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STRUCTURAL HEALTH MONITORING OF A RAIL BRIDGE STRUCTURE IMPACTED BY MINING OPERATION

SYSTEM MONITOROWANIA KONSTRUKCJI MOSTU KOLEJOWEGO PODDANEGO ODDZIAŁYWANIU EKSPLOATACJI GÓRNICZEJ

Abstract

Structures located in areas affected by mining operation are subjected to movements and tilting. Continuous monitoring of the structure's response to these forces allows for the control of their impact on the technical condition of the structure. In the case of railway structures, the measurements may allow further determination of the impact of modifications to the geometry of the structure on the track. This paper presents the results of observing indications of Structural Health Monitoring installed on an actual bridge construction under which mining operations were being conducted.

Keywords: Structural Health Monitoring (SHM), mining deformations, bridge, displacement measurement

Streszczenie

Obiekty zlokalizowane na terenach podlegających wpływom eksploatacji górniczej ulegają przemieszczeniom i przechyłom. Ciągłe monitorowanie odpowiedzi obiektu na wymuszenia pozwala kontrolować ich wpływ na stan techniczny konstrukcji. W przypadku obiektów kolejowych pomiary mogą umożliwiać dodatkowo określanie wpływu zmiany geometrii konstrukcji na torowisko. W artykule zaprezentowano doświadczenia z obserwacji wskazań systemu monitorowania zainstalowanego na rzeczywistym obiekcie mostowym, pod którym prowadzona była eksploatacja górnicza.

Słowa kluczowe: systemy monitorowania konstrukcji (SHM), deformacje górnicze, most, pomiar przemieszczeń

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1. Introduction

Mining operations can cause damage to structures [1]. The basis for the control of the technical condition of the structure is information gathered regarding the occurring changes. Obtaining such information is possible through regular inspections, surveying, and by installing an automatic Structural Health Monitoring system [2–4]. Bridge structure susceptible to terrain deformation requires constant monitoring of its geometry. The use of an automatic SHM system allows for an increased quality and accuracy of information relating to the changes occurring within the structure, while reducing the amount of work for data acquisition and analysis, resulting in a significant increase in the safety of the structure [5, 6]. This paper presents an analysis of the requirements to control the structural health of a bridge structure and presents the first results of the automatic SHM system installed on the structure, within the proximity of which, mining operations are conducted.

2. Location and description of structure

The presented railway bridge is located in Pawłowice over Wyzwolenia Street and the Pawłówka stream. The street and stream intersect with the axis of the structure at a near right angle. The stream is a small body of water in a partially fortified bed.

The bridge is located on the 23.449 km railway line No. 159 Orzesze–Wodzisław Śląski, trail Warszowice-Studzionka station branch. On the bridge, or rather two parallel bridges, two railway tracks are laid – one track on each of the structures.

Railway No. 159 is heavily loaded. Intense cargo and passenger traffic make repairs on the bridge structures difficult.



Fig. 1. View of the east side of the bridge

The bridge consists of two parts which are separate structures. These two structures are assigned individual tracks:

- under track No. 1 is a riveted steel structure,
- under track No. 2 is a welded steel structure.

Each structure is a two-span design, with two simply supported girders. In each of the spans there are twin steel plate girders. The bridge deck was designed to be open. The intermediate support (pillar) was designed from reinforced concrete, abutments are placed on a mound, and the wings are made parallel to the axis of the track.

2.1. Track 1 – riveted steel bridge (west)

This is an older structure, erected in 1946. The components are joined using steel rivets. The construction of the bridge consists of two long main spans (23.7 m each) and two short spans, with a much smaller cross-section, which are about 2.0 m in overall length, and extend beyond the main plate girders by 1.6 m (Fig. 2) . These spans, due to their short length and low stiffness, do not significantly affect the performance of the main girders. The bearings at the outer ends of the spans mainly limit their deflection.



