28.09.13	75.8	92	17.09.13	61	08.09.13
	October	10.7	24.4	13.10.13	–2.9	05.10.13	75.5	95	16.10.13	55	28.10.13
2014	September	14.8	26.4	12.09.14	3.4	29.09.14	82.6	95	27.09.14	68	19.09.14
	October	10.1	24.4	11.10.14	–4.3	29.10.14	85	99	23.10.14	67	08.10.14
2016	September	15.5	27.8	12.09.16	4.5	27.09.16	76.9	94	19.09.16	64	29.09.16
	October	8.2	24.0	01.10.16	–1.7	28.10.16	79	90	22.10.16	64	31.10.16

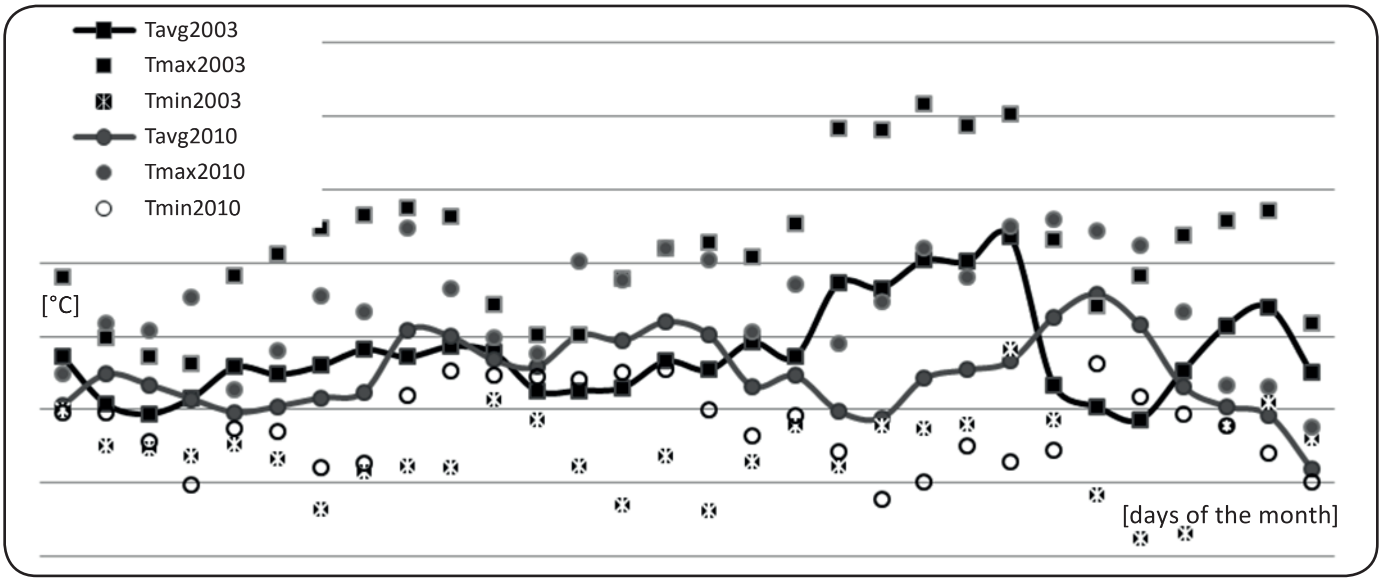


Fig. 5. Variability of average, maximum and minimum temperatures in September 2003 and 2010 at Nowy Sącz station (based on IMGW data)

this approach can be illustrated by graphs of temperature and humidity for Nowy Sącz stations for September 2003 and 2010. It can be clearly seen that with very close daily averages there can be significantly large differences between the maximum and minimum temperatures of a given day. At the same time, very large temperature variations are visible between 18 and 24 September (Fig. 5).

