Efficiency of monitoring system of a cable-stayed bridge for investigation of live loads and pier settlements

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Abstract The cable-stayed bridge over the Vistula River in Płock, 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: eight sensors of force in selected stays, two inclinometers located on the tops of pylons, ten strain gauges located on the steel structural members, three temperature sensors located inside the main span, two 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. Moreover, the analysis of piers’ settlement influence on force distribution in stays is given. Several topics of comments are added. The analyses are performed to answer the question if it is possible to identify the selected phenomena of behavior of the bridge based on the records from a simple monitoring system.

Keywords Structural monitoring · Cable-stayed bridge · Stays’ forces · Piers’ settlements · Sensitivity of measurements

1 Introduction

Measurement techniques have been undergoing significant development since the second half of the twentieth century and, as a result, many structures have been equipped with systems monitoring their technical condition in terms of internal forces and deformations. These data are used in the assessment of the current effort of a structure and in the comparative analysis of the real static state against the design assumptions. Structures equipped with measurement systems include mostly bridges but also high buildings, hydro-technical structures, industrial plants, and other. Measurement systems installed in bridges usually consist of sensors of forces, deformations and displacements as well as devices measuring environmental impacts, e.g., wind velocity and the temperature of air and structure. Such monitoring system has been installed in the cable-stayed bridge built in Płock, Poland. The measurements described in this paper have been conducted continuously since 2005, when this bridge with the longest theoretical span in Poland (375 m) was completed. The paper demonstrates how measurement of forces in the stays can be applied to assess the real loads of carriageways caused by motor vehicles and by displacements of piers resulting from vertical displacements.

2 Analyzed structure and monitoring system

The examined structure is a cable-stayed bridge with an entirely steel structure, excluding the reinforced concrete piers [1]. The main cable-stayed part of the bridge consists of five spans with theoretical lengths of 60 + 60 + 375 + 60 + 60 m. The total length of the cable-stayed structure is thus 615 m, as presented in Fig. 1. There are two pylons of ca. 63 m above the level of the bridge deck. These are steel towers placed in the central dividing strip, stiffly connected with the structural elements of spans. The whole steel structure (including pylons) rests on piers with bearings. The cable-stayed system is limited to one plane of stays...
and consists of 28 double stays, each made of several tens of strands.

The measurement system installed in the main part of the bridge consists of three basic elements: sensors, cables and service panels, a data acquisition unit [2]. Five types of sensors have been applied: anemometers, inclinometers on tops of the pylons, sensors of force in the stays, strain gauges in the main span and in the pylon, and thermometers in the main span. The primary goal of the system is to gather data in the computer memory including the following measurements:

- Wind velocity and direction (on top of one pylon and on the deck, in the middle of the main span);
- Inclinations of the axes of both pylons from the initial position in the longitudinal vertical plane (measured on tops of the pylons);
- Values of forces in eight selected stays (1, 5, 7, 12, 13, 14, 24, 28), as presented in Fig. 2;
- Changes in strains in selected points in the main span and in one of the pylons;
- Temperature of the steel structure of the main span in the area of the upper and lower deck, and temperature of air inside the central cell of the box girder type main span.

The obtained data concerning velocity and direction of wind, force values in selected stays, inclination from the initial position in the vertical plane of the pylon axis, changes of strains in the selected points in the main span and one of the pylons, and temperature are recorded simultaneously at specified time intervals. The software managing the recording process prepares files containing collations of data on a daily, weekly, monthly and yearly basis. The selected results are presented in [2].

3 Formulated issues

Two analytical issues can be solved on the basis of the data recorded over a longer period of operation of the bridge equipped with a monitoring system. The first issue is determination of the weight of motor vehicles located on the bridge spans on the basis of changes of the recorded forces occurring in the stays. The other issue concerns the assessment of force changes in the stays caused by the vertical displacements of the span on the piers, e.g., due to the settlement of the foundations.

The first issue pertains to short-term phenomena, i.e., temporary occurrence of a vehicle (truck) on the bridge spans leading to a sudden change of forces in the stays. The second issue employs a long-term perspective pertaining to the settlement of piers over a period of a couple of years. Nevertheless, the team conducting the tests had also the opportunity to use measurement data connected to a temporary vertical displacement of the structure that resulted from the lifting of the structure over the bearing undergoing repairs.

