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Original Research Article

ANALYSIS OF CHANGES TO STEEL FOOTBRIDGE GEOMETRY WITHIN 25 YEARS IN SERVICE

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Abstract

Identification of the technical condition of bridge structures should be supplemented by determination of structural displacements in relation to the adopted frame of reference and measurement of changes to the geometry of its individual elements. Of special value are the results of measurements of the same values obtained along an extended service life. They provide an opportunity to compare results, track down tendencies, and more quickly recognise signs of aggravating technical condition of structures.
The paper presents an analysis of changes to the geometry of a bridge structure – a cable–stayed footbridge used for pedestrian and bicycle traffic across the Brda river in Bydgoszcz. Measurements were made by means of surveying techniques within a period of 25 years of the structure service life. The collected data enabled numerous comparative analyses to be conducted. Displacements of footbridge structural elements observed across time led to formulation of recommendations for further use of the footbridge. For instance, recommendations for footbridge adjustment, including improvement of its geometry, were provided. In addition, a general analysis of the effect of footbridge displacements on its static operation was conducted.

Keywords: technical condition of structures, measurements of the geometry of structures

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1. INTRODUCTION

The Building Law Act [8] imposes an obligation on a built structure owner or user to use the structure in accordance with the intended use and environmental protection requirements, and to keep it in proper technical and aesthetic condition. Technical condition of built structures has to be periodically inspected – reviewed. The method most commonly used for structure assessment during such reviews is visual inspection; however, it only enables the evident, plainly visible signs of damage or failure to be diagnosed. Full, accurate, and unambiguous determination of the technical condition of a structure requires an array of tests and analyses to be conducted and can be a difficult and complicated endeavour [1, 3]. Displacement measurement employing surveying techniques is one of relatively simple tests that can provide support while evaluating the technical condition of a structure. The ability to compare displacements in a structure across different periods of its service life is particularly valuable. Correct interpretation of results and translating them into technical condition evaluation requires sufficient engineering expertise combined with an understanding of actual operation of the structure.

In case of new structures or those erected relatively recently, periodic measuring of structural displacements can be scheduled. In order to store the collected data, one can use modern systems, e.g. those using BIM (Building Information Modelling) technology, which serves the purpose of generating and using data about the structure in the course of a full cycle of service [4]. Older built structures generally have not been periodically tested with surveying techniques. Moreover, not all data (including design data) and measurement results have survived to this day, and those that have are often incoherent and, for example, do not enable full comparison of structure condition in different periods.

The subject matter of this paper is a footbridge intended for pedestrian traffic located in Bydgoszcz. Preserved archival technical documentation of the structure and current measurements allowed us to track down its displacement states virtually across its entire service life, i.e. over a span of about 40 years. On the basis of displacement analysis, conclusions regarding technical condition of the footbridge were drawn and recommendations for further use were formulated.

2. ANALYSIS OF SOURCE MATERIALS

The built structure covered by the study is a cable-stayed bridge (footbridge) designed for pedestrian and cycling traffic across the Brda river in Bydgoszcz. Location of the structure in the centre of the city, in the vicinity of the ‘Łuczniczka’ sports, show, and fair arena, makes it very intensively used. The footbridge is a construction with suspended steel structure. It consists of three spans of the following lengths: 8.00 m + 50.0 m + 8.0 m. Extreme spans are placed entirely above the riverbanks and the 50.00 m span is the main span. The footbridge has two intermediate supports placed at the edges of the banks and founded on piles. The upward pulling extreme supports are founded on wells and connected to the span structure with bolts.

Extreme spans of the footbridge were designed as spans freely supported by reinforced concrete supports. The central span consists of eight steel segments, each 5.5 m long, and one central segment which is 6 m long. The segments are connected with joints and suspended on cable stays attached to the pylon top. An expansion joint that enables longitudinal movement has been constructed between the central segment and the right-bank pre-central segment. Steel pylons are inclined toward the central span at an angle of approx. 65° from the horizontal plane and supported by intermediate supports using joints, whereas their heads are connected with extreme supports using stays. Total deck width is equal to 4.10 m and the width between handrails is equal to 3.40 m.

