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Application of Structure Monitoring Systems to the Assessment of the Behaviour of Bridges in Mining Areas

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Abstract. Structure monitoring systems are increasingly used to assess the technical condition and improve the safety of structures. Monitoring the structural behaviour becomes necessary in the case of structures located in areas with complicated ground conditions. Due to the risk of failures and the resulting economic and non-material costs, monitoring should be in particular applied to linear structures, including railways, tramlines, motorways and expressways, as well as related facilities (e.g. bridges). Monitoring shall consist in regular observations, measurements and documenting all significant data during construction, after its completion and during usage, and in analysing and evaluating the results. This paper presents the application of structure monitoring systems to the assessment of the behaviour of bridges exposed to the impact of mining operations.

1. Introduction

Mining area deformations have a negative impact on bridges. In the case of structures whose static diagram is a simply supported beam, displacement and rotation of spans with respect to abutments take place. Properly selected bearings shall transfer the predicted horizontal displacements. Bridge tilt related to the mining area, which plays an important role for the rolling stock may require span rectification.

Structures with a diagram of a simply supported beam undergo greater deformations than rigid-frame, hyperstatic structures [1, 2].

Land deformations that are larger than those predicted during the structure design stage typically lead to the destruction of bearings, impeding free movement, and in some cases may result in serious construction disasters (e.g. in the case of bearings on tall piers with narrow caps) [3]. Many factors, such as the geological structure of the soil (cohesive and non-cohesive soils, plastic soils, loose soils) and foundation method (direct founding, piles) are not taken into account in mining predictions. The interaction between the structure and soil may significantly affect the values of individual indicators that describe land deformations (surface deformations, land tilt T , curvature radius R). For the reasons set out above, it is appropriate to apply another approach to the control of bridge behaviour in areas with grounds undergoing mining deformations.



This article presents basic rules for building simple monitoring systems for typical structures with diagrams of a simply supported beam, describes most commonly used measuring sensors and system structure and lists examples of the operation of completed systems and discusses the most interesting results.

2. Monitoring system of structure

2.1. General information

In this article, the term monitoring (SHM – Structural Health Monitoring) refers to the set of actions related to the continuous measurement of selected physical values, which are conducted automatically with the use of electronic sensors. During the monitoring system design stage the expected variability of the measured parameters must be initially determined in order to define proper ranges of measuring sensors.

The first step is the definition of targets and the formulation of tasks to be performed by the system designed for a certain bridge structure. These tasks shall be defined in a conscious and precise manner in order to get a valuable response from the performed measurement [4, 5, 6, 7, 8, 9]. Physical quantities selected for monitoring shall be the most significant ones, for example from the point of view of the safety of structures or the verification of calculation models (depending on the set monitoring targets). In the case of mining areas, the basic target is to ensure the safety of structures on deforming soil. Typically, the operation of bearings and expansion joints is controlled, as well as the tilt of the structure (piers, abutments) as compared to its initial configuration. These values are measured statically because their variability in time is so slow that individual measurements can be taken at minute- or even hourly intervals.

Apart of static influence of mining deformations, resulting in measured displacements, the dynamic impact of paraseismic activity of mines should be also considered. Such influence cannot be measured in a long-time perspective, however, at least for the construction phase, dynamic monitoring should be provided. Example of simultaneous influence of mining and geotechnical works on the adjacent structures was given by Pieczyńska and Rybak [10]. Other works [11, 12] strongly emphasize the necessity of dynamic monitoring of piling and soil improvement works with a special regard to the possibility of technology calibration. Same articles [11, 12] provide numerous examples of active design of geotechnical works, understood as decision making process based on data acquired from various monitoring systems.

Parameter values registered by the monitoring system shall refer to the values determined (computed) earlier on the basis of the solution for the numerical model and mining predictions. The measurement itself, without the comparison between the measured data and limit values, shall be referred to as ‘observation’.

