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Orginal Article

Accuracy of bridge span measurements using classical and GNSS methods

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Abstract: The primary objective of the authors was to measure the deflection of a bridge span using two different methods and to draw conclusions from the analysis of the results. The Millennium Bridge in Wroclaw was selected as the test object. The bridge was surveyed using both classical geodetic techniques (tacheometry) and a static Global Navigation Satellite System (GNSS) survey. Due to the requirements of both surveying methods, it was necessary to establish a control consisting of five points. Three of these were located on the bridge and were used for displacement measurements, while the other two points were used for control. The article describes the field and office work, considering the measurement process and its analysis. Based on the results, the application of these techniques yielded different values, which influenced their final interpretation. The displacements in the Up, East, and North components are 0.013, 0.011, and 0.032 m by the GNSS technique and 0.002, 0.015, and 0.002 m by tacheometry for the P1, P2, and P3 points, respectively. Furthermore, in the case of the static GNSS measurement, the errors for each displacement did not indicate that any of them was significant according to the three-sigma rule, calculated in relation to the value of each component or point. However, the classical method showed that the displacement at point P2 is significant and is the only one that could have a real impact on the use of the bridge. The result also confirms that a combination of different geodetic technologies, both classical and GNSS, can be effectively used for monitoring cable-stayed bridges.

Keywords: static GNSS measurement, deflection measurement, tacheometry, bridge spans

1. Introduction

For centuries, bridges have been an indispensable part of communication and transport. However, not many people are aware of their significance [1]. In the simplest terms, a bridge is a structure that enables people to cross to the other side of a water body. When designing a bridge, the creators aim for the longest possible service life while also considering the influence of various factors that may cause potential damage or deformations. This is why it is so important to conduct measurements of the main elements in a bridge's structure, such as spans.

Currently, the most accessible and advanced method for evaluating bridge conditions is surveying using Global Navigation Satellite System (GNSS) is used in many engineering applications [2-3] and currently is the most accessible and advanced method for evaluating bridge conditions [4-5]. The study [6] implemented a new strategy of multi-GNSS monitoring on the Severn Bridge in the United Kingdom to explore the impact of the multi-GNSS solution on estimating the amplitude and frequencies of the bridge. Advanced technologies, such as Terrestrial Laser Scanning (TLS) [7-8] and Unmanned Aerial Vehicles (UAVs) [9-10], are also being used. Researchers worldwide have been testing new solutions for years. The study [11] evaluated and compared the effectiveness of three geodetic measurement techniques – tacheometry, photogrammetry, and laser scanning – for the dynamic testing of a 165 m suspension bridge on the Oder River in Poland. A robotic theodolite was used for the first time to measure the deflections of a short-span bridge in response to passing trains on the historical Gorgopotamos Bridge in Greece [12]. This investigation confirmed the apparent displacements and demonstrated that theodolites can be used for monitoring the dynamic displacements of bridges. There have been suggestions to use the Real Time Kinematic (RTK) technique [13-15], the Precise Point Positioning technique [16-18], or the integration of RTK and Post-Processing Kinematic surveys [19]. Furthermore, GNSS observations have enabled researchers to conduct new experiments concerning high cut-off elevations [20], relatively innovative low-cost GNSS receivers [21], or the addition of sensors such as accelerometers [22-23].

The appropriate approach to establishing the receivers on the examined object can result in obtaining a wide range of data, which then serves as the basis for analysis [24]. To date, the structural health monitoring of bridges using GNSS has evolved from continuous displacement monitoring to the identification and monitoring of dynamic features, or both [25]. The data obtained have been used to examine the displacement volume of the bridge span and the stability of the structure. In addition to the methods previously mentioned, it is also possible to utilise classical methods such as photogrammetry or tacheometry [26-27], which were used in this study.

The aim of this work was to study the results obtained from geodetic measurements of bridge span deflections. Therefore, the fieldwork included surveys conducted under conditions of heavy road traffic (during traffic jams) as well as when the traffic was minimal. These two situations allowed us to calculate coordinates and differentiate them to obtain horizontal and vertical displacements. The Millennium Bridge in Wroclaw was selected as the object of study. The bridge is part of national road no. 5 (Fig. 1).

Two points were established during the control survey beyond the bridge to serve as stations for the tacheometer and the reference GNSS receiver. A static GNSS survey and tacheometry were conducted on the previously marked points on the investigated structure. Conducting measurements using two entirely different methods allowed the authors to compare the results and determine whether there were any differences in the obtained coordinates, and if so, the extent of those differences. Consequently, it will be possible to assess the applicability and effectiveness of using a specific method for the Millennium Bridge or similarly sized cable-stayed bridges.

