The use of two-axis high precision inclination sensors in determining headframe deflection

Wojciech Jaśkowski*[1], *Mateusz* Jabłoński[1], *Małgorzata* Ulmaniec[2], and *Krzysztof* Paraszczuk[3]

[1]AGH University of Science and Technology, Krakow, Poland

[2]Cracow University of Technology, Faculty of Civil Engineering, Krakow, Poland

[3]District Mining Office in Krakow, Krakow, Poland

Abstract. Reliability of transport equipment in the shaft depends, among other things, on the accuracy of the vertical foundation of the headframe together with elements of the hoisting equipment over the shaft. Any deviations beyond the installation and movement tolerances may cause incorrect or even dangerous operation of the hoisting equipment in the shaft. Therefore the headframe is subjected to periodic inventory measurements, which prevent the movement in the shaft and the smooth operation of the whole underground mine. The Wieliczka Salt Mine developed a project for the installation of precision Nivel 220 two-axis inclinometers on Kinga and Daniłowicz headframes. The paper summarizes the initial conclusions resulting from the first year of the system operation and indicates the directions of its development.

Keywords: precise, inclinometers, headframe, deflection

1 Inventory measurements of headframe in Polish law

Inventory measurements of headframes and their range depend on the type of deformations occurring in the facility and should meet the requirements set for them in the relevant regulations. Diversified construction of these objects, as well as the purpose of inventory measurement, generally require the development of individual programs for these measurements. In particular, when there are external causes that can cause headframe deformations, for example effects of mining exploitation carried out in a shaft pillar – then the inventory measurement program should include a broadly understood control of geometry changes of particular construction axes defined in Polish Standards [1]. In such cases, unevenness of depressions at the foundation points of the headframe may lead to warping of the structure, and thus pose a threat to the use it.

* Corresponding author: jaskow@agh.edu.pl

On 9 June 2017, pursuant to the Regulation of the Minister of Energy of November 23, 2016, on the detailed requirements for the operation of underground mining facilities [2], the Regulation of the Minister of Economy of 28 June 2002 on health and safety, traffic management and specialized fire protection in underground mines [3] has been repealed. The previous Regulation left the measurer a lot of doubts, especially regarding the deflection of the headframe, mainly due to the provisions in §469.1 [3]. The problem was that the measurement should be subject to the stem of the headframe treated as an extension of the guides from the shaft, meanwhile the measurers are required to extrapolate its declination to the height of the rope pulleys, which are located on the head, the element independent of the stem. This means that the stem of the headframe has its axis, independent of the axis of the head (available on figure 3) [4, 5]. In 2017, the legislator attempted to clarify the above provision (§542.1.2 [2]), introducing another concept of "axis of the headframe", also unknown in the Polish Standard [5], so the change of the regulation did not change anything. At the same time in §542.3 there was a record enabling further use of the headframe despite exceeding the above deflection with the consent of the Chief of the Mining Facility Movement, based on the opinion of the expert.

2 Measurements of headframe's verticality changes

Measurements of the verticality of the headframe are sometimes very laborious due to the various constructions of headframes and pose a lot of technological difficulties. Often, it is sufficient to measure relative changes in headframe's verticality to assess its technical condition or the influence of external factors affecting it. The difference in the measurements of relative changes in the verticality of the headframe in relation to the absolute measurements lies in the lack of the need to determine the mutual position of the measurement points in relation to the vertical axis of the headframe. Omitting the designation of these elements greatly simplifies these measurements and allows the use of all methods regardless of the construction of the tower. There is also no need to stabilize the control points exactly in the plane of the headframe main axis.

Application of the above-mentioned principle leads to the fact that the designated coordinates of control points, located on the headframe, can be used to determine the state of its position in the vertical, after determining the initial eccentrity. This means that the cyclic positioning of these characters can be interpreted only as a periodic change in the position of the structure in the vertical (equation 1, fig. 1).

$$P_i = M_i + dP_i \tag{1}$$

where: P_i – total resultant deflection vector of main axis on level „i"; M_i – initial resultant deflection vector (initial eccentrity) of main axis on level „i"; dP_i – periodic changes of main axis on level „i".