The next step in the performance of the structure monitoring system includes its configuration, which consists in the selection of measuring elements (sensors), determination of their measurement ranges, data recording and transfer method, and the construction of algorithms to convert the values measured by the sensors to physical quantities that are useful from the point of view of structural analysis.

2.2. System structure

Due to the values of deformation of mining areas, usually at the design phase of bridges that may be prone to these deformations, the simply supported beam models are adopted. It is then correct to assume that the assessment of the safety of structure may be conducted by analysing the structure as a set of rigid volumes that move in respect of each other [3]. Thanks to this approach, the structure monitoring system contains a relatively small number of measuring devices and the indications of the sensors correspond directly to the measured physical quantities. The measurements usually cover linear displacements of spans against supports (also those that are theoretically stationary) in two horizontal directions perpendicular to each other and angular displacements of abutments and piers in two perpendicular vertical planes. Due to the long-term nature of the monitoring system operation, the most

widely used sensors are string potentiometers [13]. Sensor measurements are usually taken every dozen or so minutes. This interval is short enough to keep the probability of a significant variation in the measured value between subsequent measurements in areas prone to static influences of mining operations low. Data from sensors is transmitted via electrical cables to a recorder or recorders located on the bridge. The use of cabling is required in order to minimise the risk of interference in the measurement signal caused by external factors (e.g. electromagnetic field of passing trains or trams etc.). It is recommendable to supply recorders with current from the electrical network and not from batteries. In order to eliminate the risk of a data transmission failure, recorders are equipped with buffer accumulators with the purpose of providing backup power supply for at least 12 hours. Data stored on local discs of the recorders is sent to the measurement server via Internet. Depending on local transmission capabilities, either fixed fibre optic connections are used or GSM/LTE modems, radio networks etc. The measurement server is used to perform the analysis of data from recorders on a continuous basis, present it in a useful form (text tables, diagrams, statistical analyses) and send messages about alarm situations to people responsible for structures' safety. The monitored structures are usually located along rail, tram or car traffic routes, hence their failure could lead to significant material injuries and loss of human lives. For this reason, the structure monitoring systems must be highly reliable and guarantee measurement stability in time.

The following part of the article provides a description of two operating structure monitoring systems. Both of them operate on bridges located in mining areas.

3. Road and tram bridge in Ruda Śląska

3.1. Description of the structure

The road and tram bridge is located on the road and tramway line and creates a passage above the obstacle formed by a railway tracks, ensuring the continuity of road and rail traffic – figure 1. The structure was built in 1970s, then modernised and repaired in 2010 and 2013 in order to adapt the bridge's structure to the safe adoption of the impacts from the planned mining activities.



Figure 1. Road and tram bridge: a). view from south-west, b). view from north-east [5]

The bridge is formed by two independent spans of slab-and-beam structure and overall dimensions of $\sim 13.5 \times 18.1$ m and $\sim 9.8 \times 18.0$ m respectively, separated by an expansion joint with a design width of approx. 40 mm.

Each of the bridge's spans is supported by massive reinforced concrete abutments with direct foundations, separated by an expansion joint of a design width of approx. 0.30 m. Spans are supported on abutments via elastomer and elastomer-slide bearings. The planned width of expansion joints between the deck slabs and abutments is 80 mm in the case of northern supports and 140 mm for southern supports.

3.2. Mining

During the monitoring in 2011-2013, the bridge was located in an area affected by mining operations at two longwalls exploited using the longwall top coal caving system:

- the first longwall with a thickness of 2.1 m at the depth of 520 m – between August 2011 and February 2012,
- the second longwall with a thickness of 2.7 m at the depth of 510 m – between May and October 2013.

The results of geodetic surveys indicate that between August 2011 and February 2012:

- the area around the bridge experienced deformations leading to its compression of ~ 2.0 mm/m,
- subsidence of approx. 0.63 m (northern supports area) and 0.65 m (southern supports area) and that between May and December 2013:
- the area around the bridge experienced deformations leading to its compression of approx. 0.5 mm/m,
- subsidence of approx. 0.17 m (northern supports area) and 0.25 m (southern supports area).