Fig. 1. The Millennium Bridge, viewed from the west side. *Source*: own study

2. Methods

The Millennium Bridge, located in Wroclaw, was officially opened in 2004 and has since been a key communication route for the city. The bridge carries two two-lane carriageways and two pedestrian/cycle paths. The total length of the structure, including the access flyover, is approximately 973 m. The bridge was constructed using three techniques: as an overhanging bridge, a cable-stayed bridge, and a left-bank flyover. The 325 m long, seven-span flyover consists of spans measuring 40 m and 6 × 47.50 m. The overhanging bridge extends 357 m with spans of 67 × 2 + 47 + 50 + 126 m. The 290 m long cable-stayed section, on the other hand, includes spans with lengths of 68.50 × 2 + 153 m [28]. From a technical standpoint, the bridge also features two 50 m high reinforced concrete H-shaped pylons, rising approximately 33 m above the level of the bridge deck. Suspension cables were installed at 10.55 m intervals (Fig. 2). The Millennium Bridge in Wroclaw is particularly significant as it is the first large concrete cable-stayed bridge in Poland.

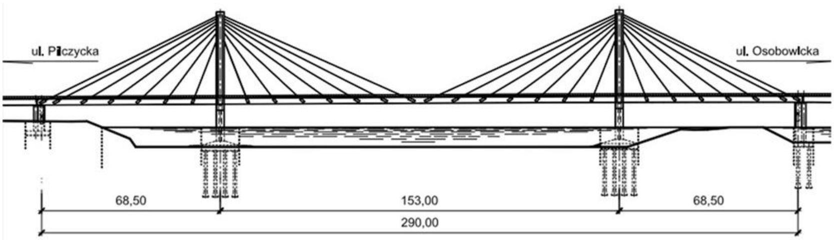

Fig. 2. Side view of the Millennium Bridge. *Source*: [29]

The work was divided into four parts:

- preliminary work, which involved selecting a measurement object, understanding its characteristics, and conducting a literature review related to the subject of the study;
- fieldwork, which initially included preparing for a field survey and developing a survey plan that covered, among other things, the location of points on and off the bridge;
- tacheometric and static GNSS measurements using a Nikon XF tacheometer (with 1" angular accuracy and 1 mm + 1.5 ppm distance accuracy) and four Leica GNSS receivers: GS14, GS15, and 2xGS18 (GPS and Galileo);
- development of results and their graphic visualisation.

During the preliminary work, it was first essential to analyse all bridge structures located in Wroclaw. After making the final decision on the bridge to be studied, the authors needed to familiarise themselves with the specific characteristics of the chosen bridge. Next, the distribution of measuring points was planned, along with the duration of the survey. The fieldwork was conducted on 26-27 October 2022, in two stages. The first stage, on 26th October, involved marking out the measuring points on the bridge and establishing control points. The control points located near the bridge were measured using a static GNSS survey, which lasted one hour. For this, Leica GS18 and GS15 receivers were used. For the survey on the following day, the reference receivers were set up at the OSN1 point, and the tacheometer station was established at the OSN2 point (Fig. 3). The selection of the OSN2 point for linear-angular measurements was based on its ability to provide good visibility to all points of the network over relatively short distances. The P2 point was established midway between the pylons, where the largest displacements were expected. The P1 and P3 points were marked out approximately 5 metres from the pylons to avoid a high level of horizon coverage. Since the distance to points P1-P3 ranged from 100 to 200 metres, the a priori accuracy of determining the coordinates of one measurement from the Nikon XF tacheometer was estimated to be 3-5 mm in plan and 5-10 mm in height.

Fig. 3. Distribution of points in the field. *Source:* Google Earth

On the second day of the survey, GNSS measurements and tacheometry were conducted under both fully and partially loaded bridge conditions. In this article, the term "unloaded" will be used to refer to the partially loaded condition when traffic on the bridge was minimal. Before starting the static survey, when it was observed that traffic was increasing, measurements were taken at points on the bridge (Fig. 4). Following this, the receivers were set up at the three points on the bridge and at the OSN1 point, and they were started synchronously. After less than an hour of surveying, it became apparent that traffic was suddenly decreasing, so it was decided to continue the measurement session without turning off the receivers and to split the observations during post-processing according to the traffic conditions visible on the road. Ultimately, the measurement of the loaded bridge took 60 minutes, while the unloaded bridge measurement took 30 minutes. After switching off the receivers, traffic remained minimal, allowing for tacheometry survey under unloaded bridge conditions.

