Sensitivity and Usefulness Analysis of Simple Monitoring System of a Steel Cable Stayed Bridge

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Abstract. The cable stayed bridge over the Vistula River in Plock, Poland, contains the longest span among Polish bridges, i.e. 375 m. The bridge was therefore equipped with monitoring system consisting of 25 sensors. They are: 8 sensors of force in selected stays, 2 inclinometers located on the tops of pylons, 10 strain gauges located on the steel structural members, 3 temperature sensors located inside the main span, 2 anemometers. The results obtained from the system, which works since the year 2005, were analyzed in terms of sensitivity of the structure as well the sensitivity of the monitoring system to the actions or loads imposed to the structure. The analysis of loads affecting stay forces is presented. Short comment on pier settlement is added. The analyses are performed to answer the question if it is possible to indentify the selected phenomena of behavior of the bridge based on the records from a simple monitoring system.

1. Introduction

In 2007, a bridge located in the middle course of the Vistula River, in Płock, was put into operation. Currently, it is a bridge with the longest theoretical span length in Poland. The main span is 375 m long. The whole river crossing consists of three sections: (i) section over the floodplains on the left bank of the river, stretching over 585 m, (ii) main section 615 m long, and (iii) the right bank flyover of 512 m. The main part of the bridge is a steel cable stayed structure. There are box spans and box pylons, a 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. There is a rigid connection between the pylons and the spans; the load from the pylons and from the spans is transferred to the reinforced concrete supports by means of bearings. There are two carriageways on the deck, each 8.8 m wide, and two sidewalks, each 2.5 m wide. The total width of the span is 27.5 m. The depth of the span structure is approximately 3.5 m. The spans are supported by the pylons by means of 56 tendons grouped in 28 pairs, with the fixed anchorages placed in the pylons and with the active anchorages placed inside the spans. The scheme of the structure is presented in Figure 1. It shows the numbering of the piers and locations of the force sensors and inclinometers. It does not present the arrangement of strain gauges, nor of thermometers, which are placed in the area where pylon P4 is connected to the main span, nor of the anemometers.

Currently, the bridge is being heavily used as it is the second river crossing in a city populated by more than 130 000 citizens, with industrial plants of strategic economic importance, including the largest oil refinery in Poland.

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2. The monitoring system

Considering the shape of the bridge, the light box superstructure, the record span length, significant localization in the country's transport network, it was decided that the bridge needed a monitoring system covering measurement of the forces in tendons, pylons' deviations, trains of the steel structure, temperature of the superstructure and wind speed. In total, the system consists of 25 sensors. It was designed in a way enabling the following actions:

- monitoring of forces in the so called 'anchoring stays' (running from the pylons to the span sections just above the supports, the superstructure is connected by cables to the piers at these locations),
- monitoring of forces in the longest and shortest stays,
- monitoring of deviations of the pylons,
- assessment of the strains of the steel structure within one cross-section of a pylon and one cross-section of the main span,
- measurement of the temperature of the main span,
- assessment of the wind impacts, with the anemometers located on top of one pylon and over the main span, above the deck.

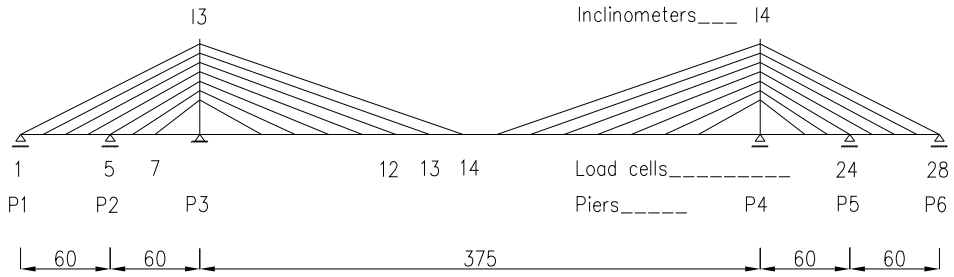

Fig. 1. Scheme of the cable stayed section of the bridge in Płock

3. Remarks and comments regarding a measurement period of several years

The measurement results have been recorded by the monitoring system since the time the structure was completed, i.e. 2005. This period has provided a number of observations regarding the following issues:

- the nature of the real service loads and of the environmental impact on the structure,
- long-term phenomena mirrored in the values of forces and displacements,
- cyclic phenomena related to the change of seasons and day-and-night cycles.