3.3. Description of the monitoring system

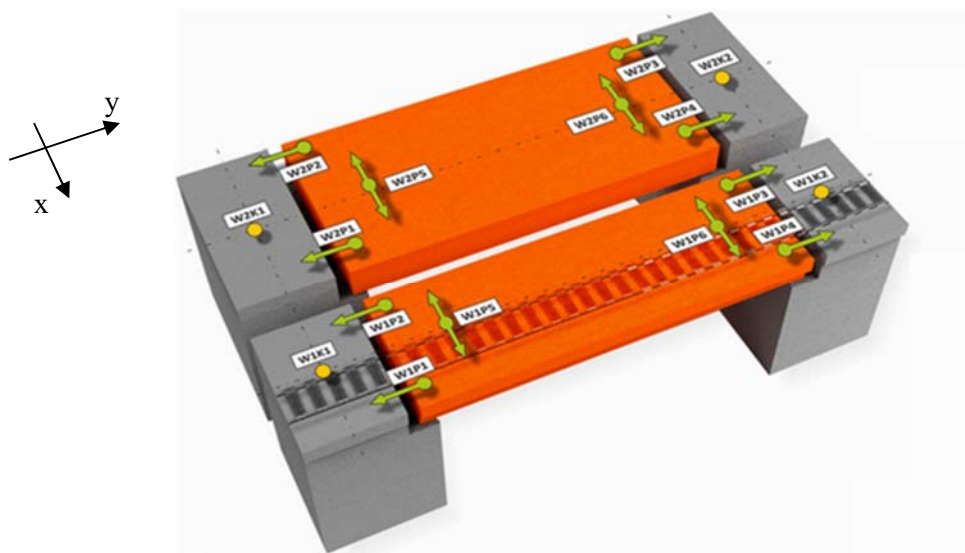


Figure 2. Location of sensors on selected structures after the modernisation of the observation system. Symbols: sensors measuring displacement – WP; sensors measuring angles – WK [5]

Initially the structure monitoring system consisted of 16 sensors (figure 2):

- 8 linear displacement string potentiometers for measuring displacements of deck's slab against abutments in the y direction – $WiPj$ ($i=1$ for the road bridge, 2 – tram bridge; $j=1\div 4$ – sensor number),
- 8 angular displacement string potentiometers for measuring abutment tilt in two perpendicular planes – with 2 sensors per each measurement point – $WiKj$ (i, j – see above).

In May 2013, 4 linear displacement string potentiometers were added to measure the displacement of the deck slab against abutments in the direction perpendicular to the bridge's structure (x-direction) – $WiPj$ ($j=5\div 6$). The monitoring system was described in detail in [4] and [5].

3.4. Measurement results and their interpretation

Figure 3 below presents measurement results for the first six months of mining operations as illustrated by the case of the road span.

