Research Article

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Displacement and deformation study of engineering structures with the use of modern laser technologies

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Abstract: Modern measuring technologies give the means to perform tasks previously impossible with conventional methods. Their main advantages include reduced time consumption and higher measurement precision. Contemporary displacement and deformation studies of engineering structures often involve application of laser technologies, which are characterised by high precision of measurements. This article presents an analysis of results obtained from measurements of changes in the geometry of an engineering structure in which two complementary measuring technologies were used, i.e. tachymetric measurement with a Leica TDRA6000 laser station and laser scanning with a 3D FARO Focus S150 scanner. The utilised laser station enabled determination of 3D displacements in the local control point network installed on the studied structure as well as transfer of point clouds obtained from laser scans into a uniform coordinate system. The hybrid technology employed and the measurement method used ensured that the accuracy of the determined displacements and deformations of the structural components of the structure was high. The described measurement and result processing technology makes it possible to comprehensively analyse the geometric performance of structures, which consequently leads to the development of more complete conclusions concerning prevention of adverse effects of displacements and deformations in engineering structures.

Keywords: determination of displacements using geodetic methods, laser technologies, laser scanning

1 Introduction

To evaluate positional changes in engineering structures or their parts over time, measurements using geodetic methods are usually performed as basic measurements. Geodetic monitoring is implemented by performing a series of measurements of a control point network installed on the structure [1,2] or by measuring the characteristic points of the structure that reflect its current geometric state in relation to the nominal state [3,4]. Displacement and deformation studies involve measurements and subsequent analysis leading to the formulation of conclusions regarding the dynamics of the incidence of positional and geometric changes in the structure. A major factor that gives rise to such phenomena is displacement in the structure foundation caused by uneven ground subsidence. Vertical displacements are studied by means of precision geometric levelling. This approach is often sufficient but in some cases the scope of the study has to be extended. Development of measuring technology broadens the spectrum of available possibilities [5,6]. Tachymetric technologies currently used in metrological industrial measurements are characterised by high precision of distance and direction measurements. It is necessary that specific measuring conditions are observed, as it allows the obtained results of 3D reference network displacement measurements to have accuracy similar to the results obtained by means of precision levelling. Not only does the implementation of the aforesaid technology facilitate the determination of 3D displacements in the local control point network installed on the structure but it also facilitates the preparation of a base of reference points for other measuring methods, e.g. for laser scanning or photogrammetric measurements [7,8].

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Combining these technologies with classic high-precision measurements allows us to capture a broader spectrum of features of the tested objects. Such solutions are successfully used in inventory measurements and monitoring of both small [9] and larger facilities [10,11] or large areas exposed to various types of risks [12,13].

The article presents a technology for determination of deformations in built structures with the use of modern laser technologies. Two measuring devices were used for the measurements – a coordinate laser station Leica TDRA6000 and a 3D scanner manufactured by FARO. The study results have been presented as a coloured map of structural deformations.

2 Study methodology

2.1 Object of study

The study was conducted on an overground skyway, located on the premises of UTP University of Science and Technology campus in Bydgoszcz, which was constructed in 2001 and has since been serving as an overground footbridge connecting university buildings. After 18 years in service, scratches and cracks on walls and the floor of this structure have been noted. They evidence the presence of structural deformations. The location and shape of the structure are shown in Figure 1.

The skyway has been designed as a reinforced concrete frame structure supported by 12 columns. It runs at a height of approx. 4 m above the ground level and its total length is 47.5 m. A view of the skyway from its western side is shown in Photo 1.

2.2 Study methods

The primary objective of the study was to ascertain the cause of scratches on walls and the floor inside the skyway. The conduct of the study necessitated the employment of a few complementary measuring methods and a subsequent analysis and evaluation of the results obtained.

In the initial stage of the study, the scratches were assumed to have been caused by settlement of the columns supporting the structure which in turn had occurred due to the presence of expansive clay in the studied area. Hence, a set of control marks was

permanently affixed to the columns and monitored for vertical displacements. A view of the marks is shown in Photo 2.

To reveal the causes of structural damage, a set of control points and reference points was also installed inside the structure. The points in the form of steel washers were permanently affixed to the floor (Photo 3) and arranged inside the skyway (points 1 through 12) directly above the columns and in adjacent buildings (reference points P1–P6). The network of these points is shown in Figure 2.

Displacements of control points located on the structure were surveyed over a period of 1 year, in different seasons and at varying temperatures.