Presenting the selected climate parameters on a statistical basis underlines the changes that have taken place over the years. Nevertheless, it should be noted that the presence of a large water surface also locally influences the temperature or humidity. Generally, the authors are inclined towards a favorable forecast of the influence of the Rożnów reservoir on the microclimate of its surroundings which can result in the development of agriculture [17]. Similar opinions are given for the local climate of other water reservoirs in Southern Poland [18]. It should be mentioned, however, that in the context of choosing dates for control measurements, future simulations of changes in thermal conditions need to be taken into account. They were developed for the entire 21st century with particular emphasis on the period 2011–2030 and 2081–2100.

It follows that for the fall season the temperature changes in the period 2011–2030 will not exceed 0.1°C, similarly to the emission scenarios for the years 2081–2100 [19].

5. Thermal influence on laser scanning of a water dam

Data from laser scanning is used in geomorphology [20], hydrology [21], forestry [22], archaeology [23, 24], hydraulic engineering and geodetic engineering [25], glaciology [26] and many other fields. Laser scanning technology can be distinguished into terrestrial laser scanning (TLS) and airborne laser scanning (ALS). The appropriate technique is chosen depending on the type of reports and research, however, each of them has its use in surface research, landslide research and engineering object measurements. Due to the different natures of data in TLS and ALS, this article concentrates on using data from terrestrial laser scanning. Terrestrial laser scanners are also combined with external sensors, so that, apart from geometric data and intensity values, a thermal or colour information as RBG values can be obtained. Applications of a thermal camera integrated with a terrestrial laser scanner can be found in the construction industry as a device to detect and evaluate thermal leakage of a building. For many years, thermal imaging has been widely used in road building, construction, spatial planning or in natural studies [27–31]. The influence of ambient temperature on the tested structure as well as on particular geodetic observations can be determined using the same instrument while controlling the object in different periods. As an example, the authors have studied the surveying results obtained from laser scanner in September-October, 2013 and 2015. The measurements relied on a laser scanning of the vented section of blind elements of the water dam in Rożnów, Southern Poland. They intended to perform the analysis of the scanning data due to the universal character of executing distance measurements by laser distance meters integrated with scanners and total-stations. Unlike discrete angle-linear measurements, the quasi-continuous character of laser scanning (X, Y, Z, intensity and thermography coordinates) in the examined area [21, 32]. In Fig. 6 the scanned structural sections are marked in red.

All recorded scans have been transformed into a uniform coordinate system defined by the signal points on the wall. These points are additionally measured using total-station and their coordinates are determined in the local coordinate system.

Fig. 6. View of the vented wall of the Rożnów water dam with the scanned area red-marked