Fig. 2. View of the abutment and span

The geometry of the structure:

- horizontal clearance: 2×20.7 m (two main spans),
- length of each span: 26.9 m (with abutments),
- vertical clearance: 8.15 m (over the road),
- total length: approximately 60 m (including abutments).

2.2. Track 2 – welded steel bridge (east)

The newer of the two parallel structures was erected in 1973 as a steel-welded beam bridge. Abutments of the bridge under track No. 2 were separated from abutments under track No. 1 by movement joints. The pillar (intermediate support) was added to the existing bridge pillar under track No. 1 in such a way that they form a single structure.

The geometry of the structure:

- horizontal clearance: 2×22.5 m,
- length of each span: 27.50 m,
- vertical clearance: 8.20 m,
- total length: approximately 60 m (including abutments).

3. Mining operation

Geodetic measurements have been performed practically since the beginning of the exploitation of coal deposits in the area of the bridge, i.e. from May 1973, by the mine KWK Pniówek. Before that date, there was no mining operation in the area. The support settlement measured from May 1973 to April 2014 was:

- north abutment approximately 2.09 m,
- south abutment approximately 1.89 m.

Horizontal displacements from March 1994 to April 2014 (before the year 1994, there were no regular abutment distance measurements):

- abutments distance under track No. 1 was reduced by 83 mm (in the axis of the track),
- abutments distance under track No. 2 was reduced by 80 mm (in the axis of the track).

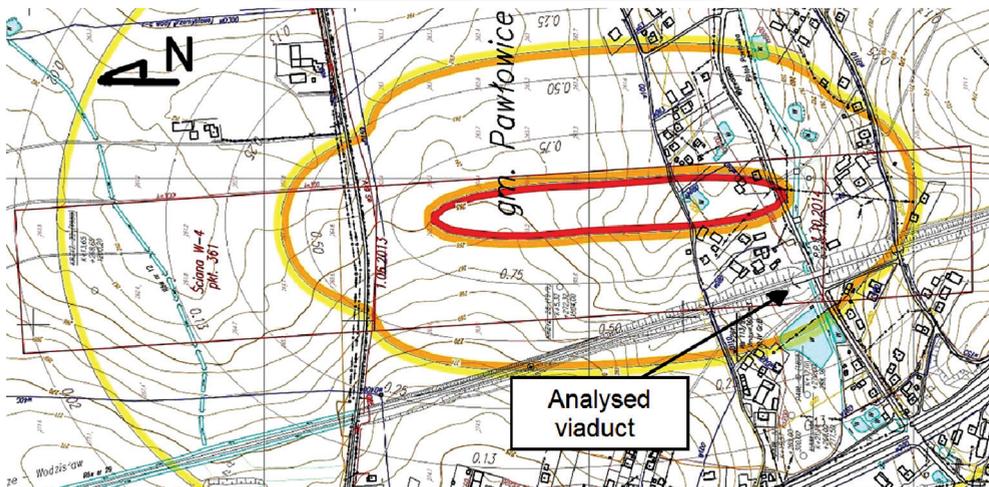


Fig. 3. The position of the bridge related to deck W4. The map of subsidence

A tilt of the abutments relative to the axis of the bridge (the track) was observed, this has resulted in changes in the distance of the abutments' edges. For example, under track No. 2 this distance decreased by 88 mm on the east side and 72 mm west side.

There have been no measurements of the width of the expansion gaps and bearing displacements (despite the fact that displacement transducers are mounted on the bearings).

Currently, in the area of the viaduct, exploitations are being conducted (in wall W4, deck 361 at a depth of approximately 900 m below ground level).

The thickness of the exploited layer is 2.6 m. Influences of the previous exploitation conducted in the area in early 2012 already revealed themselves on the surface – hence, the currently measured terrain deformation should relate to wall W4, 361 deck (Fig. 3).

In the autumn of 2013, this wall was moving closer to the structure (dispersion measured in the area). In summer of 2014, mining operations passed under the structure (axis of the wall was located east of the structure). Completion of the mining operation in wall W4 should occur the fall of 2014. The center of subsidence's the basin associated with this wall will be located southeast of the structure, and the viaduct will be on the side of subsidence's basin.