The footbridge was commissioned in 1979. Unfortunately, no archival documentation from that period has been preserved. It has only been determined that the designer of the structure was PhD Tadeusz Kabat. In 1992, the technical condition of the footbridge was surveyed [5], in all likelihood due to observed non–conformities in its operation. That survey pointed to such aspects as minute non–conformities between actual pylon arrangement and the design, permanent displacements in the footbridge (lowering of its segments suspended on cable stays), and permanent closure of the expansion gap between segments. Levelling of the construction was performed twice, on 01.06.1992 and 11.06.1992, as part of the survey. Conclusions and final recommendations suggested, *inter alia*, that the longitudinal profile of the footbridge be corrected by shortening the cable stays (the required values by which particular cable stays should be shortened were stated in the survey). In the same year, a renovation was designed [6], and involved procedures for renovation of the wooden deck, stairs, supports, and the steel structure, among other things. It also briefly referred to the stage of cable pulling. The renovation work was carried out between 1992-1994.

Cable stay adjustment was performed between July and September of 1994. Just before this operation, on 09.07.1994, another precision levelling test of the footbridge longitudinal profile was performed. Instructions for the adjustment of tie rods and longitudinal profile of the footbridge were based on that test [2]. After the tie rod correction work had been completed, precision levelling of the footbridge longitudinal profile was performed on 03.09.1994 [9]. The objective of this measurement was to check if the works that had been carried out had the anticipated effect, i.e. if the footbridge longitudinal profile was corrected properly. Differences observed between the values assumed before the adjustment and the values achieved after the adjustment were specified. Analyses conducted in that survey became the basis for determination of initial design assumptions regarding geometry of the footbridge. The author of the survey had recommended that the next surveying of the footbridge be performed in 2004; however, it was not carried out.

The authors of this paper performed elevation measurements of the footbridge in 2017. Finally research material has been obtained – it included results of the following measurements:

- designed condition of the footbridge (by estimation),
- condition of the footbridge before the renovation of 1992-94,
- condition of the footbridge after the renovation combined with adjustment of the geometry of its deck,
- current condition of the footbridge.

3. TEST RESULTS

The bridge elevation measurements performed on 12.10.2017 employed the trigonometric method with the use of Leica TDRA6000 laser station. The device provides accurate measurement to 1.5" RRR prism that enables determination of vertical displacements with an average measurement error of 0.2 mm [7].

Between 1992-1994, the footbridge was being renovated and adjusted to improve its geometry. The 2017 measurements were performed with reference to technical documentations received from the Municipal Road and Public Transport Administration in Bydgoszcz (in the same points). According to the documents, control points were placed at the outer edges of footbridge spans, above stay cable fixing points (Fig. 1). Points on the left lane of the footbridge were labelled with the letter L, those on the right lane – with the letter P.

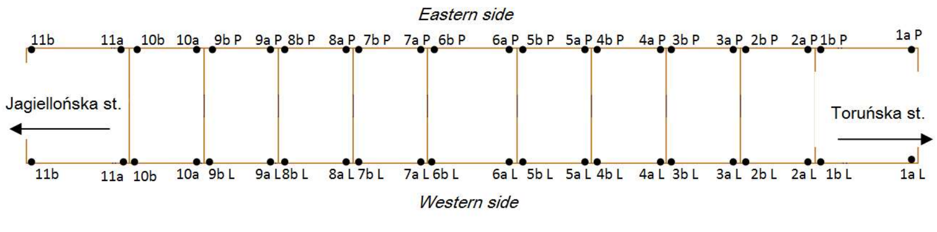

Fig. 1. Plan of control point arrangement

Each point was referred to the benchmark located in the vicinity of point 11bP on a support on the Eastern side. Elevation of the benchmark was assumed to be 37.2800 m.