The changes of forces in the stays have various patterns and are caused by different factors. Frequent and multiple changes of tension in the cable-stays occur during operation as a result of loads caused by motor vehicles. In the recorded force values in the stays, this fact is observed in the form of multiple peaks (increase in force values significantly diverging from the background). Cyclic or slow changes of tension in the stays are the result of an atmospheric impact of the environment, i.e., mainly thermal fluctuations, as demonstrated in Fig. 3, including daily fluctuations of temperature and seasonal changes. Changes of tension in the stays ensue also from rheological factors (relaxation of steel), the applied prestressing technology.
and anchorages. In addition, factors having a long-term impact on the structure include the settlement of piers and other types of deformations. Influence of both factors mentioned above is difficult to separate based solely on the results of measurements of tension in the stays and observations of their changes.

4 Vertical displacements of supports

The analysis of displacements of the superstructure’s supports was done on the basis of the foundation settlement measurement as well as on the basis of measurement of displacements during lifting the superstructure on one of the piers during the repair of the neoprene bearing. Changes of the levels of span supports can be written as a vector:

\[ r = \text{col} \{ r_A, r_B, r_C, r_D, r_E, r_F \} \quad (1) \]

where A, B, ..., F are the designations of the piers, as shown in Fig. 2. The values of displacements \( r_i \) are obtained on the basis of measurements (e.g., geodetic measurements), realized in the time range \( t_0 > t > t_a \) (\( t_o \) reference time and \( t_a \) current time). Differences in levels in these measurements \( g_i(t_a) \) and \( g_i(t_0) \) result in \( i \)—consecutive component of the vector \( (1) \) calculated according to the formula

\[ r_i = g_i(t_a) - g_i(t_0) \quad i = A, B, ..., F. \quad (2) \]

Change of forces in the stays that occurred in the analyzed range of time \( t_a - t_0 \) is defined in the form of vector

\[ s = \text{col} \{ S_1, S_5, S_7, S_{12}, S_{13}, S_{14}, S_{24}, S_{28} \} \quad (3) \]

where index \( i = 1, 5, 28 \) designates the stays subjected to force measurements, as shown in Fig. 2. Displacements \( r \) are related to the changes of forces in stays \( s \) according to the following relationship:

\[ s = L_{sr} \cdot r \quad (4) \]

using the influence matrix \( L_{sr} \) [3, 4]. For the examined bridge, elements of this matrix are determined on the basis of a computational model that takes the following form:

\[
L_{sr} = \begin{bmatrix}
6.181 & -6.392 & -1.479 & 4.781 & -1.682 & -1.420 \\
-3.573 & 8.652 & -5.606 & 1.701 & -0.450 & -0.708 \\
-2.460 & 4.997 & -2.612 & 0.298 & -0.034 & -0.186 \\
0.943 & 0.528 & -2.258 & 2.385 & -0.703 & -0.894 \\
2.280 & 0.115 & -3.755 & 3.921 & -1.326 & -1.237 \\
4.164 & -0.316 & -6.008 & 5.991 & -2.236 & -1.604 \\
-0.708 & -0.451 & 1.700 & -5.612 & 8.651 & -3.573 \\
-1.420 & -1.683 & 4.784 & -1.483 & -6.397 & 6.181 \\
\end{bmatrix} \times (\text{kN/mm}) \quad (5)
\]

From the values of elements and from the general structure of the matrix \( L_{sr} \) it follows that for displacements of piers—given in \( r \) (1), where all displacements are characterized by linear dependence (i.e., they are proportional), the analyzed points are collinear—there arise no changes of forces in the stays \( s \) (3). Such dependencies result from general principles of structural mechanics.