The time period for the effects of the exploitation to manifest themselves on the surface, is anywhere from about 2 months to as long as 1.5 years. This time period depends upon the geological structure of the rock above – the greater the strength of the rocks, the later the effects of mining on surface will reveal themselves and generally, the increase of deformation occurs faster.

Currently (beginning of July 2014), there is a downhill creep on the site, the abutments are getting closer to each other. Eventually, in connection with the exploitation of wall W4 (deck 361), it is estimated that it is possible for the abutments to get as close as approximately 60 mm.

Projected values of ground deformation (at the end of 2014):

- $w = -0.40$ m (subsidence),
- $T_{\parallel} = 1.0$ mm/m (deflection in the vertical plane parallel to the axis of the bridge / the south-bound track),
- $T_{\perp} = -1.7$ mm/m (deflection in the plane perpendicular to the axis of the bridge / the east-bound track),
- $\varepsilon_{\parallel} = -1.2$ mm/m (creeping in the plane of the axis of the bridge / track),
- $\varepsilon_{\perp} = -0.6$ mm/m (creeping in a plane perpendicular to the axis of the bridge).

In 2011, a complete survey of the bearings was performed identifying the current horizontal displacements of the platform relative to the supports; measurements of width of expansion gaps, the grade line and lateral inclination of the tracks were made. Utilizing mining projections, an evaluation of current and required capabilities of kinematic spans was conducted. It has proved necessary to reconstruct the bearings and adjust the width of certain expansion gaps. It has been calculated that by 2020, each of the abutments can get as close as 150 mm to the central pillar. At the end of 2012, the structure was adjusted to 2020 mining forecasts which would influence the structure.

4. Need for monitoring

Real dangers associated with the planned mining exploitation:

- creeping (compression) of land is forecasted, which will cause the abutments to approach each other,
- tall cracked the pillar of reinforced concrete is prone to deflection and horizontal forces,
- one-directional bearings might become locked as a result of the twisting of abutments – in this structure, there are slide bearings and roller bearings. Slide bearings (bridge under track 1) and roller (track 2) work properly only if the displacements occur along one axis. In the analysed case, the nature of deformation is inclined to the structure, the abutments and the pillar can thus be twisted relative to the axis of the structure. In instances of locking of the bearings, new cracking of the pillar and abutments would occur. It is also possible for damage or even destruction of the fixed supports and bearings to occur.

The structure is sensitive to the torsion of the abutments, as the one-directional plain bearings become rapidly wedged in the case of simultaneous rotation and linear horizontal displacement of the outer supports. As a result of this phenomenon, the ability of the span to move independently relative to the abutments. This creates a couple of horizontal forces in the horizontal plane. The spans, which are not prepared for such a bending moment, are at risk. Also, the cracked pillar is not resistant to shearing forces in the lower plane bearings. In order to ensure safety of the structure, it is important to perform frequent rectification of the lower plates of the bearings to eliminate the impact of abutment torsion on the span.

Due to the complex geotechnical conditions in the area of the structure (the presence of the stream), the nature of deformation is difficult to predict. The pillar is built on native soils (clay sands, silt sands and clays dominate in the soil). Substantial force is transferred from the pillar on to the ground due to heavy weight (half the weight of the two spans plus rolling stock). Abutments are placed on an embankment, they have large foundation plates, are low and carry the load only from the middle of the spans each.

In the area of the bridge, multiple mining operations are carried out in various directions in relation to the structure, this means that the influences of individual operations overlaps in time.

