Seven Years of Structural Monitoring of a Large Steel Cable Stayed Bridge

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Abstract. The bridge including the longest span in Poland is the one built in the years 2002-2005 over the Vistula River in Płock. The theoretical length of the longest span is 375 m. There are two steel pylons standing just between two carriageways and rigidly connected to the steel superstructure of spans. The bridge is equipped with structural monitoring system consisting of 25 sensors. They are: 8 sensors of force in selected stays, 2 inclinometers located on both tops of pylons, 10 strain gauges located on the steel structural members, 3 temperature sensors located inside the main span, 2 anemometers. The records gathered in the data acquisition unit have been being analyzed for the last 7 years. The main goal of installing the monitoring system was checking the structural parameters compared to the design criteria or the hypotheses employed at the beginning of structural analysis, before construction time. The results are now reassuring, anyway several interesting processes and phenomena were observed and recorded. Some of them are presented in the paper and discussed from the point of view of the structural safety and expected service life of the bridge.

1. Introduction

The bridge over the Vistula River in Płock, Poland, was built in the years 2002÷2007. It consists of three sections: the left bank section over the floodplains (585 long), the main section (615 m) – both of them built in the years 2002 ÷ 2005, and the right bank flyover (512 m) built in the years 2006 ÷ 2007. Nowadays, the bridge is a structure with the longest theoretical span in Poland. The main span is 375 m long. The main part of the bridge is a steel cable stayed structure. The structure consists of box spans and box pylons. Single plane of cables, and two column pylons are located in the central dividing strip. The pylons stand out approximately 63 m above the deck level and approximately 80 m above the terrain. The pylons are connected rigidly to the spans; the load from the pylons and from the spans is transferred to the reinforced concrete piers by means of bearings. The total width of the span is 27.5 m. The depth of the span structure is approximately 3.5 m, which form approximately 1/107 of the longest span. The spans are supported by the pylons by means of 56 tendons grouped in 28 pairs [1]. The view of the bridge is presented in Figure 1 and the scheme of the structure of the main section is presented in Figure 2. The figure also shows the arrangement of bearings and the span lengths as well as the location of some of the sensors.

The city where the bridge was built is populated by more than 130 000 citizens. A number of significant industrial plants of strategic economic importance are established there. The bridge is being heavily used as it is only the second river crossing in this region.

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Fig. 1. The bridge over the Vistula River in Płock

2. The description of the monitoring system

The cable stayed bridge over the Vistula River in Płock is a unique structure on the European level in the following respects:
- light box structure of the bridge spans (the mass of the spans with the road surface is approximately 13000 kg/m),
- a single plane of cables that support the spans along their longitudinal axis,
- a significant length of the main span of 375 m, short side spans (2×60 m at both sides),
- upward forces on four out of six supports,
- rigid connection of the pylons with the spans and placement of the whole steel structure (pylons and span together) on the piers by means of high capacity bearings,
- significance of the bridge for the transport network in central part of the country,

Considering the above factors, a decision was taken to implement a monitoring system to the bridge and to assure surveillance of the structure from the moment it was completed.

The monitoring system includes:

- 8 load cells in the selected stays (tendons selected for measurement included the longest ones, the shortest ones and the ones anchored in the spans directly above the piers),
- 10 strain gauges on the steel structure of the main span and on one of the pylons,
- 2 inclinometers on tops of both pylons,
- 3 thermometers measuring the temperature of the steel structure (2 sensors) and the air temperature inside the main span (1 sensor),
- 2 anemometers, one of which is placed over the main span in its mid-length, and the other on top of one of the pylons.

The system also includes indispensable elements such as a computer recording the data, a router for on-line connection via mobile phone network ensuring fixed internet connection, and an uninterrupted power supply device [2].

The system works continuously. The measured parameters are recorded with a frequency of a couple of seconds; it is possible to constantly view the measured parameters as well as to acquire the data from any place through internet connection.

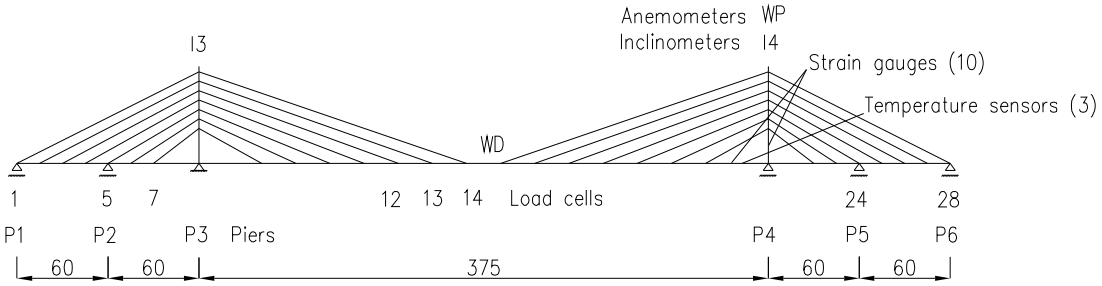

Fig. 2. The scheme of the cable stayed section of the bridge in Płock with the arrangement of the monitoring system elements.