At this step, an orthogonal transformation of coordinates can be employed which does not change the distances between the points. In the new (transformed) coordinate system, the coordinates are modified to be more convenient. Among the variety of coordinate transformations, the beneficial one in this case is a transformation where zero values of any two freely selected points occur. For example, given \( w_C = 0 \) and \( w_D = 0 \), a reduced displacement vector is obtained in the following form

\[ w = \text{col} \{ w_A, w_B, w_E, w_F \} \quad (6) \]

as well as a narrowed influence matrix \( L_{sw} \) from (5) taking the following form

![Fig. 3](image_url) Seasonal (year 2013) and daily (4 May 2013) fluctuations of forces in the stay No. 1, due to weather cycle (the force per one strand)
The vector of dislocations, as in (4), is now as follows

$$s = L_{\text{sw}} \cdot w \quad (8)$$

and the results of calculations in the form of vector $s$ obtained from (4) and (8) are the same.

## 5 Settlement of piers

Results of pier settlement observed in the period from December 2005 to October 2009 are used as examples in the analysis. Measured (by means of geodetic method) settlement of piers is presented in Table 1. The settlements of all piers were always of the same direction, i.e., downward. In the case of piers B and E, only slight settlement was registered, which ensues from the negative reaction due to the resultants of loads (coming from the spans) directed upwards.

Because of the geodetic measurements given in Table 1 and applying the formula (2), the vector of displacements was defined (1) with the following elements

$$r = \text{col} \{2.6, 0.6, 5.5, 5.1, 0.2, 0.4\} \text{ (mm)} \quad (9)$$

and after the orthogonal transformation, as in (6), negative values of displacements are obtained

$$w = \text{col} \{-2.104, -4.152, -4.948, -4.796\} \text{ (mm)} \quad (10)$$

which means an uplift of the piers A, B, E, F over piers C and D. For these displacements, on the basis of formula (8), the change of the tension in the stays occurs

$$L_{\text{sw}} = \begin{bmatrix} 6.181 & -6.392 & -1.682 & -1.420 \\ -3.573 & 8.652 & -0.450 & -0.708 \\ -2.460 & 4.997 & -0.034 & -0.187 \\ 0.943 & 0.529 & -0.703 & -0.894 \\ 2.280 & 0.115 & -1.326 & -1.237 \\ 4.164 & -0.316 & -2.236 & -1.604 \\ -0.708 & -0.451 & 8.651 & -3.573 \\ -1.420 & -1.683 & -6.397 & 6.181 \end{bmatrix} \text{ (kN/mm)} \quad (7)$$

Therefore, the dependence between the forces in the stays and displacements, as in (4), is now as follows

$$s = L_{\text{sw}} \cdot w \quad (8)$$

and the results of calculations in the form of vector $s$ obtained from (4) and (8) are the same.

### Table 1 Settlement of piers

| Pier | Settlement value, at benchmarks (mm) | Average value (mm) |
|------|-------------------------------------|--------------------|
| A    | 3.2                                 | 1.6                |
| B    | 0.7                                 | 0.7                |
| C    | 5.9                                 | 5.3                |
| D    | 5.1                                 | 5.0                |
| E    | 0.3                                 | 0.3                |
| F    | 0.6                                 | –                  |

There are four benchmarks at each pier

The changes of forces in strands of stays due to settlement of piers are presented in column 2 in Table 2. The table provides also various numbers of strands. Conversion of forces in a stay into individual strands is thus different in each case.

The calculated values given in (12) and shown in Table 2 (col. 2) are very small. Change of the real values of the average forces in the stays in the period 2005–2009 is significantly bigger and the signs are not respected, therefore the settlement of piers is not the main cause of the recorded changes of average forces in the stays. In consequence, the rheological factors related to the structure should be considered to have much more significant impact on the changes of forces in the stays.

### Table 2 Changes of forces in strands of stays due to settlement of piers

| Cable-stay designations | Force changes in strands (kN) |
|-------------------------|------------------------------|
|                         | From calculations | From measurements |
| 1                       | +0.199             | –3.15             |
| 5                       | –0.137             | +0.37             |
| 7                       | –0.154             | –4.58             |
| 12                      | +0.026             | –2.04             |
| 13                      | +0.050             | –5.38             |
| 14                      | +0.071             | –5.24             |
| 24                      | –0.139             | –1.15             |
| 28                      | +0.078             | –3.63             |