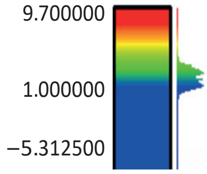
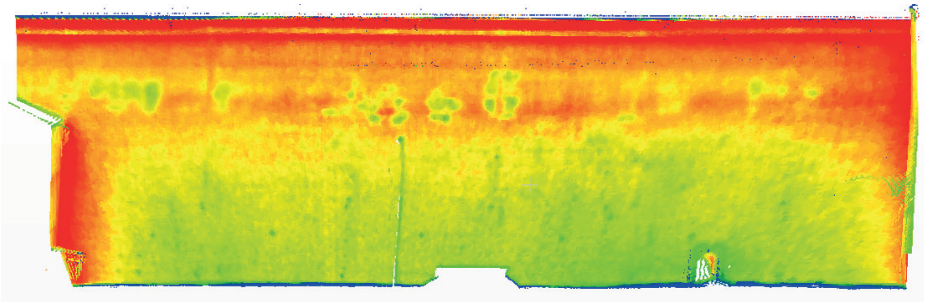
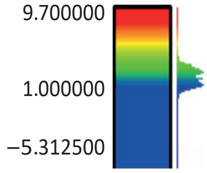
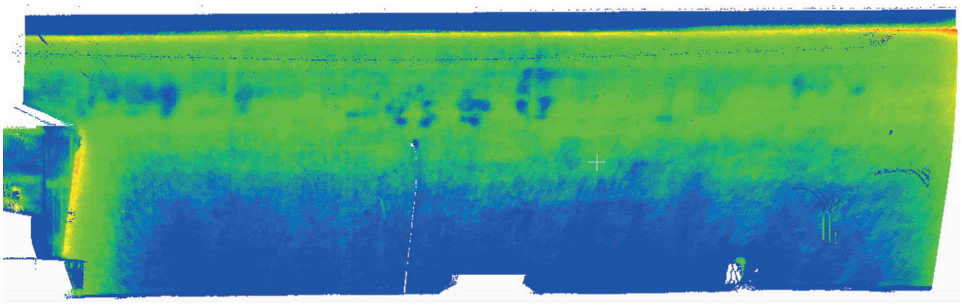
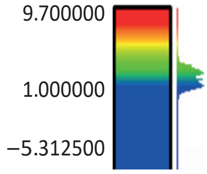
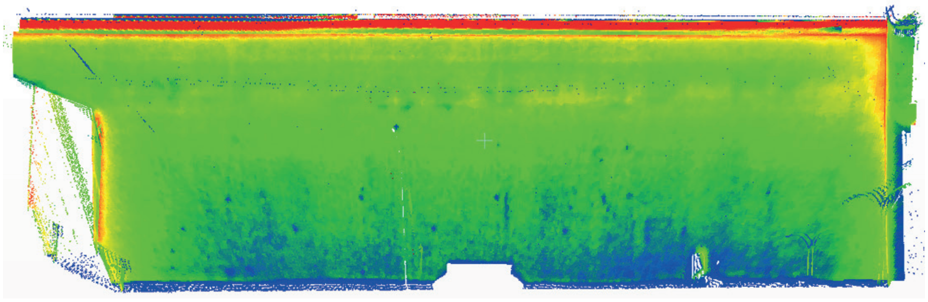
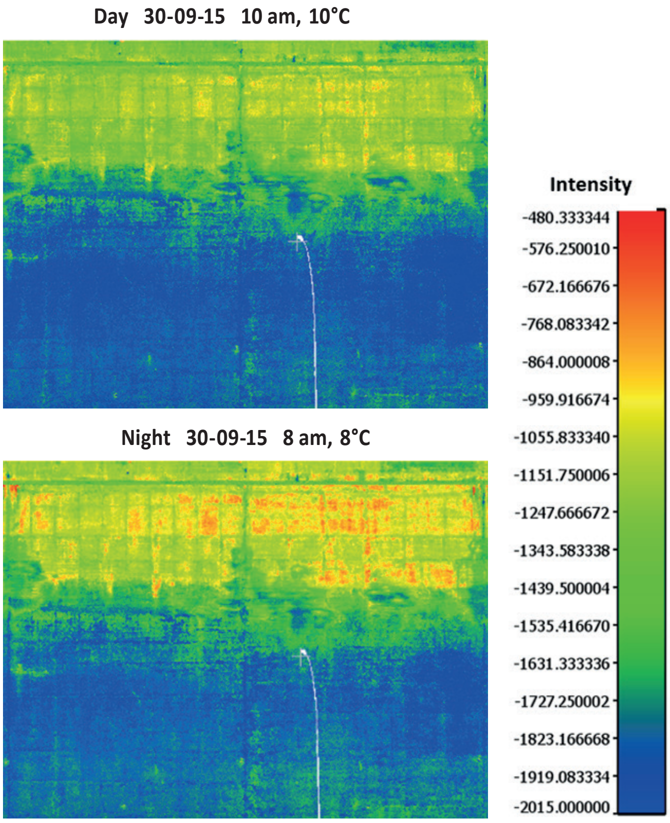
Date, time, air temperature, temperature value range	**Thermal images**
28.09.2015, 6PM, 10.0˚C, 	
3.10.2015, 10AM, 8.0˚C, 	
3.10.2015, 6PM, 12,0˚C, 	