To obtain the angular value of the tower inclination (η_i), the vector should be divided by the height (H_i) of a particular level, relative to the basic girder of the shaft. Due to small values of vectors on particular levels in relation to their height, the function of small angles could be used, determining the values of deflections from the equation 2 for changes in total deflections of individual levels and 3 for periodic changes of deflection of individual levels.

$$\eta_i = \frac{P_i}{H_i} \tag{2}$$

$$d\eta_i = \frac{dP_i}{H_i} \tag{3}$$

where: H_i – height of level „*i*", according to regulation [2]

It follows from the above that observations that determine the coordinates of control points in a cyclical manner allow only to determine periodic deviations of the tower structure from the vertical. Determination of initial inclination M_i is based most often on inventory measurements of characteristic axial points of the structure. This makes it possible to determine the total deflection of the construction axis from the vertical. It should be remembered that the headframe's inclination value determined in this way - in the form of a displacement vector at a given height are – only information related to the moment of the measurement. Therefore, such measurements should be carried out in the absence of any additional factors affecting the structure.

When measuring verticality or changes in verticality of the headframe, it is important to determine the changes of the headframe during its operation. Also, the determination of the impact of external conditions, such as solar radiation, wind pressure and impact of mining shocks, allows for a more complete picture of the behaviour of the structure. Determination of the maximum values of dynamic changes in the position of the headframe, caused by the above-mentioned factors, allows taking into account these values in the measurements of the structure verticality. Thus obtaining the actual values of the tower deflection, can then be compared with the limit values.

The solution to these problems is the use of measuring methods that provide quasi-continuous measurement of changes in the hadframe's deflection. These methods, included in the telemetric methods, automate the measurement process, ensuring the receipt of information sets characterizing at each programmed moment. The measurement results are used further to calculate and evaluate the process. Most of telemetry systems used in geodesy are based on electrical systems [6]. The signal source in such measuring system is the sensor, on which the measured quantity acts directly. In the case at hand, this is the change in inclination. Inclinometers are tools for measuring instantaneous and continuous changes in structure inclination to determine the deformations that occur on them. The use of precise inclinometers allows to determine from obtained changes the actual values of the inclination of headframe's axe. The arrangement of inclinometers on the construction elements of the headframe, located at different heights also allows defining the deformation of the headframe structure [7]. The use of two-axis inclinometers (eg Leica's Nivel 220 [8]) allows simultaneous determination of these values in two perpendicular directions [9-11].

The data recorded by sensors show the current slope of the plane on which they are located. Recalculation of data from inclinometers on the values of declination changes in headframes is made according to the equations 1 and 4 (fig.1).

$$dP_i = D_i \tan\alpha \tag{4}$$

where: dP_i – periodic changes of main axis on level „i"; α – the inclination angle obtained from the inclinometer; D_i – height of inclination sensor location.

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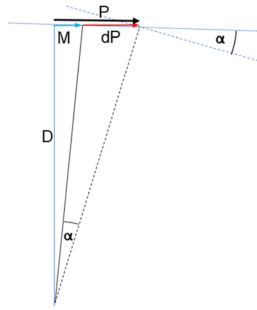

Fig. 1. An algorithm for converting data obtained from inclinators into values of changes in the headframe's inclination, variables according to equations 1 and 4.

3 Measurement system for continuous monitoring of Daniłowicz and St Kinga headframes in the Wieliczka Salt Mine

To support the inclinometers installed on the headframes that ensure full use of these devices in continuous monitoring of changes in headframe’s inclination, a device design has been developed (Fig. 2). The designed device has been equipped with a microcontroller, whose task is to acquire data from two-axis inclination sensor Nivel 220 (Leica Geosystems AG) through the RS485 interface. The data is archived on a removable SD memory card installed in the device. The microcontroller was also connected to the WiFi transmission module, which enables the transfer of data from the inclinometer via a network with a computer installed in the mine's measurement department, but due to technical reasons this form of communication was abandoned. The device is powered from the 230V mains supply to the level of pulleys in the TNS network configuration.