The paper analyses the results of three measuring sequences. Dates of the measurements and ordinates of the control points for these sequences have been presented in Table 1.

Table 1. Ordinates of bridge control points [m]

Point No.	Abscissa [m]	Measurement 2 1994-07-09		Measurement 3 1994-09-03		Measurement 4 2017-10-12	
		L	P	L	P	L	P
01a	0.95	37.7906	37.7919	37.7911	37.7914	37.7892	37.7917
01b	8.3	37.7840	37.7843	37.7839	37.7841	37.7840	37.7841
02a	9.5	37.7076	37.7160	37.7073	37.7168	37.7058	37.7126
02b	14.12	37.7465	37.7470	37.7548	37.7592	37.7531	37.7555
03a	14.27	37.7461	37.7501	37.7544	37.7623	37.7527	37.7592
03b	19.65	37.8850	37.8797	37.8902	37.8888	37.8855	37.8829
04a	19.76	37.8826	37.8889	37.8872	37.8985	37.8844	37.8926
04b	25.12	38.1014	38.1050	38.1081	38.1105	38.1009	38.1028
05a	25.25	38.1138	38.1152	38.1201	38.1204	38.1170	38.1101
05b	30.53	38.4122	38.4131	38.4252	38.4261	38.4202	38.4211
06a	30.8	38.4205	38.4179	38.4332	38.4310	38.4261	38.4292
06b	36.02	38.3905	38.4005	38.4149	38.4264	38.3988	38.4188
07a	36.15	38.3944	38.3991	38.4203	38.4246	38.4050	38.4141
07b	41.53	38.0992	38.0966	38.1130	38.1149	38.0999	38.1031
08a	41.65	38.0887	38.0961	38.1027	38.1144	38.0891	38.1031
08b	47.02	37.8696	37.8683	37.8810	37.8888	37.8712	37.8818
09a	47.15	37.8666	37.8673	37.8774	37.8881	37.8667	37.8812
09b	52.52	37.7361	37.7263	37.7400	37.7529	37.7326	37.7488
10a	52.64	37.7356	37.7340	37.7385	37.7601	37.7311	37.7560
10b	57.42	37.6883	37.7032	37.6891	37.7065	37.6807	37.7030
11a	58.45	37.7614	37.7679	37.7615	37.7675	37.7594	37.7704
11b	65.85	37.7655	37.7705	37.7654	37.7701	37.7657	37.7725

According to the preserved archival documentation, in places where the cable stays are fixed to platforms, the elevation above chords connecting abutments of the footbridge on both sides is equal to (Table 2):

Table 2. Elevation above the chord

Point No.		Elevation [mm]
Western side	Eastern side	
2aL	2aP	0
2bL 3aL	2bP 3aP	45
3bL 4aL	3bP 4aP	180
4bL 5aL	4bP 5aP	405
5bL 6aL	5bP 6aP	720
6bL 7aL	6bP 7aP	720
7bL 8aL	7bP 8aP	405
8bL 9aL	8bP 9aP	180
9bL 10aL	9bP 10aP	45
10bL	10bP	0

[L = left; P = right]

For the purposes of analyses contained in this paper, values of theoretical ordinates were calculated on the basis of the values stated above, and then the differences between measured ordinates and theoretical ordinates were calculated. Values of these differences for measurement 2 and 3 were shown in Table 3. Their graphical representation was shown in Figure 2 and 3.

Table 3. Difference between measured ordinates and theoretical ordinates [mm]

Point No.	Measurement 2 (1994.07.09)		Measurement 3 (1994.09.03)	
	L	P	L	P
01a	-	-	-	-
01b	-	-	-	-
02a	0.0	0.0	0.0	0.0
02b	-4.2	-12.8	4.3	-1.6
03a	-4.6	-9.6	3.9	1.5
03b	1.5	-13.6	6.8	-5.8
04a	-0.9	-4.4	3.8	3.9
04b	-4.9	-11.8	1.7	-7.9
05a	7.5	-1.6	13.8	2.0
05b	-6.9	-17.3	5.9	-6.2
06a	1.5	-12.4	14.0	-1.2
06b	-26.4	-28.4	-2.3	-4.7
07a	-22.5	-29.8	3.1	-6.5
07b	-0.5	-15.8	12.9	0.0
08a	-11.0	-16.3	2.6	-0.5
08b	-2.9	-17.7	8.0	0.1
09a	-5.8	-18.6	4.4	-0.6
09b	0.8	-23.2	4.0	0.3