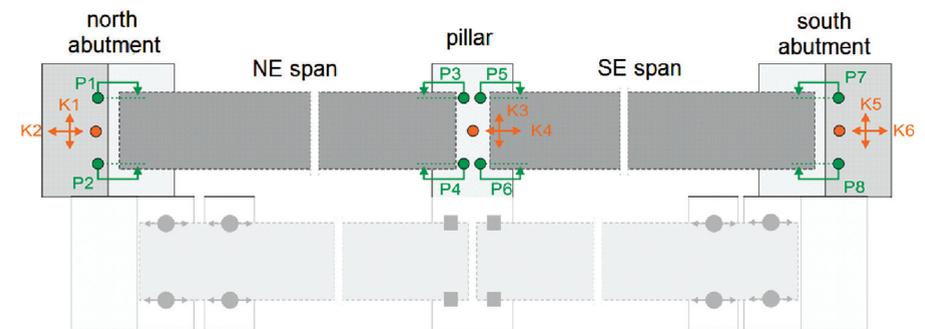
These factors make the predicted values of horizontal displacement of the past significantly different from the measured values, hence it is necessary to conduct regular surveying and possibly re-adjust the position and width of the of the bearing joints before 2020.

5. Structural Health Monitoring

In October of 2013 on the eastern part of the structure, automatic Structural Health Monitoring system was installed. The system consists of an observation subsystem, responsible for collecting information and data transfer, as well as acting as a warning subsystem responsible for the analysis of the obtained measurement results and informing the user about forthcoming hazards. In accordance with ITB Instruction 443/2009 [7], this device can be classified into the group of SHM systems.

As physical parameters, which change and have impact on the changes of the technical condition of the structure, were selected. In the analysis of the structure's deformation, it was assumed that each element behaves like a rigid body [8].

The location of the measuring points and the principle of signing the values of linear and angular displacements are shown in Fig. 4.



The principle of signing the values of linear (P1-P8) and angular (K1-K6) displacements

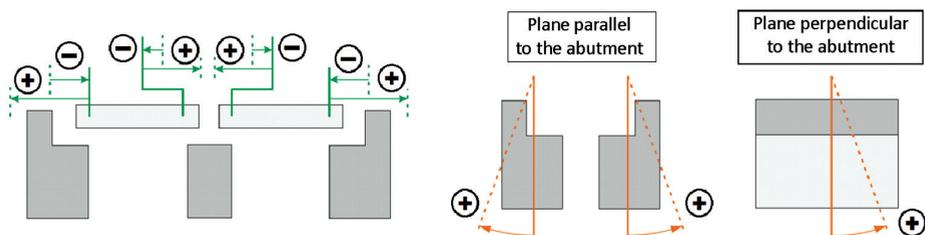


Fig. 4. Distribution of measurement points: P – measurements of horizontal displacement, K – measurements of supports angles



Fig. 5. Support structures for mounting angle sensors and displacement sensors at the intermediate support (view on the west side)

Due to the planned 10-year monitoring period, stringed displacement sensors (transducers) were utilized with a measuring range of 200 mm as well as string angle sensors.

The system is powered by battery, replaced during the periodic inspections of the structure. The sensors are read every 15 minutes, and once a day, readings are sent via the GSM network to the measuring server where they are processed and automatically analysed. The system generates daily reports on the structure's behaviour and sends them to the persons responsible for its safety.

6. Measurement results

System installation and start of data collection in the fall of 2013 allowed observing the beginning of the unfolding impact of mining activities on the monitored object. Changing in the span distances relative to the abutments was observed at the beginning of April 2014. During this time, the mining operations passed under the structure.

The negative sign in measurements on the charts below indicates closing of the expansion gaps. The increase in horizontal displacements is particularly visible on the northern abutment (sensors P1 and P2 in Fig. 6).

The non-existence of a linear relationship between of displacements recorded by sensor P2 with temperature changes demonstrates either locking of or permanent damage to the bearings on the support of the structure.