3. The method of data acquisition and analysis

The data are automatically recorded on a hard disk of a computer placed inside the bridge; day, week, month and year files are created. Depending on the type of the file, the record takes place in a cycle of several seconds up to several dozen minutes. The frequency of the records can be adjusted by the system operator. The values of the measured parameters can be viewed at any time by means of the internet connection, or on the spot, inside the bridge. The data can be also downloaded through network connection, remotely, using the mobile phone network or on the spot, using another computer connected to the recording one, inside the bridge.

The data can be viewed by means of an individually designed software enabling reviewing the data acquired from monitoring system. The tool enables calculation of mean values, searching for extreme values, searching for values higher or lower than the declared threshold values. The measurement data are presented in the form of diagrams; it is also possible to automatically print reports. At the current stage of the system development, no procedure has been developed yet to automatically alert the system operator about any transgression of the threshold values. Overview of the key parameters (pylon deviations, force values in tendons) is performed at specific time periods (virtually every couple of days) and the full analysis of data is performed once a quarter and it includes the following:

- the recorded transgressions of the threshold values,
- the tendencies of mean values differences for measured parameters in the medium and long term,
- the values of the environmental parameters (extreme temperatures, extreme values of wind speed – the strongest wind recorded so far was 34 m/s),
- the bridge response to the weather changes (daily and seasonal).

The measurement results are gathered in the monitoring system since the bridge completion time, i.e. 2005. This period has provided a number of observations regarding the following issues:

- the real service and environmental loads,
- long-term phenomena manifested in the values of forces and displacements,
- cyclic phenomena related to the changes of year seasons as well as of day and night.

4. Long-term processes

4.1 General remarks

A number of phenomena have been observed based on the data obtained from the monitoring system. The most interesting ones include:

- long-term persistent changes (reductions) of forces in stays related to the rheological processes,
- gradual displacements of the tops of pylons resulting from autonomous elongation of the stays and settlement of the supports,
- cyclic, seasonal changes of forces in the stays related to the changes of seasons or to the weather changes,
- cyclic, seasonal changes of pylon deviations,
- significant temperature differences between top and bottom slabs of the spans (>15°C).

4.2 Long-term changes of forces in the stays

An interesting, although expected, observation was the reduction of forces in the tendons in the course of time. Figure 3 presents diagrams of mean force values in selected tendons from the period 2005 ÷ 2012, where the force values in individual strands are given on the ordinate. Each stay is created by several dozen strands with equal forces within one tendon. The diagram shows force values in strands in the following tendons: 5, 7, 14, 28. It is noticeable that there is a marked reduction in force values in the initial period of the bridge operation and stabilization of the values in the recent years, although minor changes of force values can be still observed, in accordance with the general downward tendency. The visible increases in the force values in the winter periods 2005/2006, 2009/2010, 2010/2011 are connected with seasonal air temperature drops (or snow cover) resulting in the increase in the force values in the tendons.

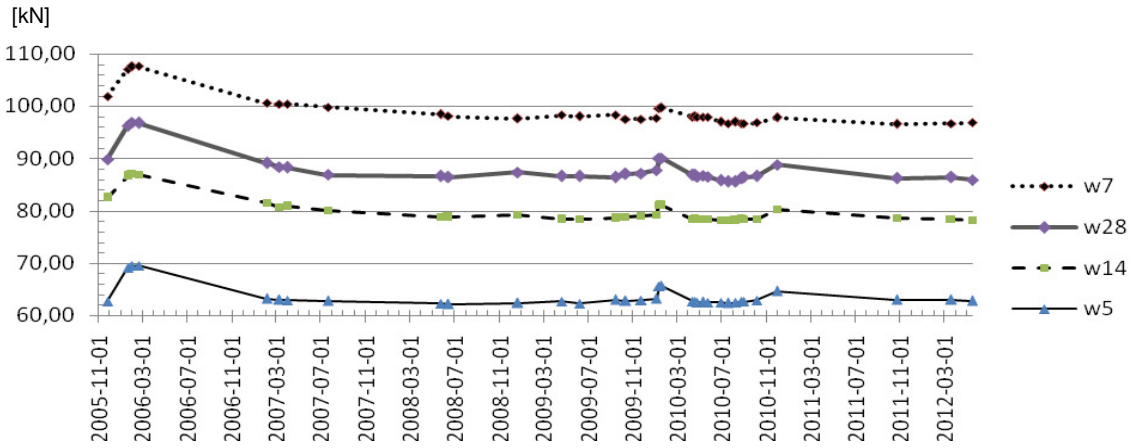

Fig. 3. Changes of the force values in stays in the period 2005 ÷ 2012.