Fig. 4. From the top left points: OSN1, OSN2, P1, P2, and P3. *Source*: own study

The GNSS survey was processed using RTKLiB software [30], utilising GPS observations for the points beyond the bridge and GPS + Galileo observations for the points on the bridge. Initially, only GPS was used for the calculations, but due to horizon obstructions on the bridge and the resulting data quality for the points located there, it became necessary to add another satellite system for these three points to achieve the highest possible percentage of fixed solutions. Ionosphere and troposphere models were also applied. Since the OSN1 point served as a reference for the points on the bridge and the OSN2 point was the station for the tacheometer, it was necessary to calculate the coordinates of these points in relation to the WROC station, located approximately 5.5 km from the measured object. The study utilised the following files: navigation messages, antenna calibration models (igs14.atx), and precise orbit and clock products from the Centre for Orbit Determination in Europe (CODE) (Fig. 5).

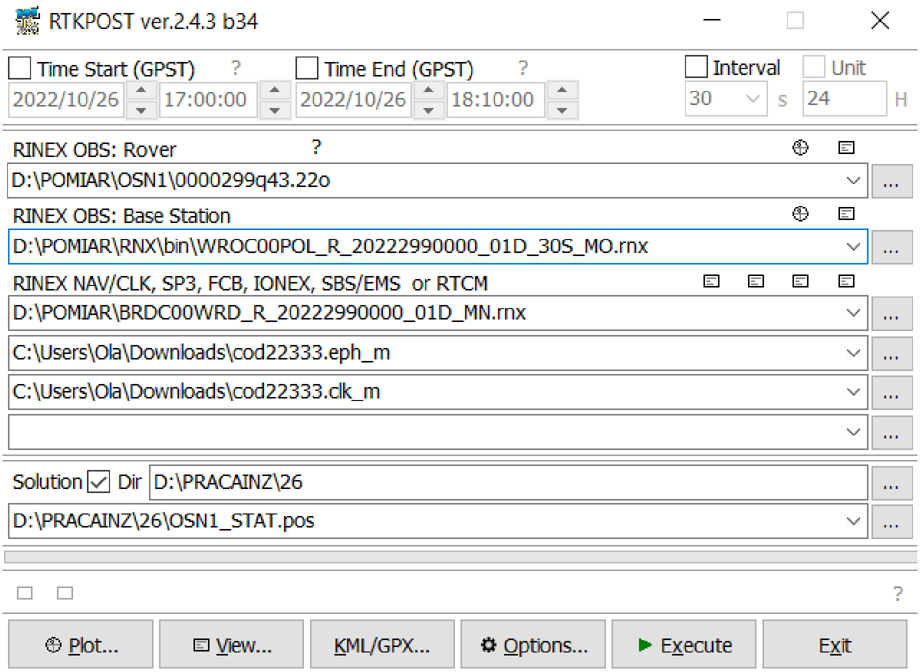

Fig. 5. Input files for the OSN1 point. *Source*: own study

The computations were performed in static mode using the L1 frequency and a 5° cut-off angle. Additionally, the filtration type was set to *Combined* mode, and the ionosphere correction was chosen as *Broadcast*, utilising the Klobuchar model. The troposphere correction was set to *Estimate ZTD*, allowing for a more precise estimation of the tropospheric layer. In the section concerning satellite ephemeris and clocks, it was necessary to select the *Precise* option due to the uploading of precise products in the main window. Finally, the integer ambiguity resolution was set to *Continuous* mode.

3. Results

After calculating the coordinates of the OSN1 point from both days, no divergence was observed that could suggest any errors in the survey or the post-processing procedure.

Therefore, it was decided that the position of OSN1 could be reliably used as the reference for the points on the bridge. Due to the proximity of the pylons, an elevation mask of 15° was applied, and the filtering type, as well as the troposphere and ionosphere corrections, were set as they were for the static calculation. However, in this case, the L1 + L2 frequencies and both the GPS and Galileo systems were used, and the integer ambiguity was resolved using the *Fix and Hold* mode, which proved to be more effective for analysing kinematic studies.