10a	0.4	-15.5	2.6	7.6
10b	0.0	0.0	0.0	0.0
11a	-	-	-	-
11b	-	-	-	-

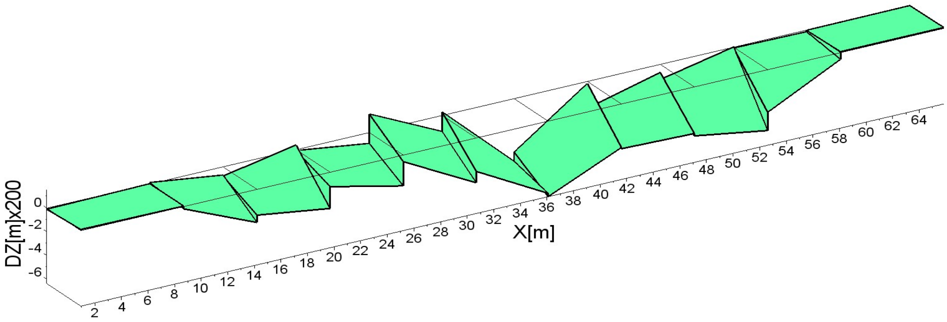

Fig. 2. Graphical representation of differences between the measured ordinates and the theoretical ordinates for measurement 2

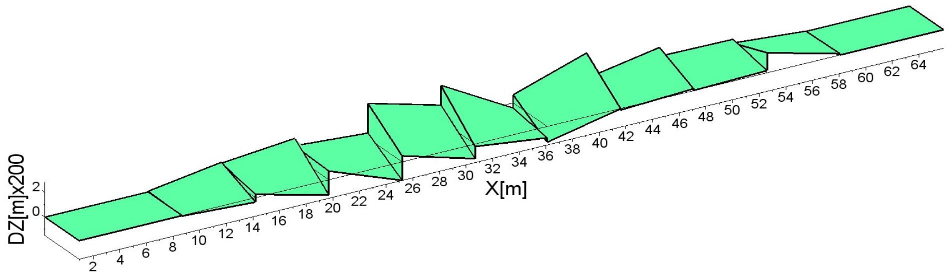

Fig. 3. Graphical representation of differences between the measured ordinates and the theoretical ordinates for measurement 3

Values of ordinate differences for measurement 2 showed that there are divergences relative to the geometry assumed to be theoretical. Therefore, bridge geometry was corrected after this measurement, and a third, control measurement was performed after the correction. Analysis of ordinate differences for measurement 3 shows significant improvement in bridge geometry after its correction. It is notable that the correction of geometry in points with significant divergence from the theoretical geometry negatively affected neighbouring points. However, values of these differences are visibly lower from those from before the correction.

The bridge geometry had not been tested between measurement 3 and measurement 4 (a period of 23 years). In order to check how the bridge geometry had changed during these years, difference between the measured ordinates was calculated (Table 4). A graphical representation of the change in ordinates measured in measurements 3 and 4 was shown in Figure 4.

