Examine changes in geometric parameters of a suspension bridge using various geodetic methods

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Abstract

The main aim of the research was to compare and evaluate the possibility of using different survey methods used to determine changes in the geometry of suspension bridge. Three measurement methods have been tested, ie: (i) tachymetric, (ii) photogrammetric and (iii) a scanning laser (two attempts with various scanners resolution). The above-mentioned methods were tested on the main span of a suspension bridge with a span of 165 m on the Oder River. The scope of the research included measurements of changes in bridge deflection and suspension ropes by the above-mentioned methods during the operation of the conveyor and its staging. The measurements were made with the precise total station Leica TC2002. The photogrammetric method used digital photography, a camera with high resolution, GigaPan EPICPro turntable and Kolor Autopano Giga 3.X software. The combination of the equipment and software allows for precise positioning of rotation axis for the specific set of digital camera plus lens having a constant focus which allows for precise stitching of dozens shots in a vast panorama. The method of laser scanning is a relatively new measurement method allowing to obtain a quasi-continuous spatial representation of the surface of the tested object. The ideal to the research of bridges would be using all three methods simultaneously.

1 Introduction

In order to validate structural specifications, or to provide diagnostic surveys for planning maintenance and modernization of bridges, dynamic and static tests are carried out.

Typical experimental tests are usually carried out using accelerometers, strain, inductive and wireless sensors and levelling (Anigacz & Kokocinska-Pakiet 2014). Installing most of these sensors require direct contact with the structure. However, examining structures can cause accessibility problems, often requiring using scaffolds. That is why, we decided to analyse in this paper three measurement methods intended for non-contact monitoring of the construction displacements. Fast developing measurement techniques, especially geodetic, and in particular the mass measurements, in theory and practice, enable to obtain full information on the structure and changes in the bridge geometry. The authors of the article have a modern technologies, the latest equipment (often prototype-pre-production), the latest software, and adequate knowledge and experience (Kwiatkowski 2014). The interesting way of measuring displacements of bridges using the microwave interferometry method was presented by Beben & Anigacz (2014). Most of researchers (Jauregui et al. 2003, Schofield & Breanch 2007, Tang et al. 2006, Yu et al. 2013) have a classic approach to the

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structure examinations, which means that they put a reference measurement grid outside the tested object and on the object itself. They mark (signalise) points that are measured. Such approach is fully correct in the case of conducting long-term tests. The reference points outside the tested structure allow to determine changes of the bridge structure geometry in the absolute frame of reference comprised of the reference points, with coordinates determined, for instance, using the GPS method. In the first case, we wanted to minimize the preparatory works. It was decided to use well-visible details of the bridge structure as the measurement points. Only for the tachymetry method – as the reference method, a dozen of measurement targets (on magnets) were temporarily installed. In the second case, a few points were signaled by the targets (chessboards) and the spheres on the construction of the bridge and a few points outside the bridge - as reference points. Yu et al. (2013) reported a very interesting comparison of the measurement methods, measurement accuracy, measurement type, bridge type and measurements costs. Tang et al. (2006) compared potential of the tachymetry method and laser scanning in the measurements of bridges. They reported values of the measurement errors on real objects. The main objective of the study was to compare and assess the suitability of different geodetic measurement methods for determination of changes in geometric conditions of the suspension bridge. Information on the change in the shape of the bridge bearing structure under the service load are very important for a number of reasons. Knowing the changes in the structure shape, the correctness of the project assumptions can be evaluated. Besides, the obtained experience can be used in the similar projects. Additionally, after some period of exploitation one can obtain information if the bridge displacements do not exceed the code limit. In the current work, the main span of the suspension bridge of 165 m over the Oder River near Opole, Poland was subjected to the experimental examinations. The following three measurement methods were used: (i) tachymetry, (ii) photogrammetric, and (iii) laser scanning. Every method has some specific properties, more or less useful in measurements of such type. In the article, exemplary results of the measurements of changes in displacements of the main span of a bridge were presented. Advantages and disadvantages of individual methods were also characterised.