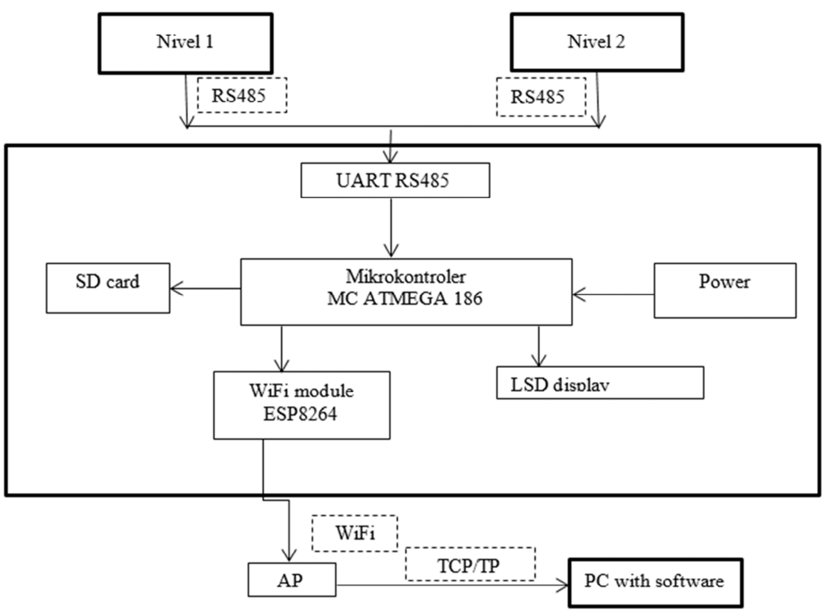

Fig. 2. Diagram of the device for recording and transmitting measurement data.

Obtained data are transferred to the recording device via the RS485 port. On the computer (and at the same time data server) specially created software has been installed. That allows converting data from inclinometers into headframe inclination changes and their visualizations. The recording of data takes place in the recording device on the SD card with a 68-second interval.

The Daniłowicz and St. Kinga headframes have a similar height of the rope pulleys, 22.3 m and 23.5 m, respectively. Their maximum allowable deflection is about 45mm. Regarding both towers it was decided about the need to look independently at the stem and head (fig. 3). One inclinometer was installed on the rope pulley platform (at a height of about 23 m), the other on the highest possible beam of the tower stem (about 21 m on the Daniłowicz headframe and about 20 m on the St Kinga headframe) (Fig. 3).

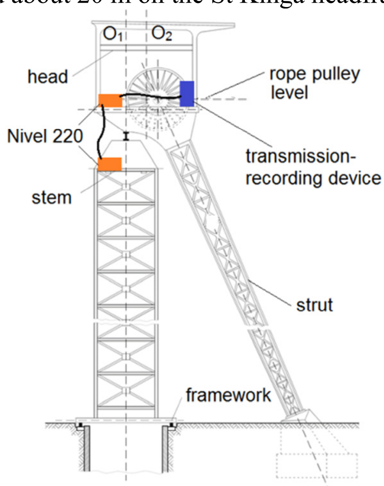

Fig. 3. Scheme of sensor arrangement on a headframes. O_1 – stem axe, O_2 – head axe.

4 Data analysis

The system was launched at the end of October 2016. Due to large changes occurring in the first days of data logging, it was decided to analyse the deviations from November 1st, 2016. Currently, laboratory tests are underway on the time of stabilization of the system depending on the time of transport, the position of sensors in transport and changes in temperature or voltage. This will allow future errors in the interpretation of data to be avoided. One of the biggest problem of the analysis were data writing errors. They were probably caused by temporary power interruptions or overvoltage. The second problem of the analysis was measurement noise caused by diurnal changes in the inclination. Under the operating conditions of the headframes in the Salt Mine Wieliczka, they are conditioned by:

- wind pressure on the structure
- operation of hoisting equipment machines
- insolation of the structure.

Analysis of deflections does not require monitoring of changes in the momentary deflection of the tower, so it was decided within an interval of 68 seconds, hence it was decided to take into account only observations from each day at 4 am (CET). The temperature is then stabilized after a night cooling (this is especially important in the summer). The Wieliczka Salt Mine works in a 2-shift system (6 am to 10 pm), while the service of tourists takes place between 6 am and 7 pm or 9 pm (depending on the season).

Occasional events organized underground can take place in the evening, but usually end around 2 am. At 4 am therefore, the impact of the work of the hoisting machines is not expected.