Table 4. Difference between ordinates measured in measurement 3 and 4 [mm]

Point No.	Difference between the measured ordinates [mm]	
	L	P
01a	-1.9	0.3
01b	0.1	0.0
02a	-1.5	-4.2
02b	-1.7	-3.7
03a	-1.7	-3.1
03b	-4.7	-5.9
04a	-2.8	-5.9
04b	-7.2	-7.7
05a	-3.1	-10.3
05b	-5.0	-5.0
06a	-7.1	-1.8
06b	-16.1	-7.6
07a	-15.3	-10.5
07b	-13.1	-11.8
08a	-13.6	-11.3
08b	-9.8	-7.0
09a	-10.7	-6.9
09b	-7.4	-4.1
10a	-7.4	-4.1
10b	-8.4	-3.5
11a	-2.1	2.9
11b	0.3	2.4

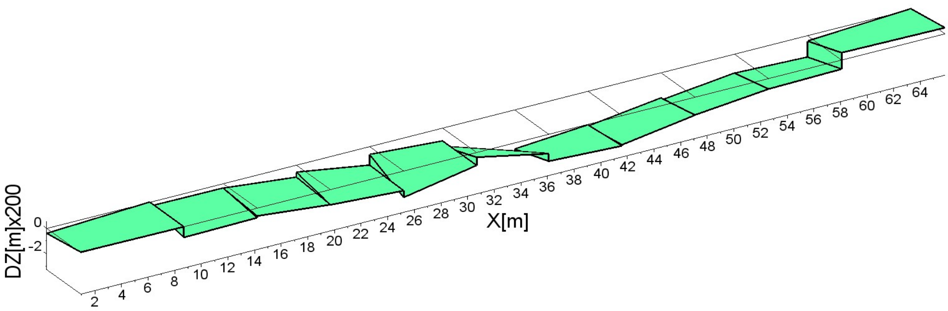

Fig. 4. Graphical representation of the difference between ordinates measured in measurement 3 and 4

Values of the differences obtained are nevertheless half as big again as those during the initial period of service (the years 1979-1992).

While analysing the geometry of the footbridge, one can observe that there is a difference between ordinates measured in points lying in cross sections on its opposite sides, i.e. the so–called crosslevel. In order to analyse this geometrical anomaly of the footbridge, the difference between the crosslevel calculated on the basis of measured ordinates and the one calculated on the basis of theoretical ordinates was determined. This quantity was shown in Figure 5 and marked with the symbol *dp*.

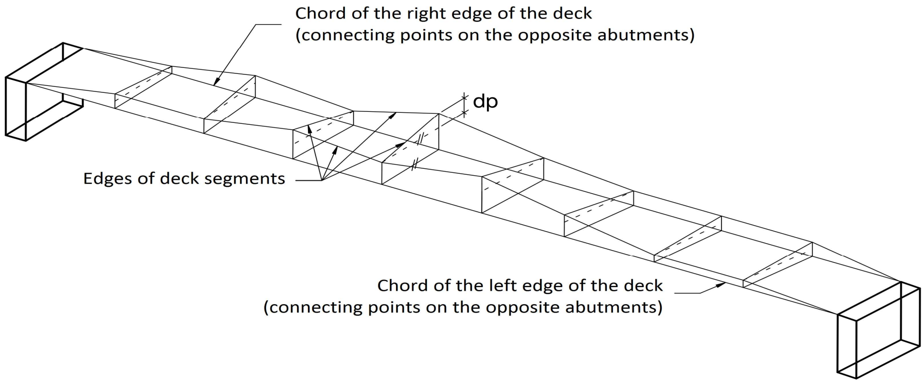

Fig. 5. View of the footbridge with the *dp* quantity shown

Values of *dp* for measurements no. 2, 3, and 4 were shown in Table 5.

Table 5. Difference between the measured crosslevel and the theoretical crosslevel [mm]

Point No.	Measurement 2 1994-07-09	Measurement 3 1994-09-03	Measurement 4 2017-10-12
01a	-	-	-
01b	-	-	-
02a	-0.4	0.5	0.1
02b	8.2	6.4	6.1
03a	4.7	2.9	1.9
03b	14.8	13.1	12.8
04a	3.2	0.4	2.1
04b	6.7	10.2	9.9
05a	8.9	12.3	18.8
05b	10.2	12.6	12.7
06a	13.7	15.8	10.6
06b	1.9	2.9	-4.7
07a	7.2	10.1	6.2
07b	15.3	13.4	13.8
08a	5.3	3.7	3.1
08b	14.8	8.5	8.1