The most significant observations concern the following:

- long-term persistent changes (reductions) of forces in tendons related to the rheological processes,
- gradual displacements of the tops of pylons resulting from autonomous elongation of the tendons and settlement of the supports,
- cyclic, seasonal changes of forces in the tendons related to the changes of seasons and the weather changes,
- cyclic, seasonal changes of pylon deviations,
- incidental, large deviations of the pylons connected with rapid atmospheric phenomena, not infrequent occurrence of strong speed winds (over 20 m/s),
- specific day-and-night distribution of vehicle load of the superstructure,
- significant temperature differences between the top and bottom slabs of the spans (over 15°C)

- significant temperature values of the top slab under the carriageway surface (over 45°C)

Given the values of the measured parameters, it should be stated that there has never been any threat to the structure's safety. In each case, forces in the stays remained within the assumed value scopes, the structure's displacements were assessed as acceptable, although the environmental loads (wind and temperature) were determined as significant; in one case, additional special inspection of the cable system was posited as necessary (after an occurrence of wind speed at 34 m/s).

Considering the large number of data, after the data had been reviewed, it came up as interesting to test whether a more detailed description of the nature of external loads is possible, i.e. the arrangement and value of the weight of vehicles on the basis of the force values recorded by the system and the values of the settlement of the supports on the basis of the deviations of the pylons. These issues are the subject of the next part of the paper.

4. Assessment of the weight of vehicles on the basis of force changes in the cable stays

One of the many types of bridge loads is discussed below. It takes the form of a single vehicle staying in an invariant position on the carriageway of the bridge for a period of time. Thus, a situation is being considered when the measuring devices in selected points of structure record a change of forces (induced by the vehicle in question) of the following values:

$$\boldsymbol{s} = \mathrm{col}\{S_1\ S_2 \ldots S_i \ldots S_k \ldots S_n\} \quad . \tag{1}$$

In formula (1), the numbers of the cable stays are provided in force index S as in Figures 1 and 2. The task to be solved is the assessment of the vehicle weight Q and its position along the length of the bridge, i.e. x_q.

To solve the problem, we need to apply the influence function $f(x)$ (influence lines in this case) of forces in two arbitrarily selected cable stays: (i) and (k). Assuming an arbitrary position of the vehicle in the point with a coordinate x_q, the following system of equations is obtained:

$$\begin{cases} f_i(x_q) \cdot Q = S_i \\ f_k(x_q) \cdot Q = S_k \end{cases} \tag{2}$$

Assuming that the kinematic method [3] is used to create the influence function of axial forces in the cable stays $f_i(x)$ and $f_k(x)$, the exciting forces take the following values:

$$N_i = \frac{EA_i}{L_i} \quad \text{oraz} \quad N_k = \frac{EA_k}{L_k} \tag{3}$$

where EA_i and EA_k are the rigidness of the cable stays, and L_i and L_k are their lengths. As a consequence of the loads given in (3), two bending lines, being the influence functions $f_i(x)$ and $f_k(x)$, are obtained in accordance with the Rayleigh's rule.