2 Short bridge description

The examined structure is a two-pylon steel suspension bridge over the Oder River intended for connecting the “Folwark” marl mine with Gorazdze cement factory with the transport line (Fig. 1). The bridge comprises five spans – four outmost flood spans and the river span. The structure of the transport gallery is suspended with hangers under the main bearing cables distributed over two pairs of pylons.

Fig. 1: View of the bridge from the upper water side.

The pylons are 26.50 m high each, and the total length of the entire bridge structure is 285.00 m. The key structure element of the object is the river span suspended on cables, 165.00 m long in the space of the pylons' axis (Fig. 2). The flood part of the bridge consists of spatial truss galleries of the span of 30.00 m each, with the upper roadway (as extension of the suspended galleries), two on each side of the river span. The bridge was designed as a structure suspended on two steel pylons, through which a set of 2×6 bearing cables of 48 mm diameter.

The pylon, 26.5 m high, rests on the reinforced concrete foundation through steel articulated bearings. The bridge is intended for transporting the limestone output with a belt conveyor placed in the transport gallery. Weight of the output transported through the bridge is 900–1100 Mg/hour, and the speed of the belt conveyor movement was 2 m/s. Generally, in the monitored bridge, no signs of deformation, cracks, nor perforations were observed. Overall rating of the bridge structure according to the field inspection (Janas & Michalak 2008) was "satisfactory".

Fig. 2: The pylon oft he bridge.

3. Research methodology

Geodesy has a high range of measurement methods, from which we need to choose the most useful ones for measuring changes in the deflection value of the suspension bridge of the span of 165 m. One of the most significant factors influencing the selection of the method is the geometric specificity of the bridge. In the analysed case, it is a linear structure with the span 165 m long. The bridge span is significant because the accuracy of determination if the location of the measurement point decreases with the distance. The experimental tests were carried out after forty years of service of the bridge. The bridge displacements were registered during normal service, continuously for 12 hours. On the examined bridge structure, three measurement methods were tested, i.e.: (i) tachymetry, (ii) photogrammetric, and (iii) laser scanning (two cases: two different scanners). Based on this methods, the displacements of the river span of the bridge were determined.

3.1 Tachymetry method

The tachymetry method depends on the field determination of the spatial polar coordinates, i.e. distances and vertical and horizontal angles from the set of chosen directions. Tachymeters are available theoretically measuring the distances with the accuracy of 1 mm and the directions with the accuracy of 0.5’’ (0.15 mgon). The accuracies obtained under the field conditions are usually much lower and oscillate within the range of 1–5 mm for the distances and 3–10’’ for the determination of the directions.

The angular resolution of the measurement device has high significance especially for the identification of details, e.g. edges in the case of big distances (Berenyi et al. 2009, Luhmann & Müller 2007). In the analysed case, the stations of the tachymeter were placed on both sides of the river in order to lower the target lengths, i.e. distances between the tachymeter station and the measurement point. In the presented case the distances did not exceed 100 m (Fig. 3). Despite of such a significant difference between the accuracies obtained in the laboratory conditions and in the field conditions, the tachymetry method is currently the most accurate method of determining the position of the points in space (Luhmann & Müller 2007). The characteristic feature of this method is the measurement’s discreteness. For the studies, the total station TC2002 manufactured by Leica was used and dozen or so different measurement targets (Figs 4 and 5). Calculations of the displacements were conducted using the authors’ programmes (Anigacz & Kokocinska-Pakiet 2014).

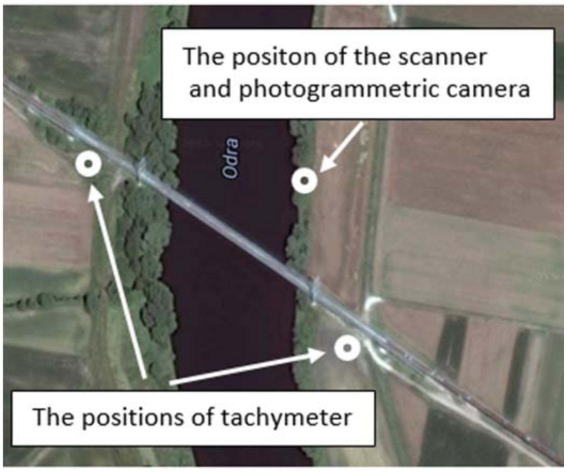

Fig. 3: Placement of the tachymeter measurement stations and the scanner and photogrammetric camera station.