The coordinates were transformed into the PL-2000/18 system, while the heights were kept in the ellipsoidal system. The software reports provided essential information for each point and method, including position error m_p, mean alignment error m_0, and height error m_h. Table 1 includes a set of coordinates for both methods and the differences between them for the loaded bridge. As shown at the bottom of the table, the smallest differences between the coordinates obtained by the two methods were calculated for point P1, with values of 0.3 cm and 0.2 cm, except for the height coordinate, which showed a difference of 21.7 cm for the X, Y, and h coordinates, respectively. In the case of P3, the differences are larger, with the greatest discrepancy being in height – 21.5 cm. The largest differences were observed for P2, with values ranging from 21.9 cm to 128.5 cm. Such large discrepancies are most likely due to the placement of P2 (in the middle of the span, where the changes are the most dynamic) and the time shift between the two measurements.

Table 1. Coordinates of points for the loaded bridge

Method	Coordinate [m]	Point number		
		P1	P2	P3
GNSS	X	5667041.933	5667004.531	5666966.110
	Y	6429555.884	6429497.513	6429438.327
	h	166.112	165.897	165.492
Tacheometry	X	5667041.936	5667003.717	5666966.086
	Y	6429555.846	6429496.228	6429438.339
	h	165.895	165.678	165.277
	Difference [cm]			
	X	0.3	81.4	2.4
	Y	0.2	128.5	1.2
	h	21.7	21.9	21.5

Table 2 contains a set of coordinates for all points and both methods, along with the differences between them for the unloaded bridge. As can be seen, the differences for each point and coordinate are fairly consistent. The differences for each coordinate do not vary significantly when compared to other points. The largest difference between measurement techniques is observed for P2 in the height component. Additionally, the greatest difference between points also pertains to the height component, with a value of 4.2 cm (P2-P3).

Depending on the measurement method, the results differ, most likely due to a time shift between the tacheometric and GNSS measurements. Based on the coordinates obtained for each method and bridge loading, it was possible to calculate the displacement vectors. Fig. 6 provides a graphical interpretation of the horizontal displacement results, along with error ellipses for each measurement method (top part – GNSS, bottom part – tacheometry).

Table 2. Coordinates of points for the unloaded bridge

Method	Coordinate [m]	Point number		
		P1	P2	P3
GNSS	X	5667041.929	5667004.529	5666966.109
	Y	6429555.886	6429497.512	6429438.324
	h	166.099	165.886	165.460
Tacheometry	X	5667041.957	5667004.487	5666966.086
	Y	6429555.836	6429497.453	6429438.366
	h	165.893	165.663	165.279
	Difference [cm]			
	X	2.8	4.2	2.3
	Y	5.0	5.9	4.2
	h	20.6	22.3	18.1

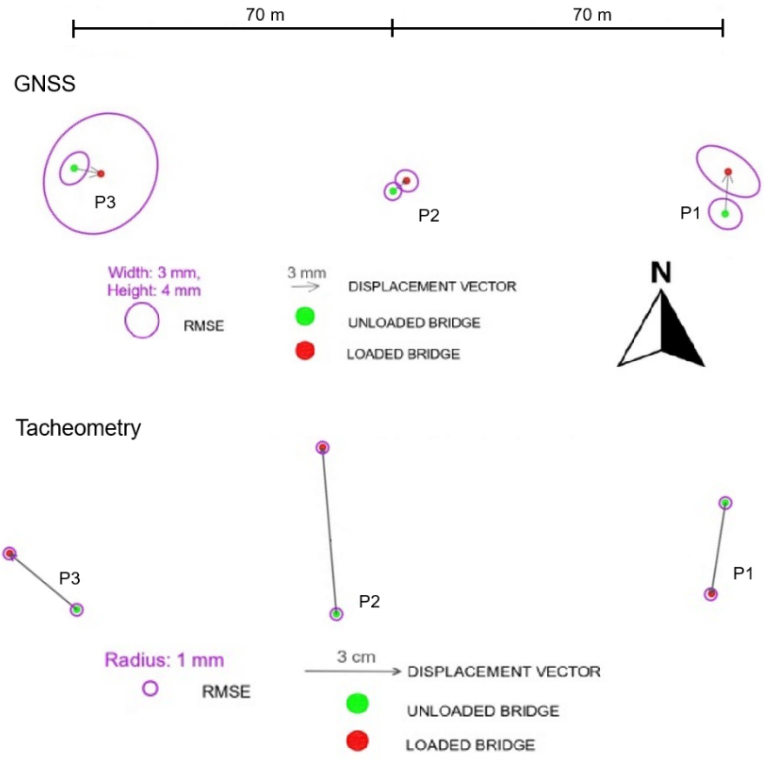

Fig. 6. Horizontal displacements by GNSS (top) and tacheometry (bottom). *Source*: own study