The last column includes the calculated differences between average values of force in Fall 2009 and Winter 2005, for the strands of eight stays specified in the first column, (see Fig. 2)

$$s = \text{col} \{26.67, -22.79, -14.51, 3.59, 7.22, 11.31, -23.30, 11.98\} \text{ (kN)} \quad (11)$$

These forces, converted into the forces in individual strands, form the vector

$$s_1 = \text{col} \{0.199, -0.137, -0.154, 0.026, 0.050, 0.071, -0.139, 0.078\} \text{ (kN)} \quad (12)$$

The vector $s_1$ shows the forces in individual strands as the measurement is performed by the load cell installed in one strand per one stay. Anyway the force measured in one strand is valid for the remaining group of dozens of strands in the stay in question, because the Isotension® system was employed during construction of the bridge, which ensures the equal force in all strands of one stay.

It should be emphasized that the cable-stays contain various numbers of strands. Conversion of forces in a stay into individual strands is thus different in each case.

Therefore, it can be stated that according to the assumed computational model the changes of force values in the strands should, over a period of 4 years, be expected as presented in column 2 in Table 2. The table provides also the measured changes of force values in the stays (column 3) over the same period.

The calculated values given in (12) and shown in Table 2 (col. 2) are very small. Change of the real values of the average forces in the stays in the period 2005–2009 is significantly bigger and the signs are not respected, therefore the settlement of piers is not the main cause of the recorded changes of average forces in the stays. In consequence, the rheological factors related to the structure should be considered to have much more significant impact on the changes of forces in the stays.
6 Lifting of the span during repairs of the bearing

During repairs of the bearing on pier B, it was necessary to lift the superstructure. As a result of a forced deformation of the structural geometry of the superstructure, changes in the internal forces occur, including forces in the stays, determined by the dependency (8). Example of such a change is presented in Fig. 4. During repairs of the bearing on pier B, it was necessary to lift the superstructure. As a result of a forced deformation of the structural geometry of the superstructure, changes in the internal forces occur, including forces in the stays, determined by the dependency (8). Example of such a change is presented in Fig. 4.

The changes of forces in stays 1, 5, 7, 28 only are given in vector (17) as no significant changes of forces were registered in the remaining ones. It can be thus observed that the results of measurements correspond with the results of calculations, particularly in the case of cable-stays anchored in the surroundings of the pier B, Table 3.

7 Loads caused by motor vehicles

The analysis of loads caused by motor vehicles used the recorded changes of forces in the stays during the presence of a truck on the bridge span. One of the many types of bridge loads is considered below—a load in the form of a single vehicle taking an invariable position on the carriageway over a certain period of time. The case described further herein is related to the halt of the truck on the superstructure of the bridge during its normal operation (service vehicle cleaning the drainage system of the bridge), which was reflected in the recorded forces in the stays. Exemplary measurement results are shown in Fig. 5. A case is thus analyzed when changes of

the following form

\[
w = \begin{bmatrix} w_A \\ w_C \\ w_D \\ w_F \end{bmatrix}
\]

and the elements \( w \) are positive

\[
w = \begin{bmatrix} 1.956 \\ 4.252 \\ 4.852 \\ 0.247 \end{bmatrix} \text{ (mm)}
\]

there occurs thus the settlement of the piers in question in relation to piers B and E.

Employing the operation which is inverse to (4) or (8), i.e., statement of \( r \) on the basis of \( s \) is not possible. It is possible to propose a lot of vectors (6) and (10) as well as (13) and (14), which all can satisfy the Eq. (8).

\[
\begin{align*}
\text{Table 3 Forces in stays due to lifting of superstructure} \\
\text{Cable-stay} & | \text{Forces in the cable-stays (kN)} & \text{Quotient of measurements and calculations} \\
& | \text{Calculations} & \text{Measurements} \\
1 & 0.207 & 0.20 & 0.97 \\
5 & -0.257 & -0.22 & 0.86 \\
7 & -0.266 & -0.27 & 1.02 \\
12 & -0.019 & - & - \\
13 & -0.004 & - & - \\
14 & 0.010 & - & - \\
24 & 0.014 & - & - \\
28 & 0.055 & 0.09 & 1.64 \\
\end{align*}
\]

a result of the conducted calculations, it was established that the forces in the strands of stays should, in consequence, demonstrate changes captured in the vector (16), which shows the change of force in each strand of all stays in question due to lifting of superstructure:

\[
s_1 = \begin{bmatrix} 0.207 & -0.257 & -0.266 & -0.019 & -0.004 \\
0.010 & 0.014 & 0.055 \end{bmatrix} \text{ (kN)}
\]