09a	12.8	5.6	4.3
09b	24.1	4.3	4.3
10a	15.9	-4.4	-4.5
10b	0.1	0.0	-0.3
11a	-	-	-
11b	-	-	-

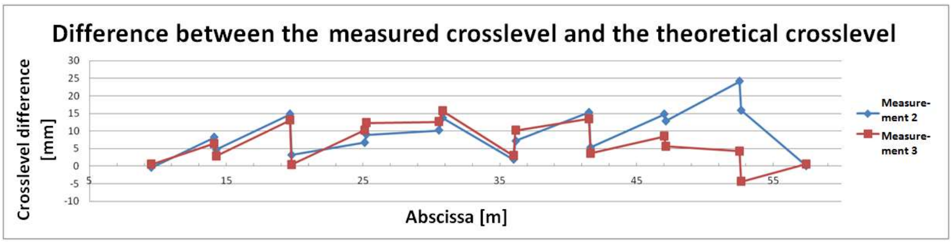

Fig. 6. Difference between the measured crosslevel and the theoretical crosslevel for measurements 2 and 3

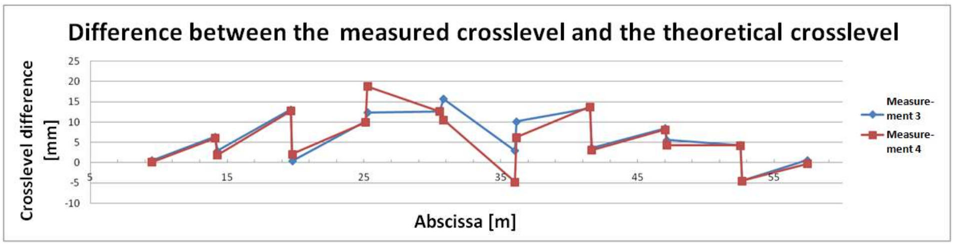

Fig. 7. Difference between the measured crosslevel and the theoretical crosslevel for measurements 3 and 4

Comparison of crosslevels resulting from measurement 2 (before the adjustment) and measurement 3 (after the adjustment) indicates that their change is significant only in the last three segments of the footbridge, at the abutment from the Jagiellońska street side (shown in Figure 6). Changes in crosslevel values along the remaining part of the main span were minor, with similar inclination tendencies being retained.

On the other hand, the charts for crosslevels shown in Figure 7 show that, in the course of the last 23 years (from the adjustment of 1994 to the next measurements in 2017), significant crosslevel changes occurred only in the three middle segments of the footbridge, whereas other segments actually retained their transverse inclination. Of particular significance is the change in crosslevel on the border of segment 3 and 4 (abscissa of ca. 25 m). This might be evidence of loosened connection between these segments or even of its being damaged.

4. CONCLUSIONS

The following conclusions regarding the status of displacements and technical condition of the bridge were drawn on the basis of the conducted analyses:

- Maximum permanent displacements of suspended segments of the footbridge in the period from its construction (1979) to its renovation and adjustment (1994), i.e. in a 15-year period, amount to ca. 30 mm (with unknown errors in construction omitted). Maximum permanent displacements from the time when the footbridge had been adjusted to 2017 (a period of 23 years) amount to ca. 15 mm. Thus, the largest displacements occurred in the initial years in its service. Such a situation confirms the predictions because it is usually precisely after construction of a structure when the greatest displacements of foundations occur and the structure is 'lying down' as a result of displacements associated with clearances created during assembly.
- The adjustment of cable stay lengths performed in 1994 did not produce results that would agree with theoretical assumptions ([5, 2]). Once the charts presented in Figures 2, 3, and 6 are analysed together, it can be seen that a significant part of the footbridge was raised without changes to transverse inclination (crosslevels) during the adjustment. This phenomenon can probably be explained by high spatial rigidity of the structure of footbridge segments (completely ignored in the analyses conducted in the years 1992-94) that prevented these segments from twisting around the longitudinal axis of the footbridge. The shortening of cable stays from the right side of the footbridge resulted in raising of a large stretch of the entire deck and simultaneous unloading of the cable stays on the left side of the footbridge. Significant rotation of three segments near the abutment from the Jagiellońska street side was probably possible owing to a change in the direction of forces acting on connections between them (due to this, rotation within the range of clearances in bolted joints became possible).
- Over the last 23 years in service, a significant change in crosslevels in the area of the middle three segments of the footbridge happened, *inter alia*. It can be assumed that, following the adjustment performed in 1994, cable stays on the right side of the footbridge were weighed down and the ones on the left side – relieved. Consequently, forces leading to inclination of the deck towards the left side began to act upon the deck structure. The twisting of segment 4 (within the range of abscissae of ca. 25 m to ca. 30 m) and huge change of the crosslevel on the boundary between segment 3 and 4 concluded from Figure 7 may be evidence of weakened segment 4 structure and weakening or even damaging of the connection between segments 3 and 4.

Allowing for the status of displacements and resultant aspects related to the technical condition of the footbridge, the following recommendations regarding its further operation have been put forward:

- Second adjustment of the pull of footbridge cable stays is recommended. While doing this, an approach to the design of this adjustment other than the one used in the years 1992-94 has to be implemented. The predicted effect of the adjustment should be achievement of correct geometry of the footbridge gradeline (as opposed to both of its edges) and equalisation of forces in cable stays. Such an adjustment will restore static operation of the footbridge as initially assumed in the design.
- A technical inspection of the footbridge should be conducted, and special regard should be paid to the structure of segment 4 and the connection between segment 3 and 4.

The case shown in this paper, where footbridge displacements in the course of two dozen years of service have been analysed, enabled formulation of the following general conclusions:

1. Land surveying measurements can and should be used as an aid in determination of technical condition of built structures (e.g. tall buildings or engineered structures). Measurement databases for built structures should be set up and periodic testing programmes should be defined to this end, while the obtained results of measurements should be gathered in structure databases (e.g. within the framework of the BIM technology).
2. Technical condition evaluation of structures on the basis of survey measurements should be preceded by appropriate analyses of the status of displacements (in the case herein displacement differences in time and footbridge crosslevels were taken into account) and must be performed by persons who have wide theoretical and practical expertise in the area of built structure operation.

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ANALIZA ZMIAN GEOMETRII STALOWEJ KŁADKI DLA PIESZYCH W OKRESIE 25 LAT EKSPLOATACJI

Streszczenie

Określanie stanu technicznego obiektów mostowych powinno być uzupełnione o wyznaczenie przemieszczeń konstrukcji względem przyjętego układu odniesienia oraz pomiary zmian geometrii poszczególnych jej elementów. Szczególnie cenne i istotne są wyniki pomiarów tych samych wartości uzyskiwane w długim czasie eksploatacji. Dają one możliwość porównywania wyników, śledzenia tendencji oraz szybszego wychwytywania objawów pogarszania sią stanu technicznego obiektów.
W artykule przedstawiono analizę zmian geometrii obiektu mostowego – kładki wantowej służącej do prowadzenia ruchu pieszego i rowerowego przez rzekę Brdę w Bydgoszczy. Pomiary wykonano technikami geodezyjnymi w okresie 25-letniej eksploatacji obiektu. Zgromadzone dane pozwoliły na przeprowadzenie wielu analiz porównawczych. Zaobserwowane zmiany położenia elementów konstrukcji kładki w czasie pozwoliły na sformułowanie zaleceń odnoszących się do dalszej jej eksploatacji. Podano między innymi zalecenia dotyczące regulacji kładki, w tym poprawy jej geometrii. Przeprowadzono również ogólną analizę wpływu przemieszczeń kładki na jej pracę statyczną.

Słowa kluczowe: stan techniczny konstrukcji, pomiary geometrii konstrukcji

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