Fig. 7. Compilation of color-coded data scanned from the same station on 28.09. and 8.10.2015

Figure 8 shows the results of scanning the vented wall surface from the station located in the middle of the island separating the active hydropower plant from the overflow sections (bottom bumps and surface overflows). Measurements were made on 28.09 and 8.10.2015 with the Z + F Imager 5010 laser scanner equipped with an integrated T-Cam thermal camera. In Fig. 8, we can observe the differences in surface temperature based on the point-cloud of the thermal data. The atmospheric conditions prevailing in measured days are presented in Table 2. The temperature of concrete recorded at level 2 of the control gallery inside the facility throughout the day was constant at 8.2°C.



Day 30-09-15 10 am, 10°C

Night 30-09-15 8 am, 8°C

Fig. 8. The results of scanning the surface of a massive concrete structure at different times of the day; test field range: 30×25 m [33]

Table 2
Atmospheric conditions – data from sensors (water dam "Rożnów")

Time	Air temperature [°C]	Air humidity [%]	Dew point [°C]	Concrete temperature [°C]	Concrete surface humidity [%]
28.09.2015					
12.00	21.00	–	–	–	–
18.00	10.00	–	–	–	–
30.09.2015					
10.00	10.00	–	in the middle of the wall (area 2, Fig. 9)		
			–	–2.00	–
20.00	8.00	–	–	21.20	–
8.10.2015					
10.00	8.0	–	–	–	88.0
11.00	9.9	67.5	4.7	–	70.5
12.00	14.6	64.0	5.8	13.2	–
14.00	19.4	42.6	7.2	17.3	–
18.00	12.0	–	–	–	–

At the top of the scans (Fig. 8), we can observe irregular, "spherical" areas. Such places are characterized by different surface properties (calcium carbonate leaks), which are clearly visible in the RGB optical image. Because of other surface properties these areas heat up and give off heat at a different rate than the concrete surface without infiltration.

Due to the large temperature variation on the surface caused by the intense daily sunlight of the open area, the authors performed an experiment to demonstrate the influence of surface temperature changes on laser scanning. The dam wall was scanned twice on a low-clouded day (30.09.2015) – in the morning (10:00 am, air temperature t = 10°C) and in the evening (8.00 pm, t = 8°C). Due to its location on the North-Western side, the wall is exposed to high solar activity during good weather and the daily temperature difference recorded on the wall surface is up to 30°C in the Autumn (September / October). The test was performed by using Leica Nova MS50 scanning total station. Registered surface colored scans of laser beam reflection intensity are shown in Fig. 9. The differences

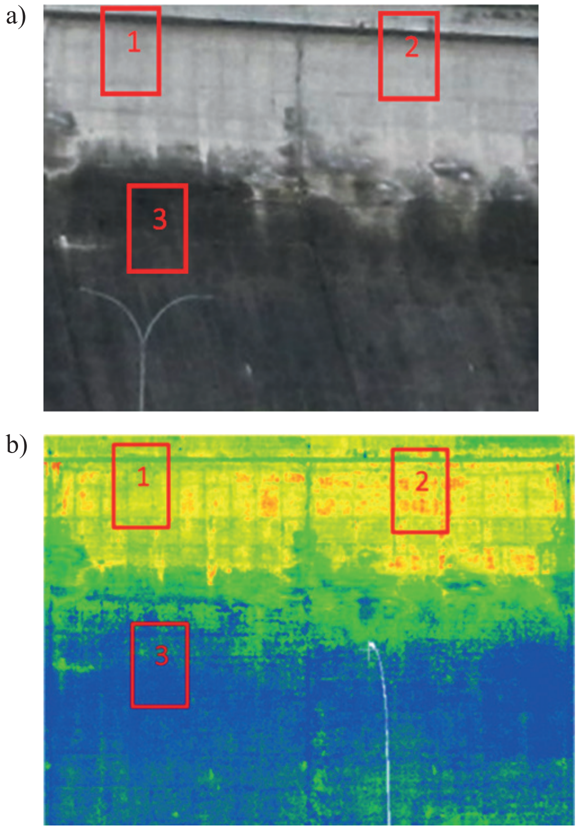


Fig. 9. Areas on the wall surface selected for analysis: a) areas marked on the optical image layout, b) areas marked on the scan (test field range: 1, 2, 3:5×3 m)