In the next step, similar to the horizontal coordinates, it was possible to calculate the vertical displacements and their associated determination errors. The displacements were obtained by calculating the differences between the coordinates on the loaded and unloaded bridge. However, to calculate the errors of the displacements, it was necessary to perform calculations based on the propagation of uncertainty (Gaussian formula):

$$m_{dh} = \sqrt{\left(\frac{\partial dh}{\partial h_1}\right)^2 m_{h_1}^2 + \left(\frac{\partial dh}{\partial h_2}\right)^2 m_{h_2}^2} \quad (1)$$

To assess the significance of the displacements, it is necessary to check whether the displacements at the points exceed three times the error of their determination. This approach allows for a more detailed analysis that reveals the characteristics of the structure. As observed in similar measurements, for the tacheometric method, the largest displacement occurred at point P2, located in the centre of the span. However, after processing the GNSS measurements, it became apparent that the largest change occurred at point P3, which also exhibited the largest RMS error, indicating a low level of confidence in the result obtained. Point P1 also showed larger RMS errors, though not to the same extent as P3 (Fig. 6, top).

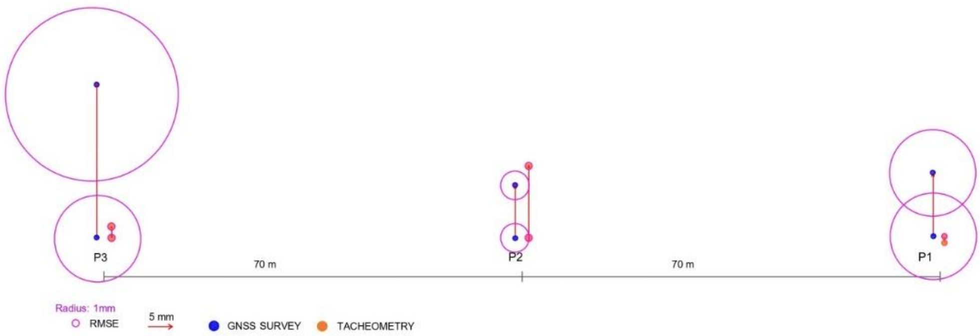

Fig. 7. Comparison of calculated vertical displacements for both methods. *Source*: own study

Overall, point P2 is the only one that shows similar displacements for both methods. Errors remain at 1 mm for the tacheometric method and 10 mm for the GNSS method. Furthermore, the calculated vertical displacement was 15 mm using the classical method and 11 mm using the GNSS method (Fig. 7). The ratio of the displacement value to the error of its determination for point P2 was 15:1, indicating that this is a significant displacement and confirming the bridge's vulnerability. Based on studies of a similar nature, discrepancies are evident, likely due to factors such as the placement of the equipment on site, the measurement technique used, the weight of the load, or the specific characteristics of the bridge being tested.

4. Conclusions

The aim of the study is to determine if there are any changes in the Millennium Bridge structure due to the load induced by traffic. Two different methods, tacheometry and GNSS measurements, were employed in the research. Given the requirements of both survey methods, it was crucial to establish control between them. To assess the dynamics of bridge span movement, three points (P1-P3) were chosen on the bridge, while additional points were marked out beyond the structure. The survey was conducted in multiple stages, necessitating a split into two days of measurements on 26-27 October 2022. The marked points near the bridge served as stations for the reference GNSS receiver and tacheometer, allowing for the synchronization of both survey techniques to estimate the bridge's load due to car traffic. Two measurement periods were selected: one when the bridge was heavily loaded with cars, including during traffic jams, and the other when the bridge was almost without cars, representing an unloaded period.

Based on the calculations, a special graphical interpretation of the horizontal and vertical displacements with error ellipses for each measurement method was constructed. The displacements in the Up, East, and North components were 0.013 m, 0.011 m, and 0.032 m using the GNSS technique, and 0.002 m, 0.015 m, and 0.002 m using tacheometry for the P1, P2, and P3 points, respectively. The largest displacement was observed at point P2 when measured by the tacheometric method, which could be considered significant due to the ratio of the displacement value to its error being 15:1. When analysing the other displacements across both measurement methods, they were not significant and had no direct impact on the operation of the bridge. However, the limited duration of the measurements and the methodology employed do not allow for a deeper analysis of the effects of external factors on the structure. To conduct specialised surveys, continuous monitoring of the bridge over several hours or days would be required. Nonetheless, even this short measurement was able to reveal the existing relationship between the structure and its users.

This study further confirms that a combination of different geodetic technologies, both classical and GNSS, can be effectively used for monitoring cable-stayed bridges.

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