In order to eliminate errors a program was created in the Python environment to denoise outliers. It was based on the selection of the appropriate data line, its analysis for correctness of data and deletion or saving to the result file. It was also necessary to check the correctness of the temperature mark, because only four characters were recorded, counting a positive or negative sign and a comma, however, the signs determining the ratio to zero were given up first. This means that at a temperature of more than 10 degrees Celsius, the character was not written to the file. For a specific day, a sign like in the previous day was assigned in such cases. The files were then formatted to a compatible version with a browser allowing additional analyses in MS Excel. The data viewer in the LabView system only allows to visualize the changes in inclinometer readings. The data collected in MS Excel made it possible to calculate periodic changes of deflection at individual levels and resltant vectors (total vectors of deflection without adopting a specific value of initial eccentrity vector M_i). Below are presented graphs of periodic changes in the deflection of the Saint Kinga (Fig. 4) and the Daniłowicz headframes (Fig. 6) and resultant vectors of the Saint Kinga shaft declination (Fig. 5) and the Daniłowicz headframe declination (Fig. 7). Sketches of towers with the designation of their own layout and the location of the sensors are shown in Fig. 8.

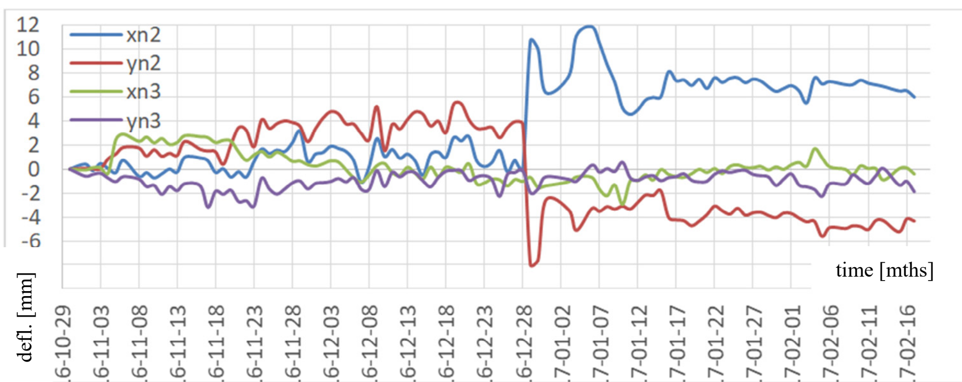

Fig. 4. Periodic deflection changes at the head (N2) and stem (N3) level, St. Kinga shaft.

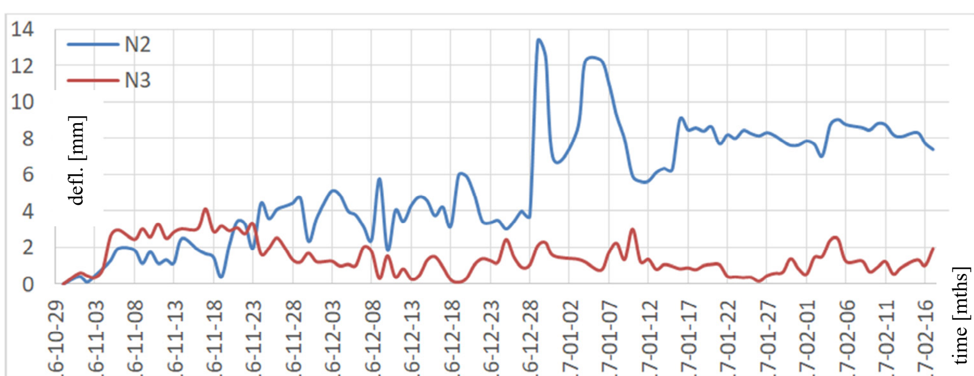

Fig. 5. Resultant deflection vectors at the head (N2) and stem (N3) level, St. Kinga shaft.