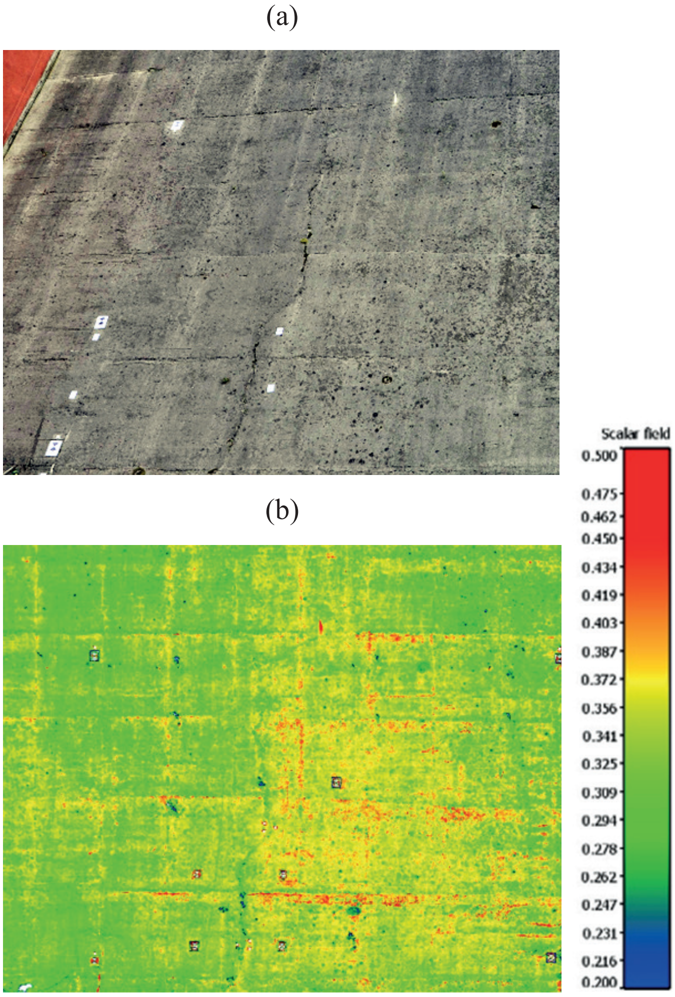


Fig. 10 Selected area for the vent wall of the Rożnów dam: a) picture from Nikon 300i – 2013 digital camera, b) picture in color intensity (I), (test field range: 10×10 m)

between recorded intensity values were compared (in selected areas – Fig. 10). In Table 3 the percentage changes of the intensity value are compared with 10 am for ten-hour solar operation.

Table 3
Changes in recorded values for selected areas of the concrete surface between 10 am and 8 pm (10-hour interval)

Area	Mean Intensity value 10 am	Mean Intensity value 8 pm	Difference (ΔI)	% (approx.)
1	–2010	–1870	140	10
2	–1050	–650	400	40
3	–1250	–1050	200	25

Based on the analysis of recorded values of laser beam reflection intensity, ambient temperature, the concrete temperature on the surface of the wall and its insolation, it was found that:

- the effect of air temperature, concrete and sunlight on the X, Y, Z-coordinates scanned with Leica Nova MS50 total-station can be estimated as ±0.005 m,
- there is a significant impact of sunlight and changing concrete temperature on recorded laser beam intensities – especially in brighter areas (upper part of the scan); these changes may be significant for the technical assessment of the facility which indicates the appropriateness of attaching data from other sources such as thermal camera.