Dividing each equation of the system (2) on both sides by the forces in the cable stays, the following is obtained

$$\begin{cases} \dfrac{f_i(x_q)}{S_i} Q = 1 \\ \dfrac{f_k(x_q)}{S_k} Q = 1 \end{cases}, \tag{4}$$

and, on the basis of this, one equation

$$\left[\frac{f_i(x_q)}{S_i} - \frac{f_k(x_q)}{S_k} \right] Q = 0 \,, \tag{5}$$

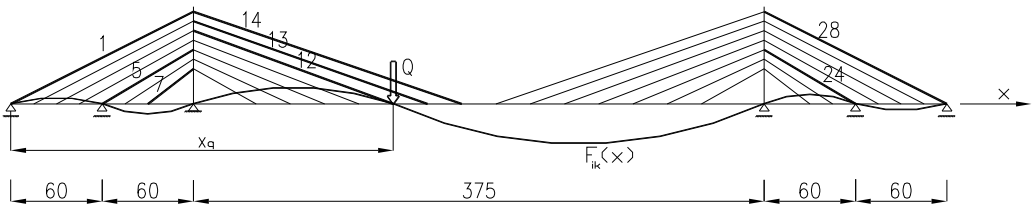

Fig. 2. Scheme of the layout of the bridge and the position of the vehicle (Q)

where the vehicle's weight Q is not significant. After comparing the influence functions corrected by the forces in cable stays S_i and S_k, with the application of the condition

$$\frac{f_i(x_q)}{S_i} = \frac{f_k(x_q)}{S_k}, \tag{6}$$

value x_q is obtained.

In the light of the relations (6), it is more advantageous to assume simultaneous loads of kinematic constraint (3), corrected by the values S_i and S_k,

$$N_i = \frac{EA_i}{S_i \cdot L_i} \quad \text{and} \quad N_k = \frac{EA_k}{S_k \cdot L_k} \tag{7}$$

As a result of the loads provided in (7), one deflection line is obtained and the point that according to (5) takes the value 0 is the point of Q load, i.e. x_q. In practical applications of computational calculations, it is recommended to use thermal analogy that is applied to determine the influence lines of the axial forces. In this case, the kinematic constraint provided in (7) can be replaced with the temperature change in the cable stay (i) $\Delta t_i = 1$ and in the cable stay (k) as

$$\Delta t_k = -\frac{S_k \cdot A_i}{S_i \cdot A_k} \tag{8}$$

As a result of the applied thermal impact, the span deflection line is obtained from calculations

$$w = F_{ik}(x) \tag{9}$$

as shown in Figure 2. The values of the function $F_{ik}(x) = 0$ occur in the point of load Q and above the support points. For this reason, the effectiveness of the algorithm provided above is satisfactory when the vehicle is located in the area between the pylons. When the vehicle is located close to supports, the results are by assumption encumbered with errors.

In order to improve the accuracy of determination of the value x_q, multiple calculations are conducted for selected pairs of cable stays. The right selection of a pair enables obtaining the right value x_q at first attempt. The value of the vehicle load Q is calculated on the basis of the equation (2), e.g. for cable stay (i) as

$$Q = \frac{S_i}{f_i(x_q)} \tag{10}$$

A significant feature of the algorithm presented above is the arbitrariness of mapping of geometrical and physical features of the structure of the spans and pylons, as shown in Figure 2. For discretization of the structure, one-, two- and three-dimensional elements can be used. The structural system can be modeled as flat 2D or as spatial 3D. From the assumed influence function ensues the fact that the vehicle moves along the bridge's longitudinal axis; therefore, the influence line $f(x)$ [3] but not the influence function is taken into consideration.

5. Assessment of the sensitivity of the system for stay forces monitoring

Influence functions $f(x)$ from the area similar to x_q with values

$$\boldsymbol{x} = \text{col}\{(x_q-\Delta)\ldots\ldots\ldots x_q\ldots\ldots\ldots(x_q+\Delta)\} \tag{11}$$

can be applied to assess the Q value. On the basis of the relation (9), the function can be created

$$Q(x) = \frac{S_j}{f_j(x)} \tag{12}$$

where (j) are the cable stay numbers. Application of a type of the influence function – the influence matrix [4] – is convenient for such analyses. Figure 3 and 4 show the results of such analyses from selected calculations that have been performed.