(16)

At the same time, taking into account the results of continuous measurements of forces in the monitoring system, it was stated that, in the course of lifting of the superstructure, the real changes of forces were in accordance with the vector (17):

\[
s_{\text{mon}} = \begin{bmatrix} 0.20 & -0.22 & -0.27 & \ldots & 0.09 \end{bmatrix} \text{ (kN)}
\]

(17)

The changes of forces in stays 1, 5, 7, 28 only are given in vector (17) as no significant changes of forces were registered in the remaining ones. It can be thus observed that the results of measurements correspond with the results of calculations, particularly in the case of cable-stays anchored in the surroundings of the pier B, Table 3.
forces (caused by the vehicle) were recorded by the force sensors on the cable-stays captured in the vector similar to the vector (3). Solution of this case consists in an estimation of the weight of the vehicle \( Q \) and of its position along the length of the bridge, i.e., \( x_q \). Values \( Q \) and \( x_q \) are thus unknown in the examined case.

To solve the problem, influence functions \( f_i(x) \) (influence lines in this case) of forces in two randomly selected stays \( (i) \) and \( (k) \) are applied. Given a random position of a vehicle in the point of the coordinate \( x_q \), a system of equations is obtained

\[
\begin{align*}
\frac{f_i(x_q)}{S_i} Q &= 1, \\
\frac{f_k(x_q)}{S_k} Q &= 1,
\end{align*}
\]

in which the weight of the vehicle \( Q \) is not crucial. In consequence, one equation can be formed

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

Based on the comparison of influence functions corrected by the forces in the stays \( S_i \) and \( S_k \) from (22), the following condition is obtained

\[
\frac{f_i(x_q)}{S_i} = \frac{f_k(x_q)}{S_k},
\]

based on which the value \( x_q \), i.e., position of the load \( Q \), is obtained.

Considering the dependency (23), it is more beneficial to simultaneously (in one set) assume loads of kinematic excitation (19) and (20), but corrected by values \( S_i \) and \( S_k \):

\begin{align*}
N_i &= \frac{S_i \cdot L_i}{E A_i} \quad \text{(24)} \\
N_k &= \frac{S_k \cdot L_k}{E A_k} \quad \text{(25)}
\end{align*}

Assuming (in one set) loads given in (24) and (25), one deflecting line is obtained and the point where, in accordance with (22), value 0 occurs is the position of load \( Q \), i.e., \( x_q \), as shown in Fig. 6.

The usage of thermal analogy applied to determine the influence lines of the axial forces proves effective in the practical application of computer calculations. In this case, kinematic excitations given in (24) and (25) can be replaced by the change of temperature in the cable-stay \( (i) \) of unit value, i.e., \( \Delta t_i = 1 \), whereas in the cable-stay \( (k) \) kinematic excitations can be replaced by the calculated temperature change as

![Fig. 5 Change of force in cable-stay 14 during service load of the span (force per one strand). The presence of truck close to the stay no 14 lasted from 16:08 to 16:36](image1)

![Fig. 6 Function \( F_k(x) \) and the position of the motor vehicle](image2)
\[ \Delta t_k = -\frac{S_k \cdot \Delta A}{S_i \cdot A_k} \]  

(26)

As a result of the applied thermal influence, considering scheme in the Fig. 1, a deflection line of the span is obtained from the calculations, as presented in Fig. 6.

\[ w(x) = F_{ik}(x) \]  

(27)

The values of function \( F_{ik}(x) = 0 \) occur in the point of load \( Q \) and, additionally, over supporting points. Based on the course of function \( F_{ik} \), it is possible to observe the scope of efficiency of the algorithm given above—the results are satisfactory when the vehicle is located between the pylons. When the vehicle is located in the area of supports, the results are by assumption inaccurate. To enhance the accuracy of determination of the value \( x_q \), multiple calculations were conducted for variously selected pairs of stays. An accurate, i.e., the most optimal, choice of the pair of stays enables obtaining the proper value \( x_q \) at the first try.