In the case of some tendons, the changes of the mean force values are approximately 4% over a period of 7 years. This phenomenon is not only due to the steel relaxation. The changes in force values are the result of a complex process of force redistribution which is connected, among others, with settlement of piers or with other phenomena. The greatest total settlement of piers is 18 mm and the differences in settlement between the piers are not greater than 13 mm (based on the measurement from 2009).

4.3 Long-term pylon displacement

The system measures the rotation of both pylon tops in the longitudinal plane of the bridge. In terms of the value, the rotation does not mean deviation of the pylons from the exact vertical position, but from the initial position present at the moment of the installation of the inclinometers. The diagrams of the changes of mean values of the rotational position of the pylon tops are presented in Figures 4 and 5.

Over the last few years, gradual changes of mean values of the position (position in the sense of rotation) of the pylon tops have been observed. Assuming that the rotation of the tops of both pylons is approximately equal to the rotation of the structure on the bearings on piers located under the pylons, it can be found that these rotations result in horizontal displacements from 25 mm (pylon P3) to 64 mm (pylon P4). Rotations of both pylons take place in opposite directions, i.e. pylon P3 deviates towards the pier P1, and the pylon P4 deviates towards the pier P6.

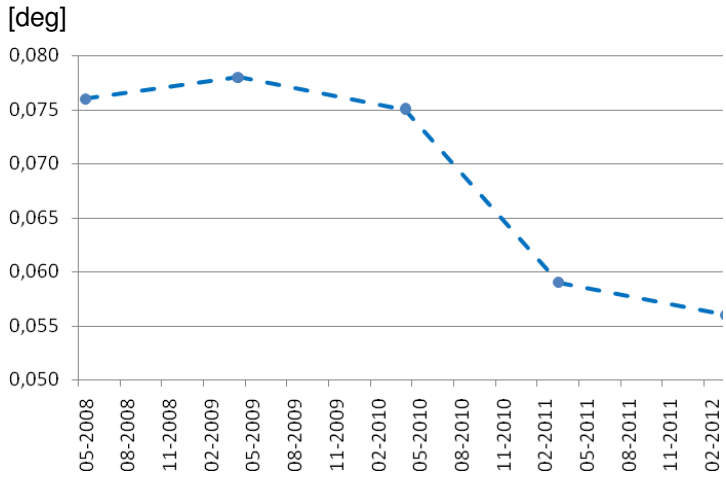

Fig. 4. Changes of rotational position of the top of pylon P3 in the period 2008 ÷ 2012.

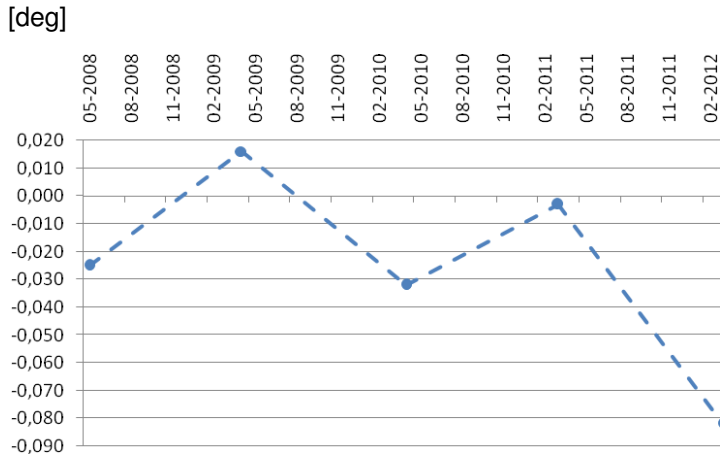

Fig. 5. Changes of rotational position of the top of pylon P4 in the period 2008 ÷ 2012.

The reason for the occurring phenomena is probably the combination of rheological processes taking place in the bridge and its soil bed: steel relaxation and settlement of piers. It should, however, be mentioned that the deviation of pylons is dependent on the seasonal variation: when the seasons change from a warm to a cold one, the pylons deviate away from each other, whereas when the seasons change from a cold to a warm one, the pylons deviate towards each other. This phenomenon is presented in Figures 6 and 7. The horizontal displacements of the pylon tops reach from 20 to 65 mm, based on the assumptions described above.