In the example 1 presented in Figure 3, the measured force values in the cable stays resulting from the vehicle load were as follows, (see formula (1), for stays no. 1, 5, 7, 12, 13, 14, 24, 28):

$$\boldsymbol{s} = \text{col}\{128{,}3 \quad 129{,}7 \quad 53{,}2 \quad 146{,}1 \quad 123{,}4 \quad 77{,}3 \quad 36{,}2 \quad 80{,}9\} \qquad [\text{kN}] \tag{13}$$

The bridge model presented in Figure 2 was used for the calculations and the vehicle's position was assessed as x_q = 268 m based on the course of the function $F_{ik}(x)$. The analysis of the effectiveness of the solution was conducted for the range $255 < x < 280$ m. Diagrams presented in Figure 3 were obtained from (12) for constant force values from (13) and for the numbering of the (j) cable stays listed on the right hand side (see Figure 3). On the basis of crossing point for selected cable stays (i) and (k) (i.e. points $F_{ik}(x) = 0$), the values $x_q(S_i,S_k)$ can be obtained. Some of the diagrams show that the values are concentrated in the area of x_q = 268 m. Some of them cross each other outside the figure area. Ensuing from the above, the assessment of x_q can be encumbered with significant error if the selection of cable stays (i) and (k) is individual, random. The selection of stays is thus of significance.

Taking into consideration the spot (abscissa) with the smallest vertical distance between the upper and lower line of the group 1 – 28 (excluding 14), it can be assessed that Q = 305 kN and the deviation $\Delta Q = \pm$ 12 kN, which means ± 4 % of accuracy. The accuracy of calculations is also influenced by the fact that the vehicle with multiple axes (of unknown layout) is reflected in the algorithm by the resultant force Q. However, this does not significantly influence the result because of the minor variability of the influence function.

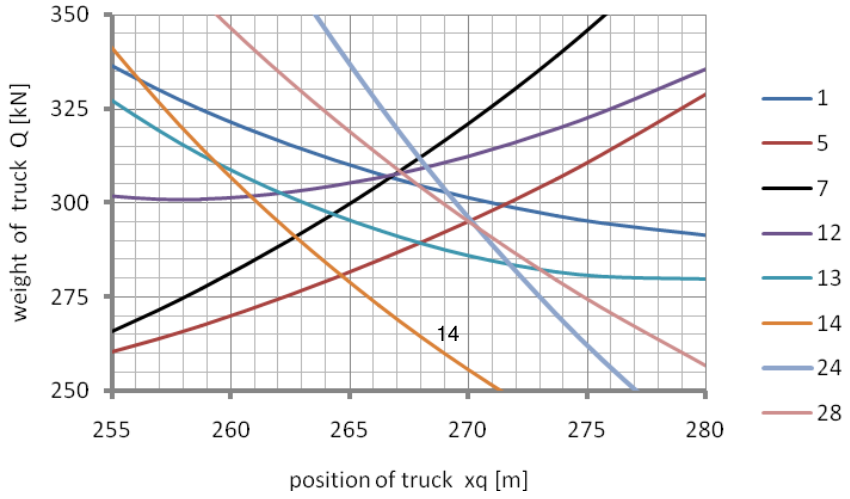

Fig. 3. Diagrams Q(x) for the example 1

In the example 2 of the calculations, presented in Figure 4, the measured force values in cable stays resulting from the vehicle load were as follows, (for stays no. 1, 5, 7, 12, 13, 14, 24, 28):

$$\boldsymbol{s} = \text{col}\{81{,}05 \quad 134{,}4 \quad 52{,}97 \quad 144{,}3 \quad 115{,}2 \quad 71{,}58 \quad 36{,}52 \quad 67{,}76\} \quad \text{[kN]} \tag{14}$$

As a result of the assessment, the position of vehicle was determined as x_q = 260.5 m. The analysis of the solution was performed for the range 240 < x < 280 m. The majority of the diagrams show the concentration in the area of the value x_q = 260 m. Taking into consideration the spot (abscissa) of the smallest vertical distance between the upper and the lower line (between the lines 1 – 28, excluding 1, 24 and 12), it can be assessed with very high accuracy that Q = 282.5 kN.

