Satellite-based techniques for monitoring of bridge deformations

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Abstract. The issues of bridge monitoring using Global Navigation Satellite System (GNSS) are considered. A technology of determining point coordinates by the differential method of satellite observations is discussed. The measuring complex for continuous monitoring of deformations of the bridge across the Malaya Neva River in St. Petersburg is described. The technological scheme of bridge monitoring is developed. The results of observations are presented. The issue of applying global navigation satellite systems in bridge monitoring is investigated. Based on the study results, diagrams of the spatial position of the upper pylon site and the middle of the channel span were drawn taking into account vehicle loads in the test mode and in the full workload mode. Further research directions necessary for forecasting the technical state of the bridge are determined.

1. Introduction

Standards-compliant methods of monitoring building and structure deformations are based on measuring horizontal and vertical displacements by traditional observation methods. When implementing these methods, theodolites, electronic tacheometers and terrestrial photogrammetric cameras are used. The regulatory GOST 24846-2012 document [1] indicates also that determining coordinates of control points is possible by means of global positioning systems (GPS, GLONASS). In this case, the accuracy of determining coordinates of reference points must be no less than the accuracy of the specified class of horizontal displacements.

The article deals with the bridge monitoring using global navigation satellite systems (GNSS) that is not regulated by the GOST.

Global navigation satellite systems are used for automated and continuous monitoring of the state of buildings and structure. These are systems that allow the spatial coordinates of the receiver’s location to be determined by receiving and processing signals coming from a satellite.

Coordinates can be obtained from observations of satellites using the following methods:

1) The absolute method. Coordinates are obtained by receiving a signal from satellites by a single receiver. Coordinates are calculated by the method of crossbearing to artificial Earth satellites, which positions are determined in the satellite coordinate system.

2) The differential method. Reception of a signal from the satellite is carried out by at least two receivers, one of which is located on a reference point with identified coordinates. As a result of
observations at the reference point, corrections for the difference in coordinates calculated from observations and known coordinates are formed. These corrections are transmitted to the receiver located at the designated point. This method provides a real-time solution.

3) The relative method. Simultaneous observations at the reference and defined points are performed with their joint processing. In this method, a defined baseline vector connects the reference and studied points. Both code and phase measurements are performed. The differential and relative methods are an order of magnitude more accurate than the absolute one (errors occur at the level of 1 cm and less). In each of the methods, measurements can be made in the static (receivers are stationary) and kinematic modes (one receiver is stationary, the other is moving). In the static mode, the accuracy is increased due to the accumulation of data at the station. The relative method of coordinate determining by phase measurements is the most accurate and is most often used in geodesy. Measurements in the kinematic mode allow obtaining the movement trajectory of an object with the installed mobile rover receiver. The main advantage of monitoring with the use of GNSS relative to other observation methods is the continuous information collection, which is possible both in real-time and post-processing modes. Classical methods of observing deformations assume measurements at different intervals, for example, every year, every half year, quarterly, monthly, and so on. Observations using GNSS are an alternative to such frequency that is justified by economic, labour and time costs. In addition to the continuity of information collection, the advantage of the satellite method of coordinate determining is the speed of obtaining observation results, high accuracy, small equipment size and independence from weather conditions.

When using satellite equipment to monitor long-term and continuous monitoring of structure deformations, daily or seasonal effects are uniquely identified as a background interference in numerical diagrams, in graphical and tabular expressions. It is very important to choose the data record frequency. For example, the frequency of data recording for high-rise buildings can be very high (first seconds and even fractions of a second), but for dams, it can be much lower (first minutes). It is expedient to use high frequencies to observe dynamic deformations in structures such as tall buildings and bridges with long spans during long-term monitoring. Recording data with a low frequency is better suited for slow and impulsively deforming structures such as a dyke with earth filling or for landslide registration [2]. The accumulated experience of using GNSS to determine deformations indicates that the differential method for determining coordinates is the most effective way to improve the accuracy of measurements. A large number of various methods of differential measurements have been developed and tested to date [3-7].

The absence of clear requirements and recommendations for monitoring of structural deformations using GNSS predetermines the relevance of research aimed at developing a system for observing bridge deformations, which makes it possible to predict its maintenance conditions.

2. Method

Currently, geodetic monitoring of buildings and structures with the use of global navigation satellite systems is becoming more common. As mentioned, the main feature of this observation method is the continuous data collection, allowing one to identify the impact of various factors on the operational characteristics of an object. In this regard, before the commissioning of the bridge over the Malaya Neva River in St. Petersburg (Figure 1), we decided to conduct daily monitoring using satellite equipment in the test mode with and without load. The length of the bridge without access roads is 923 meters, the width is 44 meters, the height of the U-shaped pylon is 44 meters. The objectives of monitoring the bridge were:

– to determine the spatial position of the bridge construction elements and their variation during the day;
– to define geometrical parameters of structural elements and to reveal the reasons for their change;
– to issue a warning to the design organisation in case of exceeding the geometric parameters of the maximum permissible values.

Figure 1. Bridge over the Malaya Neva River in St. Petersburg

During the geodetic monitoring, the spatial position of the satellite receivers fixed to the bridge elements was determined, their transmission, processing and accumulation were conducted in a continuous mode for 24 hours. When designing the monitoring, the experience of similar works during the operation of the Bolshoy Obukhovsky Bridge [8] was taken into account. The structure of the geodetic monitoring system can be divided into two blocks: the Data Acquisition Unit and the Processing and Analysis Unit for Incoming Information. In general, the technological scheme for providing monitoring can be presented in the following form (Figure 2).