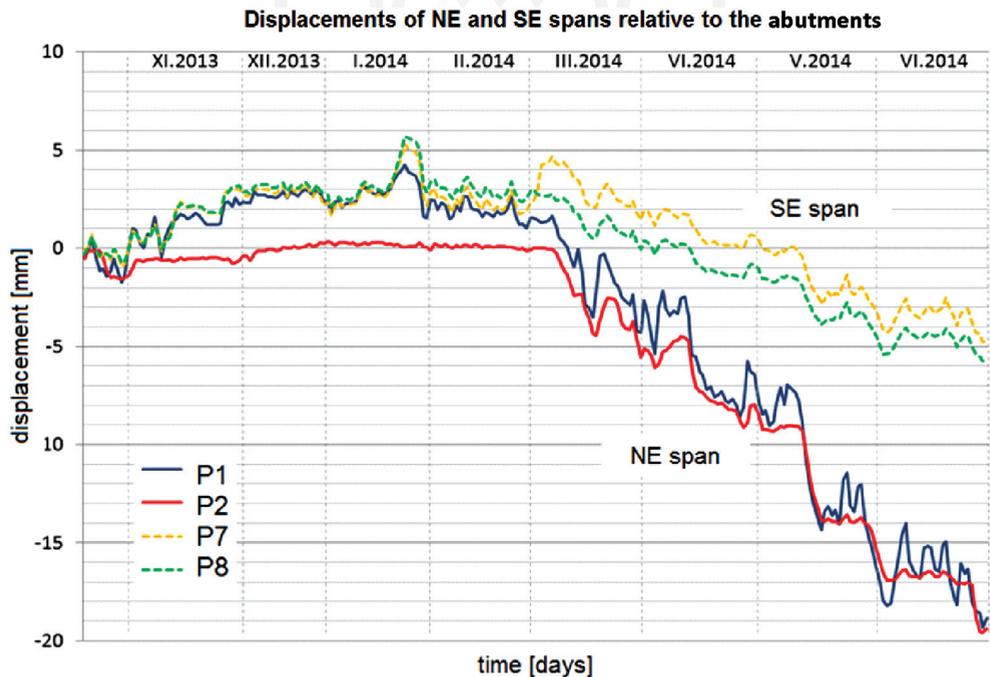


Fig. 6. Graph of horizontal displacements (along the axis of the structure) NE and SE spans relative to abutments

Displacements of spans relative to immovable intermediate support (the pillar) were observed. Values added for the NE span prove displacement towards the abutments. Part of the measured horizontal displacements are related to the depletion of slack in connections between the plate girders of the bridge, the steel support and the reinforced concrete pillar. Unfortunately, there is certainly deformation and twisting of the pillar relative to its axis.