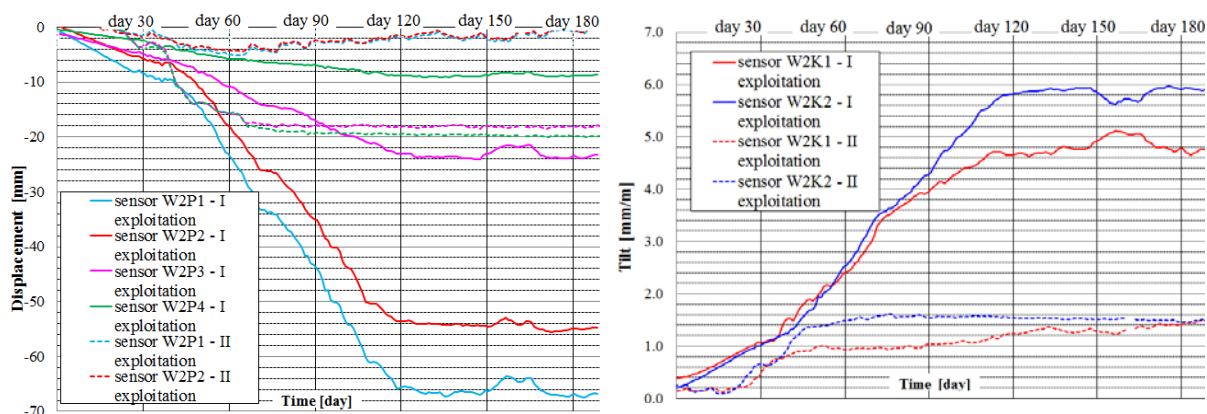


Figure 3. Results of linear and angular displacement measurements for the road span [4], [5]

Table 1. Net values of permanent relative displacements between abutments and deck slab [mm]

Sensor No (figure 2)	Longwall mining	
	first [4]	second [5]
ROAD SPAN		
<i>W2P2 and W2P3</i>	-73.8	-18.6
<i>W2P1 and W2P4</i>	-71.7	-20.6
TRAM SPAN		
<i>W1P1 and W1P4</i>	-94.3	-28.6
<i>W1P2 and W1P3</i>	-96.7	-28.7

Basing on the analysis of diagrams in Figure 3 and numerical values presented in Table 1, it can clearly be seen that the impact of the first longwall is significantly larger than that of the second longwall. This is caused by the location of mining works in relation to the bridge. Larger displacements were measured at southern abutments and larger tilts for northern abutments (Figure 3, Table 1). This observation coincides with geodetic surveys of ground subsidence. Furthermore, during the continuous structure monitoring it was noticed that as the longwall mining operations approached the bridge, relative volume displacements occurred, which was recorded in the form of linear deck displacements against abutments and angular displacements of abutments.

4. Railway bridge in Pawlowice

4.1. Description of the structure

The structure under consideration is a railway bridge carrying a two-track electrified PKP line. There is a local road and a stream passing underneath. The bridge consists of two parts, which form separate structures:

- a riveted steel structure (western bridge) under track no 1.
- a welded steel structure (eastern bridge) under track no 2 (Figure 4).

Each part consists of two steel spans, and each of them works statically as a simply supported beam. Spans are made of two plate girders that form an open deck.

Mining operations under the bridge were carried out at different levels. Longwall face approached the structure from the north and then passed underneath the bridge. Due to the direction of deposit extraction, mining land deformations first appeared on the northern side of the bridge. Because of the increasing tilt of the high pier, bearing displacements were not symmetric at the two abutments. The

response of the western structure to the mining pressure should be similar to that of the eastern bridge, hence the monitoring system was only installed on the eastern bridge to reduce costs.

The (monitored) eastern bridge was built in 1973. Steel structural components are welded. Girder flanges have constant thickness.

Structure's geometry:

- total length of each span: 27.50 m,
- vertical clearance: 8.20 m (above the road),
- operating length of the bridge: approx. 60.00 m (including abutments).

The intermediate support (pier) and abutments are made of concrete. Abutments are founded directly on railway embankments. The pier is more than 8 m high and is also directly founded. Thick horizontal cracks can be seen on the pier. Locally, their width exceeds 1 mm. The behaviour of the cracks is affected both by mining land deformations and the rolling stock (spans under both tracks have open decks without the layer of subbase/ballast that could absorb vibrations).



Figure 4. View of the eastern (monitored) bridge under track no 2

4.2. Mining

Mining operations in the surroundings of the structure have been performed since 1973. Geodetic surveys of settling between May 1973 and December 2016 showed:

- northern abutment approx. 3.55 m,
- southern abutment approx. 3.30 m.