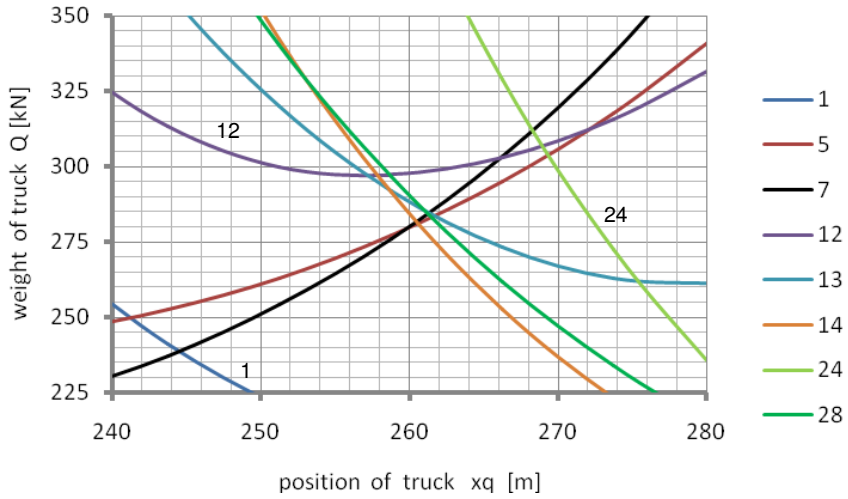

Fig. 4. Diagrams $Q(x)$ for example 2

6. Assessment of the settlement of supports on the basis of the pylons' deviations

The horizontal displacements (u) of pylon top due to the support settlement (w) can be captured by following equation:

$$\boldsymbol{u} = \boldsymbol{L}_{uw} \cdot \boldsymbol{w} \tag{15}$$

The horizontal displacement form the vector

$$u = \begin{Bmatrix} u_l \\ u_p \end{Bmatrix} \tag{16}$$

for the pylon to the left of u_l and to the right of u_p, respectively. The settlement of the supports is captured in the vector

$$\boldsymbol{w} = \text{col}\{w_1 \quad w_2 \quad w_3 \quad w_4 \quad w_5 \quad w_6\} \tag{17}$$

Thus, the displacements u_j caused by unitary settlement of supports w_i = 1 are the elements of the influence matrix L_{uw}.

In the case of the bridge in question, the relationship (15) does not capture all influences that cause displacements u. These influences, also of a long-term character, include the thermal changes in the structure's elements as well as the rheological processes (e.g. relaxation of steel) in the cable stays. For that reason, no reference was made to the results of the calculations in this paper.

7. Thermal impact on the force values in the stays

In the course of the performed measurement, it was observed that a large impact on the force values in the stays is exercised by the changes of thermal conditions resulting from the changes of the external temperature (air temperature) and from the insolation. In the light of the analyses described in 4 and 5, these changes are easily isolatable given their cyclic nature and the obvious rhythm of day and night as well as the cycle of the seasons. In the light of the settlement analysis, the temperature changes can be isolated since the magnitude and direction of the settlement are usually stable and temperature-independent in the long term perspective and the thermal changes are cyclic. The dependence of forces from the temperature is best observable in the day diagrams. Figures 5, 6, 7 present an exemplary course of forces in selected tendons and the course of temperature inside the bridge span from 24 June 2012. Note, that one stay is composed of numerous strands and the force given in the figure 5 is valid for one strand, however the forces in all strands of one stay are equal.