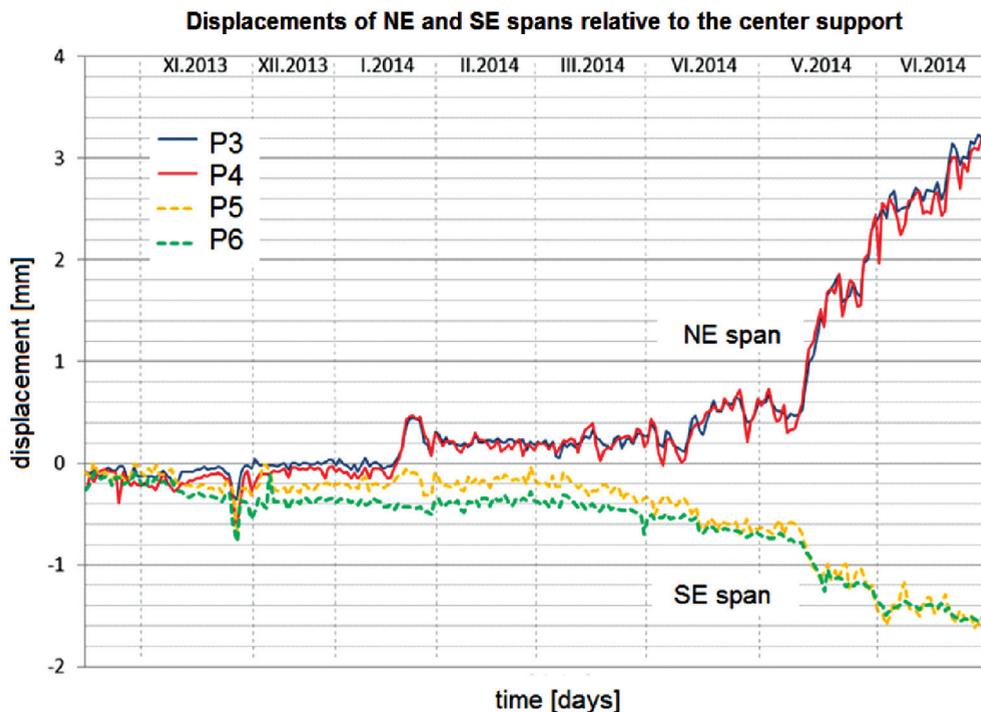


Fig. 7. Graph of horizontal displacements (along the axis of the structure) NE and SE spans relative to center support

The observed linear horizontal displacements were confirmed by the angular displacement of the abutments and the pillar. In those measurements, parts of the bridge were treated as rigid.

Figure 8 shows changes in the inclination of the north-east and south-east abutments in the period from November 2013 to June 2014. Analysis in a vertical plane parallel to the axis of the structure's angular displacement values (sensors K2 and K6), together with the values of horizontal displacements relative to the abutments and measured with sensors P1, P2, P7 and P8 shows that the abutments are getting closer. The value of this approximation in the foundation level is greater than in the level of the support platform. The horizontal displacement of the north and south abutments, resulting from their rotation, assuming the theoretical height from ground level of $H = 8$ m, is suitably $X_N = 7.0$ mm (in direction N) and $X_S = 4.2$ mm (in direction S). Displacements resulting from horizontal movement of abutments are respectively equal to $P_{NE} \approx 20$ mm

and $P_{SE} \approx 5 \text{ mm}$, wherein $P_{NE} = 0,5(P1 + P2)$ and $P_{SE} = 0,5(P7 + P8)$. If we sum up the values of displacements resulting from the horizontal movement and the rotation of the abutments, we calculate the value of creeping at ground level at 36.2 mm. Projected deformation of land is forecasted to be approximately -1.2 mm/m , which at a distance of approximately 45 m between the abutments, allows assessment of their horizontal displacement at around 54 mm. This means that at present, creeping is already about 67% of the forecasted figure.