In order to further investigate the effect of surface temperature differences on geodetic measurements (in particular on distance measurement results using a laser distance meter), a differential analysis of the wall fragment scans was performed. The scans were made on 30.09.2013 and 8.03.2013 at midday, with the same level of topwater. The results of the wall scan – color images of the laser beam intensity (I) are shown in Fig.10. Thermal imaging (T) is shown in Fig. 11c and 11d. In the right part of the scans, we can identify the difference in recorded temperature values. Maximum surface temperature differences in concrete (Δtb) equals 1.5°C. The difference in air temperature on measuring days is 6.4°C.

The selected scan sections were fitted by using least squares method as well as the scanned points were scaled from the fit

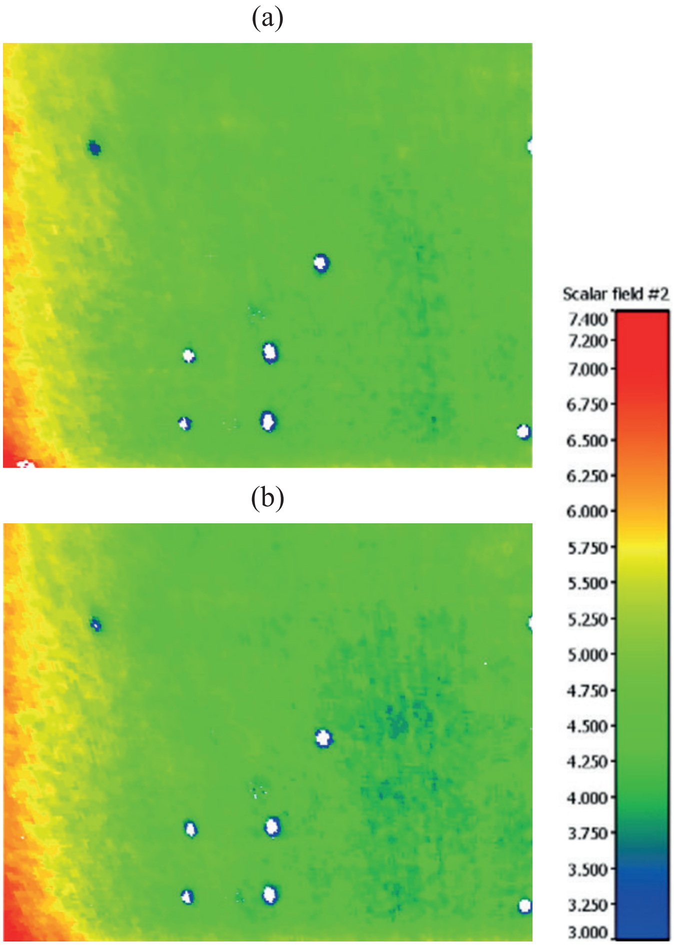


Fig. 11 Selected area for the vent wall of the Rożnów dam a) 2013, b) 2015 (test field range: 10×10 m)

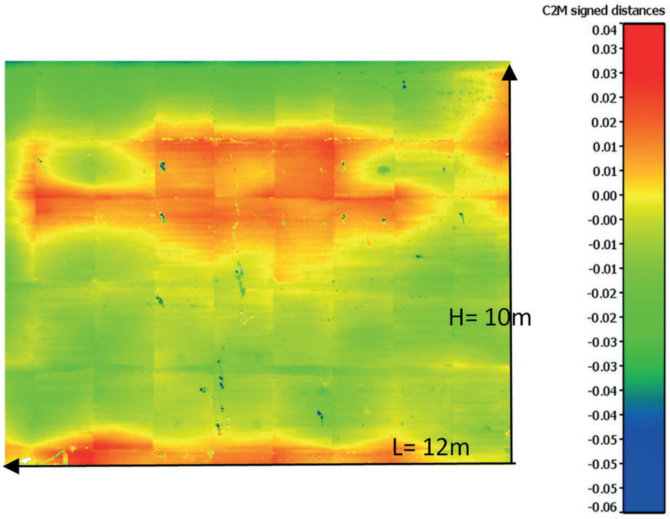


Fig. 12. Colour distance map from the fitted plane – point cloud from 2013 (in the central part of the drawing there is a gap in the concrete surface for which the distance from the fitted plane is locally greater) – test field range: 10×12 m