Fig. 4: Tachymeter TC 2002.

Fig. 5: The measurement targets (on magnets) were temporarily installed.

The results obtained with this method were adopted as the reference data for the remaining methods. The correctness of the obtained results of displacements were verified by a measurement from the second station. In order to identify the measured displacements of the bridge, two-sided telemeter targets were used that enabled measurement of the distance from both sides of the target. The measurement targets were placed in the node points of the transport gallery over the transverse beam (Fig. 5).

3.2 Photogrammetric method

In the described case, the Canon 650D camera with the lens of fixed focus of 85 mm and the GigaPano turntable were used to make the pictures (Fig. 6).

Fig. 6: GigaPano turntable with Canon 650D camera with the lens 85 mm.

The level of spherical aberrations, confirmed in the laboratory on the test rectangle (Graph paper 420×297 mm), did not exceed 3 columns of the matrix pixels (5184×3456 pixels). To process the pictures, Kolor AutoPano Giga 4.0 software was used. To calibrate the generated panorama through rescaling for defining the “size” of individual pixel, the Photoshop

CC computer software was used. The Photoshop CC software enables linear rescaling of the pixel size.

To scale the panorama of the bridge to the set pixel size, the characteristic distances were used, which in the studied case were the distances between subsequent segments of the span that previously were measured with the tachymetry method. The photogrammetric method has the following advantages, among others: short time of making measurements (time of taking a picture, sequence), possibility of visualisation with the elements of spatialisation, and possibility of multiple interpretations of the measurement. It is a relatively cheap method, and commonly available. The final analytical data illustrating the effects of the measurement session depend on three main factors:

- resolution of the matrix of the digital camera,
- quality of the optics (resolution, reduction of the spherical aberration),
- software ability of assessing the process of interaction with the user, e.g. in stitching.

3.3 Laser scanning method

Laser scanning method is a relatively new measurement method allowing to obtain the quasi-constant, spatial representation of the area of the examined structure seen in the central view. The accuracy of the results depend mainly on the distance between the scanner and the examined structure. In the last several years, fast development of the laser scanning has been observed (Beshr 2015, Jauregui et al. 2003, Kwiatkowski 2014). Scanner uses a laser beam that, after being reflected from the measured structure, comes back to the scanner. The distance is determined on the basis of a difference of phases of the generated and reflected beam. During the measurement, scanner can be turned by 360 degrees horizontally. Horizontal and vertical angle of the scanner mirror set, information on the measured distance and quality of the reflected signal are calculated in real time into the coordinates. For the bridge experimental examinations FARO Focus 3D X130 (Fig. 7) scanner was used which measures up to 1 million of points per second and allows to create clouds of over a billion of points. The accuracy, declared by the accuracy of the measurement of the distance was ±2 mm, and angle resolution is 0.009° (0.16 billion). The standard unit of resolution is dpi so a dot per inch of the length. In the technical applications where most frequently the elements of the studies structure are located in different distances from the scanner, it is more convenient to use the angle resolution, and not the dpi constantly changing with the change of the distance. Data from a scanner of such type are obtained in the .fls format. Conversion to the .rcs format was conducted with the ReCap360 software. Files with the extension .rcs are read by all the AutoDesk applications. The subsequent scans are fit to characteristic points in such a way that the next measurement sessions would be topologically consistent. This allows for significant lowering of the working time in the field. During elaboration of the results it turned out that in the case of the bridge such approach is incorrect in the first case. The quality of the scan of the bridge span was in the upper limit of the scanner coverage, i.e. 100-120 m. During the analysis of the results, it turned out that the quality (point density) of the scan was too low. In the second attempt the latest scanner Trimble TX8 (Fig. 8) with a greater measuring range than the scanner FARO Focus 3D X130 was used.

Fig. 7: FARO Focus 3D X130 scanner, first attempt.

Fig. 8: Trimble TX8 scanner second attempt.

From the presented measurement methods, the equipment and software connected to the laser scanning is the most expensive. It would be ideal to use three methods at the same time when examining bridges. Then the information on the bridge structure geometry would be a synthesis of all the used methods (Luhmann & Müller 2007).