Horizontal displacement from March 1994 (there were no measurements of horizontal displacement before) until December 2016:

- eastern bridge, western edge: -197 mm,
- eastern bridge, eastern edge: -184 mm,

It can be observed that abutments come closer to each other and pivot about the bridge axis.

4.3. Description of the monitoring system

A structure monitoring system was installed in October 2013 on the eastern part of the structure. The system consists of an observation subsystem that is intended to gather and transfer data and a warning system intended to analyse measurement results and inform users of upcoming dangers. The location of measurement points on the structure is shown in figure 5. The structure of the monitoring system from the technical perspective is described in more detail in [6].

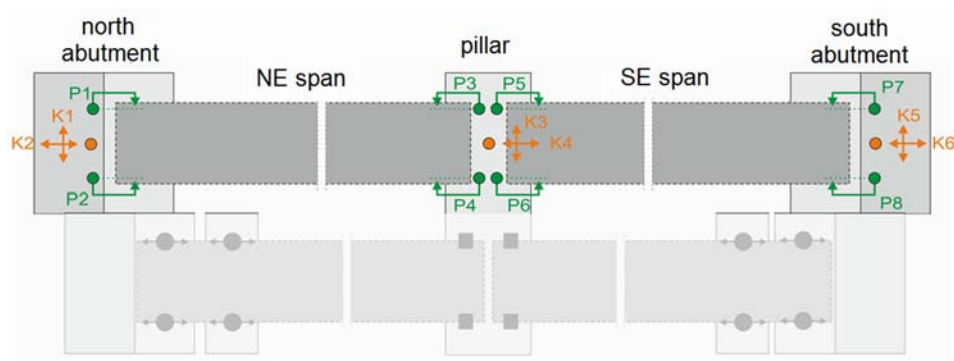


Figure 5. The location of measurement points on the eastern bridge: P – linear displacement measurements, K – angular displacement measurements

The selected physical quantities whose change significantly affects the technical condition of the structure include displacements of spans in relation to the supports along the structure's axis and angular displacements of supports (tilts) in two perpendicular vertical planes – figure 6.

The system's structure uses string potentiometers of displacement with a measuring range of 200 mm and angular displacement string potentiometers. The system is supplied by batteries replaced during periodic inspections of the facility. The readings from the sensors are taken every 15 minutes and once in every 24 hours sent via GSM network to the measurement server, where they are processed and automatically analyzed. The system generates daily reports of the structure's behaviour and sends them to people responsible for its safety. It is worth noting that as yet no emergency situation has occurred.

Apart from its control function, the monitoring system also provides information that allows for the verification of the predicted mining land deformations. It could serve as a tool to settle any disputes arising from mining damages. The land exposed to mining deformations creeps down and spread creeps as the mining face passes underneath the structure. Geodetic survey is not always performed at the moments when extreme deformation values can be recorded, i.e. the values that should be considered when assessing the impact of mining operations on the structure.



Figure 6. Support structures for mounting angle sensors and displacement sensors at the intermediate support (view on the west side)

4.4. Measurement results and their interpretation

It was assumed that the negative value of measurements on the following diagrams corresponds with the closure of the expansion joint. After the initial period of spread creeps (tension) in the subsoil, the phenomenon of soil creeping down (compression) strongly predominated. The increment of displacements was particularly visible on the northern abutment (sensors P1 and P2 in figure 5). The width of expansion joints between the span and the gravel wall on the northern abutment was approx.

90 mm in mid-April 2015. In the period between mid-October 2013 and end of March 2017 this width (sensors P1 and P2) decreased by approx. 85 mm, which means that the movement of the span against the support was practically impeded – figure 7. The expansion joint on the southern abutment was also reduced by approx. 50 mm. The difference in displacements on the opposite abutments can only partially be attributed to the tilt of the tall pier towards the north–; it can be caused by the direction of the movement of mining operations (north to south) and the variable thickness of plastic clays deposited in several layers between a few up to several tens of meters below the land surface.