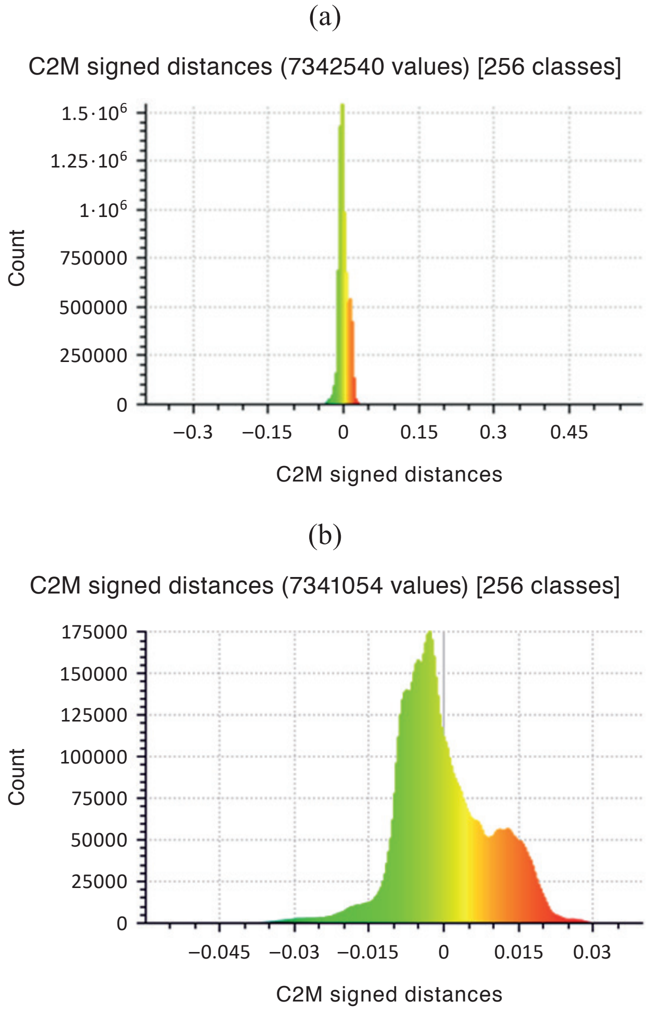


Fig. 13. Histograms of the calculated distances: recorded points from the fitted plane: a) scan from 2013, b) scan from 2015

surfaces in order to check the quality of plane fitting and to compare the principal parameters of the surface roughness [34]. Fig. 12 presents the color map of the distance from the plane (scan from 2013). On the computed histograms (Fig. 13a, b), the differences between the two analyzed scans can be observed.

Analogically, there were compared scans performed on the same day but at different times. The measurement was made on 8.10.2015 at 12.00 and 2 pm at an ambient temperature difference of 4.8°C. The calculated differences from the fitted planes reach sizes up to 5 mm within the slits and 1–2 mm in the homogeneous area. Fig. 14 presents distance maps from the fitted plane for measurements made in 2015 under different atmospheric conditions.