The weight of vehicle \( Q \) is calculated from a randomly selected equation (18), e.g., for the stay \( (i) \), on the basis of a previously defined coordinate \( x_q \), from the following formula

\[ Q = \frac{S_i}{f_i(x_q)} \]  

(28)

An essential property of the algorithm presented above is the discretion of representation of geometrical and physical features of the span and pylons. Two- and three-dimensional elements can be used for discretization of the structure. Structural system can be modeled as flat 2D or spatial 3D. From the assumed influence function, it ensues only that the vehicle moves along the longitudinal axis of the bridge, therefore, the influence line \( f(x) \) [4] is considered.

8 Sensitivity of the system monitoring forces in the stays

The influence function \( f(x) \) from the area separated from \( x_q \) by any value \( \Delta \)

\[ x = x_q \pm \Delta \]  

(29)

can be applied to estimate the weight of the vehicle \( Q \). Based on the dependency (28), functions \( Q(x) \) can be formed as dependent on the position of the vehicle on the bridge, created for a specific cable-stay \( j \), as in the formula

\[ Q_j(x) = \frac{S_j}{f_j(x)} \]  

(30)

For such analyses, it is convenient to apply one of the types of influence functions— influence matrix [3, 4].

Results of such analyses from selected calculations are presented in Figs. 7 and 8.

Example 1 The measured increases in forces in stays 1, 5, 7, 12, 13, 14, 24, 28 resulting from the load caused by the vehicle located (cf. Fig. 5) in fact on the deck were as follows:

\[ s = \{128.3, 129.7, 53.2, 146.1, 123.4, 77.3, 36.2, 80.9\} \text{ (kN)} \]  

(31)

For the calculations, the bridge model presented in Fig. 2 was taken. Based on the course of the function \( F_{ik}(x) \), shown in Fig. 6, the position of the vehicle was estimated as \( x_q = 268 \) m. The analysis of the efficiency of the solution was conducted for the range of \( 255 < x < 280 \) m. The diagrams shown in Fig. 7 were obtained from the formula (30) for force values from (31) and numbering of stays \( j \) given in Fig. 2, listed on the right hand side of the Fig. 7. Values \( x_Q(S_i, S_k) \) can be defined on the basis of the common points shared by the lines for selected stays \( (i) \) and \( (k) \) [i.e., points of \( F_{ik}(x) = 0 \)]. Some of the drawn curves
demonstrate concentration of these values in the area of 
\( x_q = 268 \) m. Some of them intersect outside the field of the 
diagram. Therefore, it can be concluded that estimation of 
\( x_q \) may be encumbered with an error from a single and 
random choice of a pair of stays: \((i)\) and \((k)\). Selection of a 
pair of stays is thus crucial.

Taking into consideration the spot with the smallest 
narrowing of the envelope of lines 1–28 (excluding 14), it 
can be estimated that \( Q = 305 \) kN and deviation 
\( \Delta Q = \pm 12 \) kN, which means the accuracy of \( \pm 4 \) %. The 
accuracy of calculations is also influenced by the fact that a 
vehicle (not specified in details, by assumption) with 
multiple axes is, in the algorithm, substituted by the 
resultant force \( Q \) only. However, this influence is not 
significant as far as the result is concerned due to the slight 
variability of the influence function.

**Example 2** The measured force values in the stays 1, 5, 7, 
12, 13, 14, 24, 28 resulting from the load caused by the 
vehicle located (cf. Fig. 8) in fact on the deck were as 
follows:

\[
\begin{align*}
  s &= \{81.05 \quad 134.4 \quad 52.97 \quad 144.3 \quad 115.2 \quad 71.58 \quad 36.52 \quad 67.76\} \text{ (kN)}
\end{align*}
\]

The position of the vehicle was estimated as 
\( x_q = 260.5 \) m. A detailed analysis of the solution was 
conducted for the range of 240 < \( x \) < 280 m. The majority 
of diagrams demonstrate a concentration in the area of the 
value \( x_q = 260 \) m. Taking into consideration the spot with 
the smallest narrowing of the envelope of lines 1–28 
(excluding 1, 24 and 12), it can be estimated with a very 
high accuracy that \( Q = 282.5 \) kN (Fig. 9).