4. Results and their analysis

Generally, during the measurements, 10 node points were analysed on the bridge's length and the two pylons. It needs to be noted that the tachymetry measurement of dozen or so measurement points was spread over time. Thus, it is most probable that the differences in the values of the deflection were caused by the lack of full synchronisation of measurements conducted with different methods. During results analysis obtained using the laser scanning method (the FARO Focus 3D X130 scanner - first attempt), the displacements were not taken into account due to the lack of their correlation (too high differences) with the results obtained with other methods. One of the more significant reasons of the uncertain results of displacements obtained with the laser scanning was the fact that the suspension bridge has an openwork structure which requires scans of more density than the obtained with the used scanner. The installation of well recognised fixed reference points outside the structure seems more suitable. From this reason, the second attempt was planned with using a scanner with higher resolution (Trimble TX8 scanner), so the obtained results are more precisely and they are more correlated with the results recieved from the photogrametric method.

The results of the displacements for the main span of the suspension bridge for the chosen three measurement points (1/4, 1/2, and 3/4 of the span) are shown in Table 1. The maximum values of displacements did not exceed 72 mm for the tachymetry method and 60 mm for the photogrammetric method. The highest displacements of the bridge were noted in the middle of the bridge span. The obtained maximum values of displacements are significantly lower than the limit value ($l/500$ = 330 mm) according to the bridge standard PN-82/S-10052 (1982) calculated like for the steel road bridges.

Table 1: Comparison of the maximum registered displacements of the bridge.

Measurement method	1/4 of span (mm)	1/2 of span (mm)	3/4 of span (mm)
Tachymetry	49	72	41
Photogrammetric	40	60	30
Laser scanning (I attempt)	*	*	*
Laser scanning (II attempt)	46	60	18

Note: * - results obtained with the laser scanning have been regarded as uncertain (too high discrepancy in comparison to other methods).

Figures 9a & 9b illustrate the results of displacements obtained with the photogrammetric method. For the measurements, well-identified points of the bridge structure were chosen. The analysis of the obtained results consisted of overlapping two photographs. The first one was taken without the load – stopped belt conveyor with no output, and the second one shows the overlap of two sequences of photographs – without the load and with the service load. On the joint picture (Fig. 9b) one pixel was scaled to 10 mm, and then it was calculated by how many pixels the measured elements were shifted against one another. In effect, quite accurately, the change in the deflection of the bridge under the influence of the service load – belt conveyor with the output (weight ranging from 900–1100 Mg/hour) moving with the speed of 2 m/s, was determined. As a result of the conducted measurements, the bridge displacement values obtained with the photogrammetric method are from 16 to 27% lower than those obtained with the tachymetry method.

5 Final conclusions

As a result of measurement of the suspension bridge of the main span of 165 m under in-service conditions, conducted with three various methods: tachymetry, photogrammetric, and laser scanning, the following conclusions can be drawn:

Fig. 9: The analysed detail in 1/2 of the bridge span: **a)** without load, **b)** overlap of two sequences of photographs (without and with load) showing the scale of the bridge displacements.

1. The greatest displacements of the bridge obtained using the tachymetry method were observed in the middle of the span and were 72 mm. The maximum displacements of the bridge created as a result of the influence of the service load need to be considered relatively small. They were significantly lower than the limit value for the bridge-type in every case. Based on the photogrammetric method, the results obtained for the values of the bridge displacements were underestimated in comparison to the tachymetry method (in the case of this bridge 16–27%).

2. The laser scanning method (first attempt) proved to be the least accurate in the case of this bridge. It was a result of too high distance from the bridge and too little resolution of the scanner (points density). The second attempt with the laser scanning method using with higher resolution scanner allowed to identify details such as: edges or elements of the circular section more precisely. Finally, the bridge displacements were identified and they are correlated with results obtained form the photogrametric method.

3. The best solution for the bridge testing is the use of these methods (tachymetry, photogrammetric and lasser scanning) simultaneously in order to fulfil the quality requirements. In this way properly accurate information on the subject of displacement of certain measurement points would be obtained. Such approach would make full synchronisation of measurements possible, however, such measurements are difficult to perform from the practical point of view.

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