Figure 2. Technological scheme of monitoring

This design solution allows receiving, processing and analysing the data continuously and in real time. Differential corrections are formed by a base station module in the form of two receivers installed on the points of the geodetic control network; the corrections are then transmitted to the control receivers via the communication module. The base station operates continuously throughout the monitoring process and includes, in addition to the satellite receiver, a power source and a lightning rod.
A permanently operating base station is controlled by a special software, autonomously and requiring no presence of an operator. Installation points of base stations are selected based on the follow-up requirements: ensuring the stability of the receiver; no obstruction to sky survey; absence of proximate objects, capable of reflecting the signal received from a satellite; absence of proximate devices creating an electric field, in order to avoid interference; availability of a stable power supply source; protection of expensive equipment.

**Figure 3. Arrangement of receivers**

The module of control receivers is represented by a system of satellite receivers fixed at control points and receiving signals from satellites and differential corrections generated by base stations. With their help, changes in the spatial coordinates of the monitored points are calculated. The module also includes a power supply and equipment for securing the receiver. Meteorological sensors collect and transmit the data on the temperature of the air and structural elements, atmospheric pressure, direction and wind speed, humidity. The module also includes equipment for fixing and transmitting information. The video surveillance system will provide data on the traffic flow and will make it possible to compose the dependence of the change in the monitored elements of the bridge on its load.

During the monitoring, the satellite receivers Leica GS14 were used. One control receiver was installed at the middle of the channel span and one was installed at the top of the pylon. Two base stations were installed on two points of the geodetic centre base on different banks (Figure 3). Taking into account the fact that oscillations occur in the span with a high frequency during the movement of vehicles, the measurement epoch of satellite receivers was set to 0.05 s. The epoch of measurements for the pylon was chosen equal to 1 s. Meteorological measurements were carried out with an interval of 30 minutes.

3. **Results**

As a result of post-processing, the coordinates of the points were determined in each measurement epoch from 8.00 a.m. on May 13 to 8.30 a.m. on May 14, 2018, in the local MSK-1964 *St. Petersburg* coordinate system and the *1977 Baltic Elevation System*. The transition to the *Baltic Elevation System* was carried out according to the local model of the geoid created for the object at the stage of exploration for construction. The receivers were turned on at 8.00 a.m. Moscow time. From 9.00 a.m., the first flow of cars was launched at the bridge in the test mode. Since 6 p.m. the bridge was opened for all vehicles. The maximum and minimum values of the coordinates of the control points were detected from the
obtained data (Table 1). The standard deviation of control point position was 3 mm in the plan and 5 mm in height.

**Table 1. Maximum and minimum values of control point coordinates**

| Place of control receiver installation | Coordinates | Maximum, m | Minimum, m | Range of change of coordinates, m |
|---------------------------------------|-------------|------------|------------|----------------------------------|
| Upper pylon part                      | x           | 96682.135  | 96682.067  | 0.068                            |
|                                       | y           | 110890.148 | 110890.103 | 0.045                            |
|                                       | H           | 64.371     | 64.310     | 0.061                            |
| Middle of the channel span            | x           | 96599.614  | 96599.565  | 0.049                            |
|                                       | y           | 110864.090 | 110863.995 | 0.095                            |
|                                       | H           | 20.124     | 19.975     | 0.149                            |

The table shows that the oscillations amplitude of the upper platform of the bridge pylon along the x-axis is 1.5 times larger than in the y-axis and varies within 6.8 cm. The amplitude of the oscillations did not exceed 6.1 cm in height. For the mid-span, the amplitude of the oscillations along the y-axis is almost 2 times greater than in the x-axis and is within 9.5 cm. The fluctuations of the middle of the span did not exceed 15 cm. All values fluctuate within the allowed design standards.

Figure 4 provides the graphs of the dependence of the vehicle load on the position of the controlled structures.

![Figure 4. a – changing coordinates of the upper pylon site during the day; b – changing coordinates of the middle of the channel span during the day](image)

The graphs show that the greatest change in the spatial position of the monitored elements occurs at the time of opening the bridge for general use. The abrupt change in the spatial position of the structures shows that after the impact of the load, the bridge moves towards its initial position.

The obtained data can be used with further forecasting of the technical state of the bridge depending on the workload.

4. **Conclusion**

The issue of the application of global navigation satellite systems in bridge monitoring is investigated. The technology of determining the coordinates by satellite methods is considered. Based on the study results, diagrams of the spatial position of the upper pylon site and the middle of the channel span were drawn taking into account vehicle loads in the test mode and in the full workload mode. The amplitudes of oscillations of the monitored elements are revealed and their conformity to the design is proven.
The study of structure deformations by satellite methods has proved itself sufficiently for the reason that measurements can be carried out continuously in any weather with a high enough accuracy and no large staff of workers is required to analyse the information from the receiver. The market is full of specialised software products able to automatically monitor the state of a facility and notify an engineer on the critical values of the strain indicators, if necessary. The disadvantage of GNSS-based monitoring is the low accuracy of height determining, in comparison with the planned coordinates. The need to use traditional methods of determining vertical deformations comes from the required accuracy of their measurements; this should be calculated individually for each object. Therefore, this drawback is not critical and in some cases, the accuracy can meet the required level. Based on the results, it can be concluded that monitoring using GNSS provides the necessary data for a conclusion on the technical state of the bridge.

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