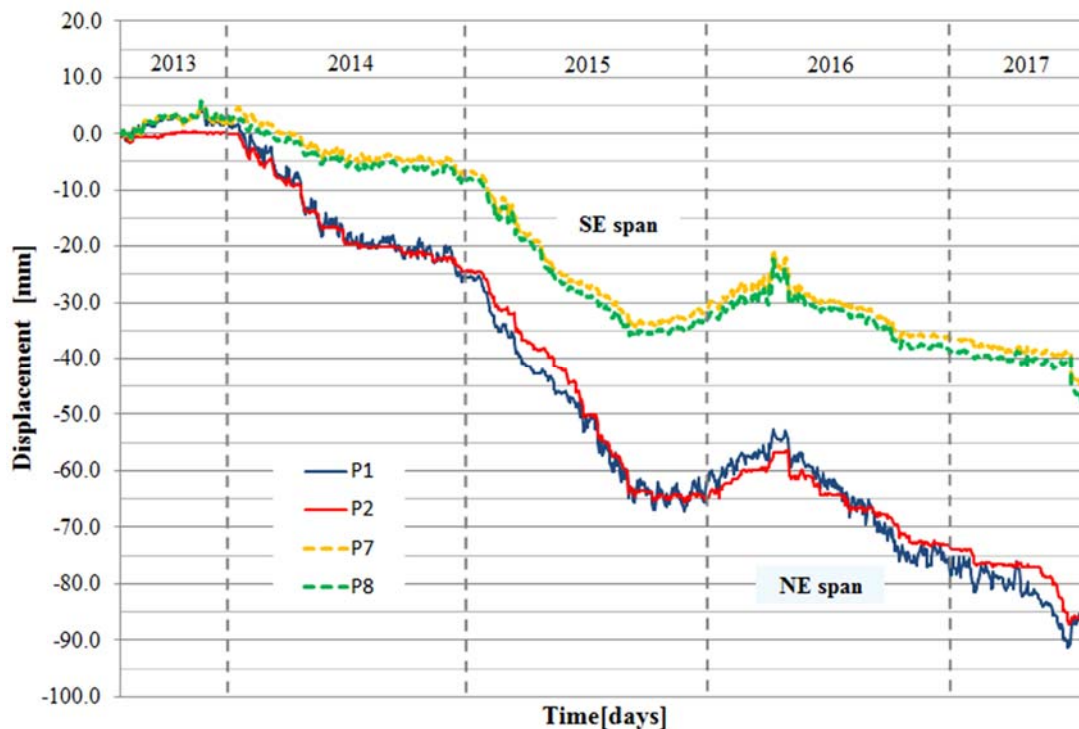


Figure 7. Diagram of changes in linear displacements of NE and SE spans against abutments along the structure's axis

Figure 8 shows diagrams of changes in the tilt of the north-east and south-east abutments in the period between mid-October 2013 and end of March 2017. The analysis of angular displacements (Figure 9) in the vertical plane parallel to the structure's axis (sensors K2 and K6) together with the values of span displacements against abutments measured by sensors P1 and P2 and P7 and P8 shows that abutments have come closer to each other. The value of their relative displacement at the foundation level is larger than at the level of deck support.

The measurement of the tilt of the north-east abutment in the plane perpendicular to the track axis provides an important observation. The measured angular value is currently $K1 \approx -0.39^\circ$. It means that the abutment tilted towards the west. However, the pier tilted towards the east: the measured angular value is currently $K3 \approx 0.18^\circ$. This behaviour of the north-east support may result in the observed interlocking of the unidirectional bearing (sensor P2).

The measurement of the tilt of the intermediate support in the structure's axis plane and in the perpendicular plane shows that the pier tilted towards the north so that the displacement of its head now amounts to approx. 25 mm, and to the east, causing a horizontal movement of the head of approximately 24 mm [6].