Measurements of the outdoor network were performed by means of precision levelling with a Ni007 level. The network of points inside the skyway was measured with a coordinate laser station TDRA6000 manufactured by Leica. The laser station allows observation of the 3D points with a maximum error of ± 0.25 mm [14]. Coordinate laser station TDRA6000 is an example of an improved accuracy distance measuring tool. The main features of TDRA6000 include [15]:

- certificate-confirmed distance measurement with a standard error of ± 0.1 mm,
- certificate-confirmed measurement of vertical and horizontal angles with a standard error of ± 1.3 c ($0.42''$),
- tracking mode using automatic target recognition and reflector tracking and
- recording of measured data with a frequency of 5 Hz.

Measurements of the network with the laser station involved recording 3D coordinates of control points on each of seven free stands. Only the nearest control points were observed from each stand. Measurements at each stand were carried out twice and calculations and processing of the data collected were performed in two stages. In the first stage, differences in elevation between points were calculated and then the network was subjected to rigorous adjustment. The second stage involved determination of horizontal displacements of the installed network. It was conducted by applying isometric transformations integrating free stands and Helmert transformations on six adjustment points (P1–P6), the purpose of which was to present control point coordinates from individual measurement series in a uniform coordinate system. Horizontal displacements of the points were determined by calculating differences in X and Y coordinates between consecutive measurement series [16].

There were a total of five series of measurements performed for both networks. Dates of the measurements

Figure 1: Layout showing the positions of the skyway and adjacent buildings.

conducted and temperatures during the measurements are shown in Table 1.

The two final measurement series, i.e. those on 10.03.2018 and 22.08.2018, also included measurements carried out by means of laser scanning with a 3D Focus scanner manufactured by Faro. These were carried out on nine stands. At the first and the last stand, the scanner recorded the position of six adjustment points (K1–K6) whose spatial coordinates had been determined in the course of measurements with the TDRA6000 laser station (Photo 4). With adjustment point coordinates as a basis, the integrated point cloud was

transformed into a uniform system established from laser station measurements.

3 Results

All deformations were determined in reference to measurement 0. The results achieved after making calculations included:

- vertical displacements of the benchmark network outside the skyway,

Photograph 1: A view of the skyway from its western side.

Photograph 2: Stabilisation of outdoor marks.

Photograph 3: The method for stabilisation of control points inside the skyway.

- vertical displacements of the network of control points arranged inside the skyway,

Table 1: Basic details of measurement sessions

	Measurement date	Temperature (deg. C)
Measurement 0	21.07.2017	23
Measurement 1	04.09.2017	14
Measurement 2	10.11.2017	6
Measurement 3	10.03.2018	3
Measurement 4	22.08.2018	27

- horizontal displacements of the network of control points arranged inside the skyway and
- deformations of internal skyway walls.

Vertical displacements of the outdoor and indoor network are detailed in Tables 2 and 3.

The results of the measurements performed with the Ni007 level show vertical displacements of marks within the range of -0.64 to 1.13 mm. The maximum mean error of displacement determination $m_{dz(max)}$ is equal to 0.11 mm, which indicates that the results are reliable. As it transpires from the data presented in Table 2, the maximum displacement occurred in mark no. 8 between the first and third series, with a value of 1.37 mm. Nevertheless, the values of the displacements determined are so small that they could not have had any significant effect on the structural performance and creation of any scratches and cracks. Such behaviour of the foundation might have been caused by changes in soil and humidity conditions occurring in the course of the year-round monitoring.

Measurements of the indoor point network with the use of the TDRA6000 laser station have shown that vertical displacement values for these points in reference

Figure 2: Layout showing the arrangement of control and reference points inside the skyway and in adjacent buildings.

Photograph 4: Adjustment points used in the laser scanning method.

to the initial measurement fall within the range of -1.89 to $+1.39$ mm. The values of mean errors of the determined displacements indicate that they are reliable and support the correctness of the measuring method applied. The maximum displacement was noted for

point no. 5 between the third and fourth series; it was equal to 2.45 mm.