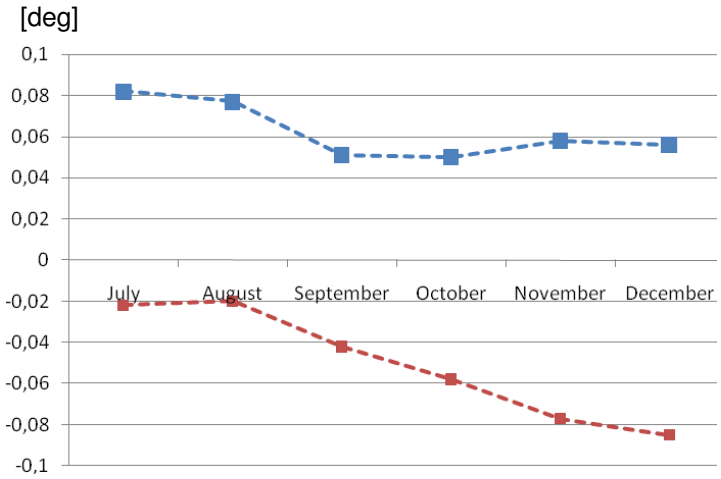

Fig. 6. Changes of the rotational position of the pylon tops in the second half of 2010. The top curve related to pylon P3, the bottom curve related to pylon P4

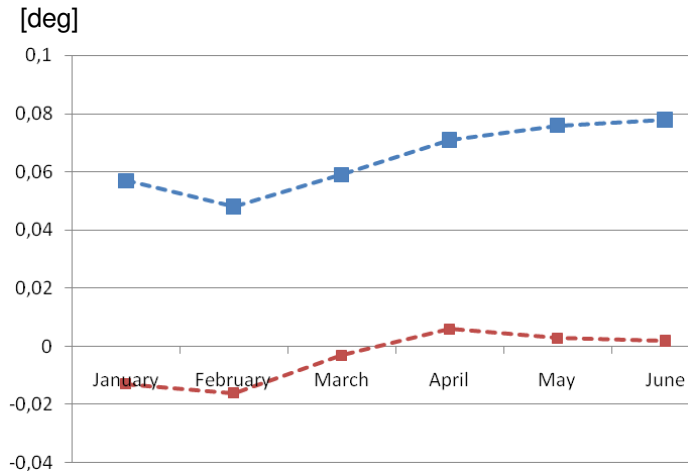

Fig. 7. Changes of the rotational position of the pylon tops in the first half of 2011. The top curve related to pylon P3, the bottom curve related to pylon P4

The phenomenon of rotation of pylon tops overlaps with the phenomenon of thermal longitudinal displacements of the superstructure; however, the observed phenomena are not entirely proportional – they are non-linear.

5. Influence of the observed phenomena on the safety and further operation of the bridge

Considering the measured parameters, in terms of the recorded extreme values and observed tendencies of mean values changes, it should be stated that the safety of the structure is not threatened in any way. The forces in stays were within the assumed scope and the displacements were assessed as acceptable. Emphasis should be put on the fact that the bridge is continuously controlled not only by the monitoring system, but also by way of traditional periodic inspections to which all bridges in Poland are subject. Moreover, selected elements of the bridge are subject to periodic expert inspections – this applies particularly to the cable stays and the tendons anchoring the superstructure in the piers no. 1, 2, 5, 6.

The observed changes of force values in stays as well as pylon displacements will be further investigated. It should be checked whether the processes will decrease, continue or increase, which is a key issue. After the tendency and pace of the changes are

determined, predictions over future safe operation of the bridge can be made. In such a case, the best fitted function according to which the changes occur can be determined and values that the measured parameters will probably reach in the future can be predicted.

For the bridge in question, when the changes in the bridge geometry are confirmed, it will be possible to adjust the forces in stays, since the applied cable stay system (Freyssinet HD2000) enables for the force in the strands to be easily increased. What is more, the applied anchorages enable decreasing the force in the cable stay system.

5. Final remarks

The observations made over a period of several years has enabled formulation of the following conclusions:

- observation of the tendencies of the changes of mean values of selected parameters, e.g. forces or displacements, is of high importance to the assessment of the long-term behavior of the bridge; the probability of a failure or a condition leading to failure caused by design or construction mistake is relatively low, however, these mistakes should be expected in the initial period of operation of a bridge; in the long-term observation, the analysis of the mean values of the measured parameters is most significant,
- performed measurement should be verifiable, i.e. there should be a possibility to verify it by means of an entirely independent method,
- extrapolation of the observed tendencies in the structure's behavior enables easier assessment of the future perspective for operation of the bridge.

The necessity to monitor the corrosion threat, given the fact the superstructure is entirely steel, is a separate issue. Monitoring consists in in-depth observation of the key elements of the bridge; some of the elements should be periodically dismantled in order to check for the presence of water and the degradation processes. If a more complex and versatile monitoring system is used, installation of water sensors should be posited for the most crucial spots, e.g. inside the anchorages of the cable stays.

References

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