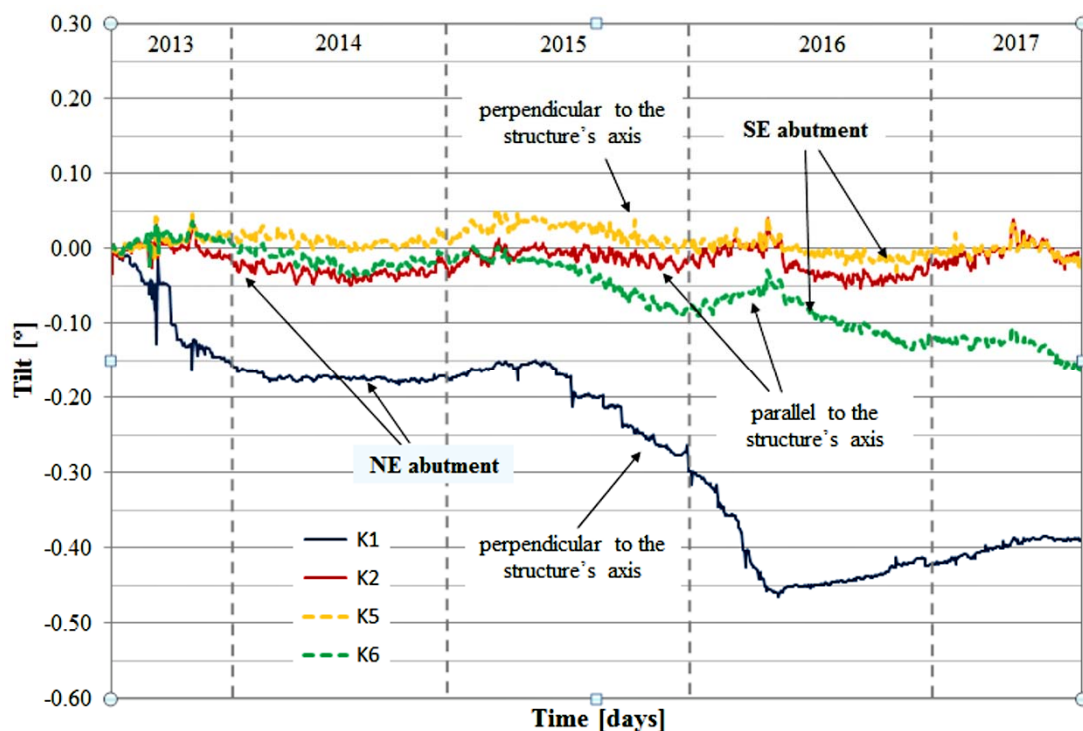


Figure 8. Northern and southern abutment tilt in the planes parallel and perpendicular to the bridge's axis (K1 '−' means a westward tilt; K2 '−' means a northward tilt; K5 '+' means a westward tilt; K6 '+' means a northward tilt)

5. Conclusions

Structures built in areas exposed to mining deformations experience displacement and tilting. Ongoing monitoring of the structure's behaviour towards the pressures allows for controlling their impact on the technical condition of the structure. In the case of railway structures, measurements may also allow for determining how the change in the structure's geometry affects the trackbed.

Structures in areas where mining operations are performed are very often subject to deformations caused by extractions of different coal deposits in different directions that overlap in time. Installing structure monitoring systems allows for taking measurements on a regular basis without involving human resources. Due to the anticipated long period before the impact of mining is revealed, this solution guarantees proper observation. Automatic measurements have the advantage of frequent data gathering, making it possible to capture the moment when a structural failure occurs.

Constant access to measurements via a dedicated measurement platform and the possibility of defining alarm values, for which the monitoring system automatically takes actions such as sending warning messages to people responsible of the structure's safety, significantly improves the safety of bridge users and allows for active managing, for example of the rolling stock traffic.

Given the amount of information provided by the structure monitoring systems and the wide range of their practical applications, it seems that the number of bridges located in mining areas that are equipped with these devices will significantly grow in the near future.

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