Differences between displacement values for benchmarks fixed to column bases (Table 2) and displacements in points located at the intersection of the skyway floor and extended column axes (Table 3) may be caused by changes in column lengths under the influence of ambient temperature variations. The maximum difference between atmospheric temperatures recorded during the measurements was noted for the third and fourth measurement sessions; it was equal to 24°C . The effect of temperature on structural displacements may be tracked on diagrams in Figure 3. Part C of Figure 3, provided to show the difference between displacements in column bases and tops, presents the structural displacements stripped of the impact of soil and humidity conditions. For most columns (numbered 3 to 12), differences

Table 2: Vertical displacements of outdoor network marks

Mark	Meas. 0–Meas. 1		Meas. 0–Meas. 2		Meas. 0–Meas. 3		Meas. 0–Meas. 4	
	dZ (mm)	m_{dZ} (mm)	dZ (mm)	m_{dZ} (mm)	dZ (mm)	m_{dZ} (mm)	dZ (mm)	m_{dZ} (mm)
1	−0.33	0.03	−0.50	0.04	−0.05	0.09	−0.36	0.03
3	−0.30	0.02	−0.36	0.03	−0.21	0.06	0.05	0.02
4	−0.25	0.03	−0.42	0.04	−0.25	0.08	0.03	0.03
5	−0.64	0.03	−0.46	0.04	−0.32	0.08	−0.45	0.03
6	−0.56	0.03	−0.35	0.05	−0.27	0.10	−0.41	0.03
7	−0.35	0.04	0.12	0.05	0.81	0.11	0.29	0.04
8	−0.24	0.04	0.31	0.05	1.13	0.11	0.34	0.04
9	0.12	0.03	0.71	0.04	0.99	0.10	0.93	0.03
10	0.13	0.02	0.74	0.03	1.08	0.07	0.88	0.02
11	0.06	0.03	0.36	0.04	0.45	0.08	−0.23	0.03
12	−0.08	0.03	0.18	0.04	0.26	0.09	−0.23	0.03

Table 3: Vertical displacements of indoor points

Point no.	Meas. 0–Meas. 1		Meas. 0–Meas. 2		Meas. 0–Meas. 3		Meas. 0–Meas. 4	
	dZ (mm)	m_{dZ} (mm)	dZ (mm)	m_{dZ} (mm)	dZ (mm)	m_{dZ} (mm)	dZ (mm)	m_{dZ} (mm)
1	0.15	0.07	−0.19	0.06	−0.58	0.07	0.18	0.08
2	0.08	0.07	−0.17	0.06	−0.43	0.07	0.18	0.08
3	−0.05	0.07	−0.99	0.07	−1.83	0.07	0.62	0.08
4	−0.09	0.07	−1.13	0.07	−1.76	0.07	0.51	0.08
5	−0.13	0.08	−1.21	0.07	−1.89	0.08	0.56	0.08
6	−0.22	0.08	−1.23	0.07	−1.89	0.08	0.37	0.08
7	−0.01	0.08	−0.69	0.07	−0.90	0.08	1.24	0.08
8	0.17	0.08	−0.50	0.07	−0.55	0.08	1.16	0.08
9	−0.07	0.07	−0.67	0.07	−0.85	0.07	1.39	0.08
10	0.06	0.07	−0.49	0.07	−0.66	0.07	1.33	0.08
11	0.03	0.07	−0.36	0.06	−0.66	0.07	0.37	0.08
12	−0.18	0.07	−0.59	0.06	−0.94	0.07	0.13	0.08

Figure 3: Diagrams of vertical displacements in the surveyed network points for all measurements. (a) Column bases, (b) column tops (intersection of skyway floor and extended column axes), (c) difference between column tops and bases.

between extreme displacement values are similar; they are equal to 2.21 mm on average. Columns 1 and 2 are less susceptible to displacements caused by temperature as they are half as long as the other columns.

Horizontal displacements of control points arranged on the floor inside the skyway are detailed in Table 4 and shown in the form of diagrams in Figures 4 and 5. The errors for Helmert transformation used to determine these displacements are specified in Table 5.

Helmert transformation errors specified in Table 5 indicate that the obtained displacement values are reliable. The maximum horizontal displacements were noted between the third and fourth measurement series, with the displacement along the X-axis for point no. 12 having a value of 6.93 mm and the displacement along the Y-axis for point no. 8 having a value of 3.00 mm. These displacements have arisen from dimensional

changes of the structure caused by temperature variation. They may contribute to structure cracking and scratching to a substantial degree.

The results of the noted horizontal displacements of the floor compelled the authors to carry out more thorough measurements intended to determine the nature of deformations in the entire skyway structure. To this end, the course of the third and fourth measurement sessions additionally included measurements with the 3D FARO Focus S150 scanner. Each of these measurements was transformed into a uniform system of coordinates on the basis of six adjustment points whose position was established using the TDRA6000 laser station.