### 9 Summary of the analysis

The overview of the measurement results and the con-
ducted analyses lead to a conclusion that a monitoring 
system combined with the herein presented calculation 
procedure is an efficient tool for tracking of the bridge 
condition in terms of its real loads. These loads can be 
located—as long as they persist for a period of time longer 
than the specified minimum—so that they are registered in 
the measuring system. This system is therefore a tool 
recording significant load incidents. Tracking of the bridge 
load condition and comparison to the design assumptions 
in terms of the loads and displacements assumed in the 
calculations is an important prerequisite to the assessment 
of safety and future operation of a bridge. As a result of the 
calculations, it has been determined that:

- The influence of the real settlement of foundations of 
piers A–F on changes of the force values in the stays is 
  small, which means that the main cause of the long-
term changes of forces recorded over the period 
2005–2009 (and later) is not the settlement of piers;
- Lifting of the superstructure over pier B (by 5 mm) 
  caused force changes in the stays of values consistent 
  with the results of calculations, which proves both the 
  measurement results and the applied analytical tool to 
  be reliable;
- Estimation of the weight of the vehicle located on the 
  bridge span on the basis of the registered changes of 
  forces enabling assessment of the vehicle’s weight as 
  305 kN in the first case and 283 kN in the second case 
  is reliable, taking into account the real vehicle whose 
  presence on the bridge was stated (three-axis service 
  truck for cleaning of the drainage system on the 
  bridge).

The influence of temperature in the tasks above can be 
neglected, because:

- The presence of the truck on the span lasts about 1 min,
  so the temperature of the structure can be taken as 
  steady,
- The long-term measurement of pier settlements goes 
  through many cyclic (repeated) seasons (few years), so 
  the influence of temperature can be eliminated.

However, the influence of temperature on the force in 
stays in medium period (few hours–few days) is obvious, 
which is illustrated in the Fig. 10.

The measurement of force in stays for investigation of 
live loads on the deck is rather not disturbed by relatively 
slow variation of temperature. The peaks of force due to 
the presence of a truck can be observed as a rise and drop 
of curve regardless of the current temperature of the 
structure. The analysis of settlement of piers regarding 
the forces in stays may not be burdened with the effect of 
temperature variations. However, the measurements should 
take each year at similar circumstances. It is indis-
pensable to exclude the influence of neither solar radiation
nor seasonal temperature level. Measurements are taken always, for instance in November or April, early in the morning, before the sun rise, or during cloudy weather.

10 Conclusions from the measurement results and analyses

The measurement results and the herein presented analyses can be basically applied in the assessment of the current strain of the structure, of the load values to which it is subjected as well as of the long-term processes taking place in the structure and its environment. These results can be directly used in the risk analysis conducted as part of the assessment of safety of the structure and its users. The performed measurements and analyses may also be helpful in designing of measurement systems, e.g., during determination of the number of sensors and their arrangement as well as during establishing of the required recording frequency of the measured values. The measurements described in this paper are continuously checked since 2005, i.e., since the completion of the bridge in Płock, Poland, having the longest theoretical span (375 m) in the country.

The conducted analyses lead to the following conclusions:

- It is possible to determine the load placed on a span of a cable-stayed bridge on the basis of the results of forces measured in the stays, both in terms of its position as well as its value,
- It is very difficult—impossible in practice—to determine the settlement of span supports on the basis of changes of forces in the stays, however, if only one support of superstructure is lowered or raised even by few millimeters for a while (for instance during repair of bearing) it is possible to measure the evident change of forces in stays,
- Slight vertical displacements of the superstructure in the points of support result in distinct changes of forces in the stays, which can be measured by means of reliable methods,
- The conducted analyses enabled assessment of the sensitivity of the monitoring system leading to a conclusion that the sensitivity is sufficient in terms of loads caused by trucks,
- Assessment of a bridge performance under operation does not require a very complex measurement system; the number of sensors (as far as forces and displacements are concerned) can be limited to so small one as the number of sensor in the bridge being examined.

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