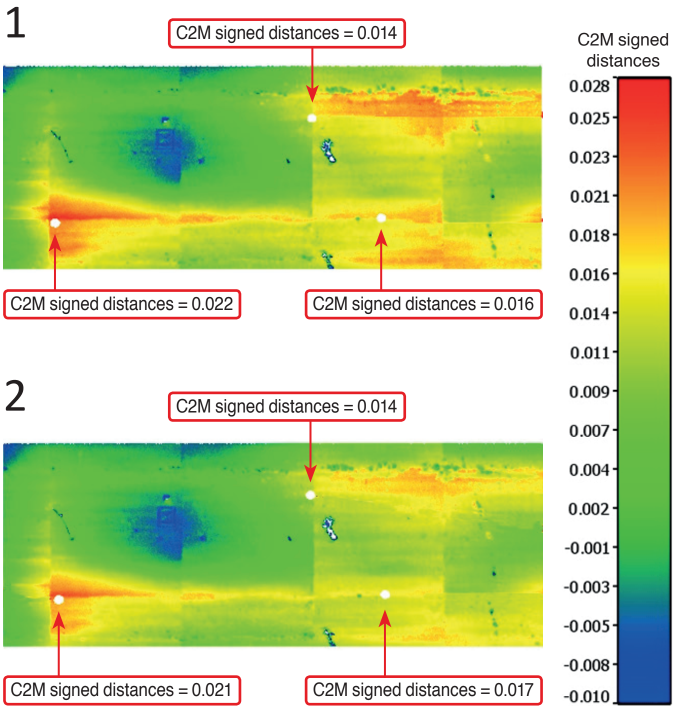


Fig. 14. Differential maps for a selected scan area performed under different atmospheric conditions (2015)

6. Conclusions

Based on the performed analyses, the dependence between the surveying results and the surface temperature can be proved. The general accuracy of such analyse does not exceed the range of 5 mm within the localized concrete slits/cracks and 1–3 mm in the areas that are homogeneous in terms of surface geometry (areas of low roughness parameters), at the changes of air temperature of 2°C÷4°C and concrete temperature range of 2°C÷20°C. The presented differences are greater than those modeled for the Rożnów dam toward the mean direction of the load caused by water damming.

According to the model described in [35], the maximal displacements in the area of the analyzed scans equal from

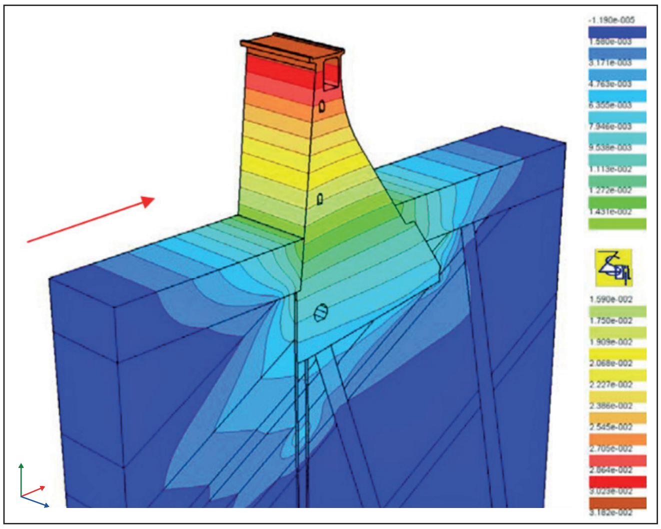


Fig. 15. Isoline model of the Rożnów dam: horizontal displacements in the X direction (marked with red arrow). Displacements were calculated assuming the maximum damming level [35]

1.4 mm to 3.18 mm. The authors elaborated and discussed an isoline model of predicted object displacements (Fig. 15). The real occurrence of control point displacements larger than the 50% may cause object failure. The observed differences in the results of measurements performed on days with different air temperatures show how important it is to perform measurements under similar atmospheric conditions.

The analyses of archival meteorological data have shown that the variability of temperature and humidity in the studied periods are statistically significant, which is particularly evident in the case of annual and seasonal averages. It can also be concluded that the displacement measurements of hydro-technical objects should not be planned for spring but definitely for autumn, when annual changes in temperature and humidity have the smallest values.

Acknowledgments. The authors wish to thank the company LASER-3D Jacek Krawiec for renting a laser scanning set and Ms. Maria Kowalska, M.Sc. Eng. for her support in the preparation of the paper figures.

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