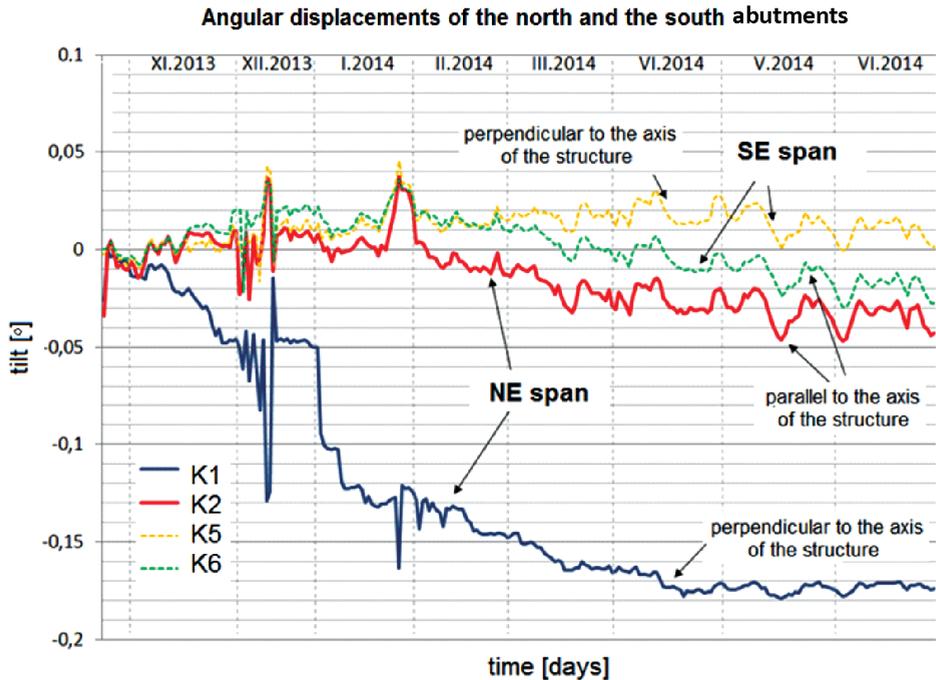


Fig. 8. Chart of tilting of the northern and southern abutments in a plane parallel and perpendicular to the axis of the structure

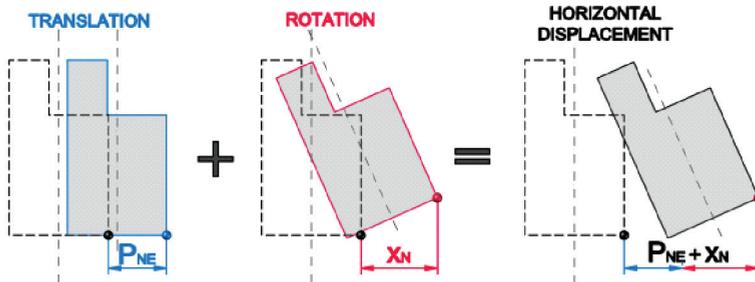


Fig. 9. Horizontal displacement of the north abutment resulting from translation and rotation

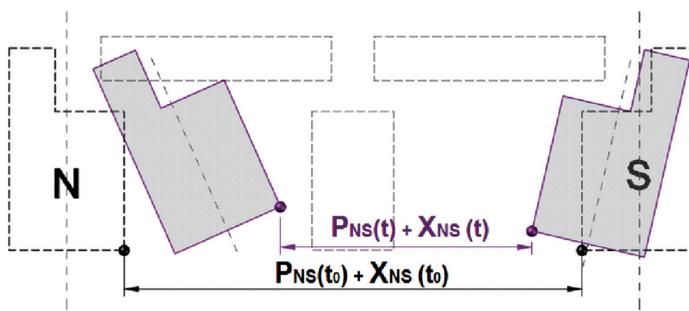


Fig. 10. Relative displacement of abutments – visual drawing

An interesting observation is the measurement of the tilt of the northeastern abutment in a plane perpendicular to the axis of the tracks. The value of the measured angle is now $K1 \approx -0.18^\circ$. This means that the abutment (assuming the theoretical amount $H = 8$ m) is tilted so that the upper part of the structure has moved approximately 25 mm to the west. Such behaviour of the northeastern support may result in the observed locking (wedging) of rolling bearings (probe P2).