Laser scanning was carried out under radically different temperature conditions (Table 1). An analysis of point clouds obtained from laser scans allowed for the determination of internal structural wall deformations

Table 4: Specification of horizontal displacements of the indoor network

Point no.	Meas. 0–Meas. 1		Meas. 0–Meas. 2		Meas. 0–Meas. 3		Meas. 0–Meas. 4	
	dX (mm)	dY (mm)	dX (mm)	dY (mm)	dX (mm)	dY (mm)	dX (mm)	dY (mm)
1	0.45	0.94	0.50	0.30	0.97	−0.07	−0.29	−0.50
2	0.44	0.86	0.72	0.06	1.17	−0.40	−0.23	−0.41
3	0.17	1.18	0.14	−0.41	0.23	−0.83	0.04	−0.72
4	0.24	1.13	0.31	−0.58	0.38	−1.01	0.08	−0.59
5	−0.35	0.77	−0.82	−0.66	−1.51	−1.78	0.47	0.04
6	−0.34	0.66	−0.81	−0.82	−1.27	−1.99	0.49	0.17
7	−0.87	0.19	−1.81	−1.37	−2.74	−2.54	0.95	0.15
8	−0.83	0.11	−1.67	−1.50	−2.64	−2.78	1.22	0.22
9	−1.57	0.19	−2.71	−1.21	−3.60	−1.90	0.82	−0.83
10	−1.69	0.14	−2.80	−1.23	−3.94	−1.84	1.18	−0.72
11	−1.90	0.28	−3.25	−0.10	−4.66	0.01	1.92	−0.60
12	−2.09	0.13	−3.56	−0.34	−5.04	−0.31	1.89	−0.48

Figure 4: Diagram of horizontal displacements of control points for all measurements. **Figure 5:** Diagram of recorded horizontal displacements for three selected control points (M1, M2, M3, M4 – consecutive measurements).

caused by the temperature factor. Exemplary 3D views of the deformations (deviations across the scanned states of the structure) are shown in Figures 6 and 7.

Faro Scene software was used for processing the point clouds. The point clouds were merged and adapted to the coordinate system. A colour deviation map was

Table 5: Specification of Helmert transformation errors

	m_x (mm)	m_y (mm)	M (mm)
Meas. 0–Meas. 1	0.34	0.36	0.49
Meas. 0–Meas. 2	0.47	0.60	0.76
Meas. 0–Meas. 3	0.50	0.73	0.88
Meas. 0–Meas. 4	0.54	0.61	0.81

obtained by comparing both point clouds. To make this comparison, the reference scans were processed into a triangle net. Point clouds were matched using the “cloud to cloud” method. The average matching error between scans ranged from 0.2 to 0.7 mm for the first measurement and from 0.5 to 1.5 mm for the second measurement. The resulting integrated cloud was matched to six reference points. The average matching error was 1.4 mm for the first measurement and 1.7 mm for the second measurement. The internal skyway wall deformation

values obtained fully correspond to displacement tendencies shown by the points on the skyway floor. This is supported by the fact that the skyway structure moves under varying temperature conditions. Adjustment of the point clouds obtained from laser scanner measurements to a frame of reference established by means of a laser station gives a means to analyse the obtained results in a more comprehensive manner.

4 Summary and conclusions

The results of the year-round survey of control points on the structure have revealed that displacements in the studied structure depend on varying soil and humidity conditions only to a small extent. A majority of the displacements observed are determined by changes in the temperature of the structure. Their impact in the

Figure 6: A view of internal structural wall deformations rendered from scans (north-western side of the skyway). **Figure 7:** A view of internal structural wall deformations rendered from scans (south-eastern side of the skyway).

studied period effected vertical structural displacements (detectable on the floor inside the overground skyway) of up to 2.66 mm (2.21 mm on average).

Thermal expansion also causes extensive horizontal displacements in the overground part of the structure. At ambient temperature extremes, the maximum value of displacement towards the skyway main axis reached 6.93 mm (for point no. 12). Due to the specific shape of the structure (geometric deflection in points 7, 8, 9 and 10), transverse displacements were also present – they reached 3.0 mm in point no. 8. The scale of these displacements may be detrimental to the durability of the entire structure.

In addition, supplementary laser scanning enabled determination of spots of particular susceptibility to the effects of deformation. An in-depth analysis of the results in terms of structural engineering may be indicative of actions to be undertaken in order to eradicate adverse effects of the displacements.

The described measurement and result processing technology provides the means to conduct comprehensive analyses of the geometric performance of structures, which in consequence induces formulation of more complete conclusions concerning prevention of adverse effects of displacements and deformations in engineering structures. The obtained results confirm that laser techniques are suitable for monitoring the technical condition of structures and for damage cause analysis.

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