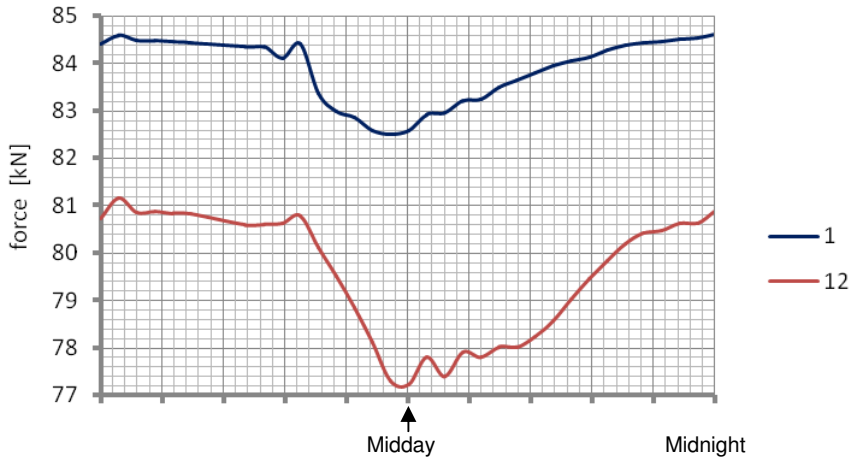

Fig. 5. Day-and-night course of forces in tendons: no. 1 (top curve) and no. 12 (bottom curve)

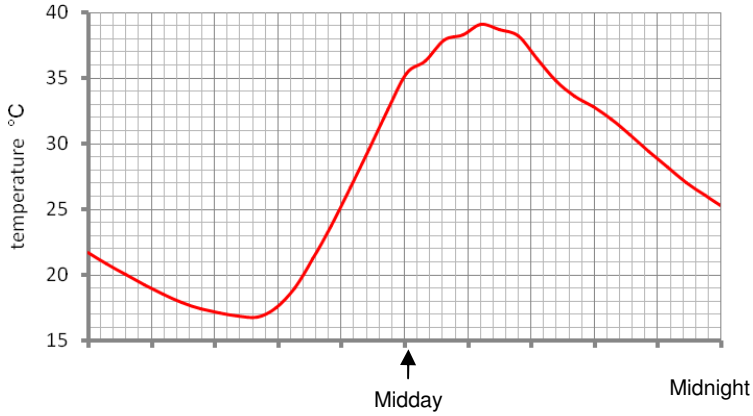

Fig. 6. Day-and-night course of the temperature of the top slab of the bridge span

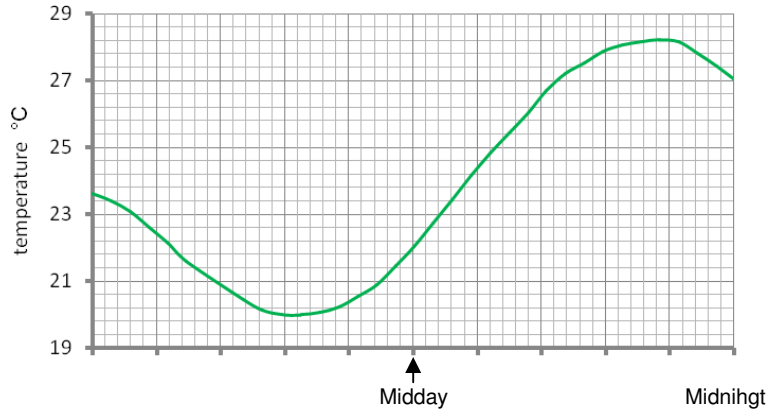

Fig. 7. Day-and-night course of temperature inside the main span of the bridge

8. Conclusions

A simple and moderately complex system of structure monitoring is used in the case described. The conclusion from the measurement results and conducted analyses is that the system along with the presented calculation procedure is an effective tool for monitoring of a bridge condition in terms of the real loads. These loads can be localized if they are present persist on the bridge for a period of time longer than the determined minimum. The measuring system is also a convenient tool for recording significant load incidents resulting particularly from the environmental phenomena. The monitoring of the bridge load and comparison of the results to the design assumptions in the context of the loads and displacements assumed in the calculations form an important ground for the assessment of safety and future operation of the bridge.

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