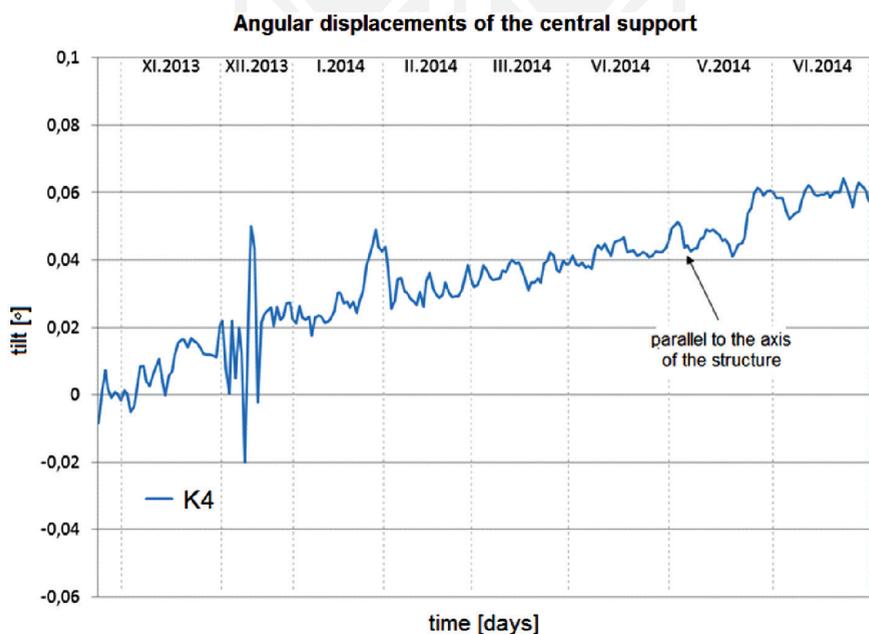


Fig. 11. Chart of tilting support in plane parallel to the axis of the structure ('+' denotes a tilt towards the north)

The above findings inconsistent with the forecasted indicator of deformation, which in this plane, is $T_{\perp} = 1.7$ mm/m (deflection in the plane perpendicular to the axis of the bridge on the eastbound track) at a height of abutment equal to 8 m – this should mean a displacement

of the upper surface of the support of 14 mm in the opposite direction to that which was measured.

Noteworthy is the fact that the southeastern abutment is not subject to tilting in the plane perpendicular to the axis of the bridge.

The measurement of the tilt of intermediate support (the pillar) in the plane of the object's axis (Fig. 11) indicates that the pillar tilted towards the north so that the horizontal displacement of its head is currently approximately 8.4 mm.

7. Remarks and conclusions

Structures situated in areas influenced by land deformation caused by mining, are subject to movements and tilts. Anticipating these extortions enables the design of structures adapted to variable geometry of the land. Ongoing monitoring of the structure's response to these extortions allows for the control of their impact on the technical condition of the structure. In the case of railway structures, the measurements may allow further determination of the impact of changes in the geometry of the structure on the track.

Structures in areas where mining activities are carried out are often subjected to overlapping deformations derived from the extractions from different coal deposits in different directions. Installation of Structural Health Monitoring allows for regular measurements without the involvement of human resources. In view of the long disclosure period of the mining operation influences, this solution ensures the proper conduct of observations.

Continuous access to the measurements via a dedicated measurement platform as well as the ability to define the threshold values at which the monitoring system will automatically take action related to, for example, sending information about risk to the persons responsible for the structure creates a significant increase in its security and allows active management such as the movement of rolling stock.

The Structural Health Monitoring system installed on the structure in Pawłowiec already provided very important information, a moment was captured in which the terrain deformation caused modification of the geometry of the bridge. Currently, there is monitoring of the horizontal displacements relative to the support, therefore, it was possible to point out the support in which blocking occurs and recommend changing the direction of the bearing work. The control of horizontal displacement in the place of the theoretically fixed central support allows for the monitoring of the technical condition of the split top plate of the reinforced concrete pillar and permanent bearings – this has a real consider changing to 'significant, positive' impact on the safety of the structure.

Real dangers for the structure are the breaking (cutting) of permanent bearings on the pillar and blocking of one-way roller bearings on abutments. Monitoring system allows to notice the displacement on permanent bearings and the lack of transfers on moving bearings in the certain period of time what allows controlling both threats and in the emergency e.g. immediately close the viaduct for the railways.

Analytical evaluation (computational) of the influence of mining deformations on the height concentration tension of structure is, in this case, inappropriate. A large numbers of variables, for example, those relating to damage (splits, cracks) of the pillar and abutments, and certain visible deformations of the geometry of steel girders as a result of earlier mining

deformations, are important factors which make it difficult to create a good computational model. Additionally, the mining extortion is slowly growing, a redistribution of stresses is scheduled and as a result, the inner strength of the structure will fall – this phenomenon is not well understood and requires further research.

The use of simple geometrical relationships allowed the estimation of deformation in the area and for comparing the findings with the forecasted values.

Given the amount of information provided by SHM systems and the various possibilities of their use in practice, it seems that in the near future, the number of bridges located within mining areas equipped with this type of device will significantly increase.

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