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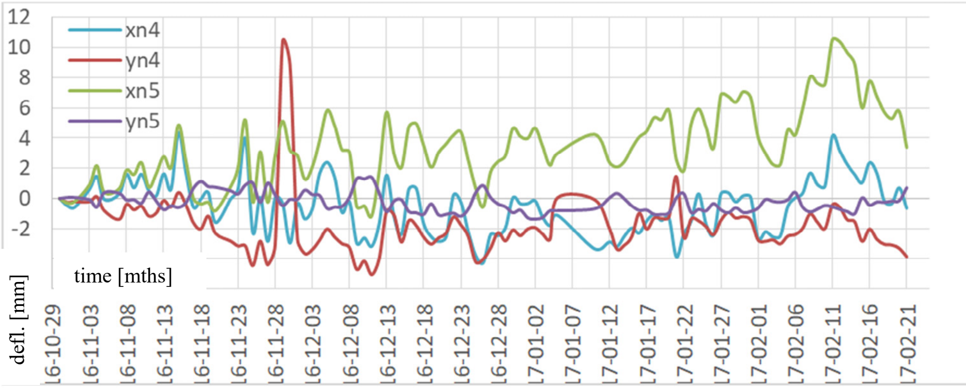

Fig. 6. Periodic deflection changes at the head (N4) and stem (N5) level, Daniłowicz shaft.

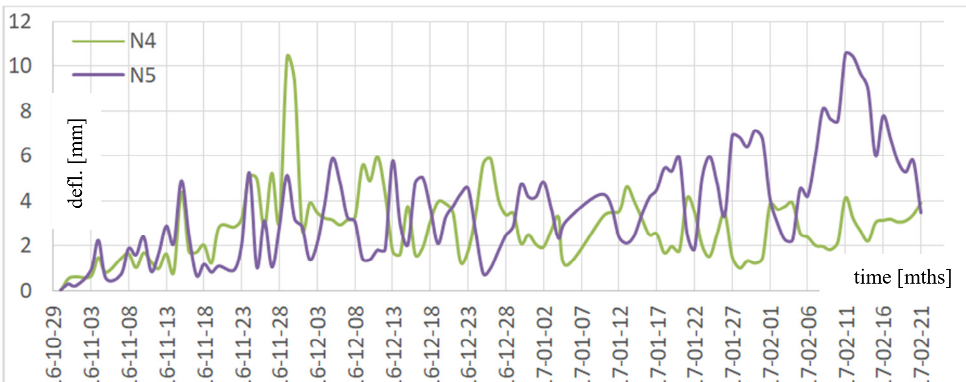

Fig. 7. Resultant deflection vectors at the head (N4) and stem (N5) level, Daniłowicz shaft.

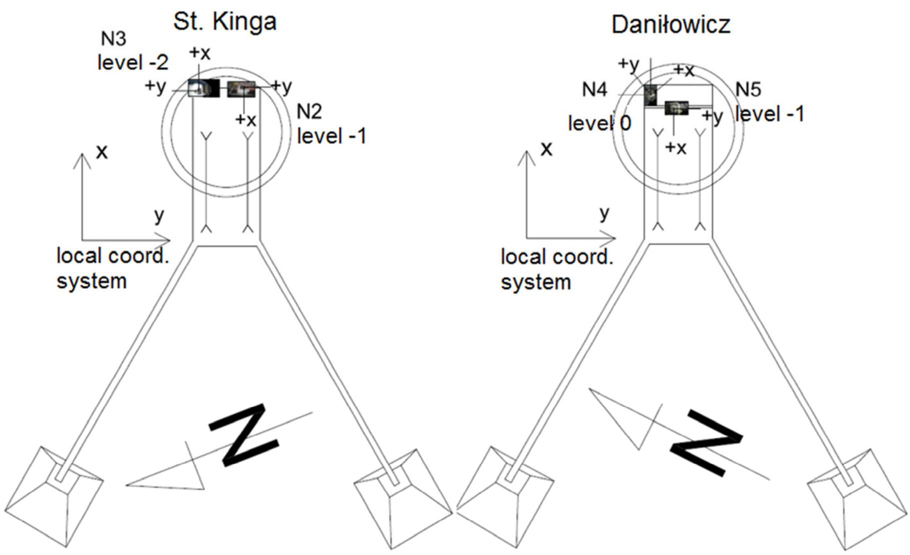

Fig. 8. Sketch of headframes with designation of local coordinate system.

After installing the sensors and the reading system at the end of October 2016 and carrying out the review in mid-November 2016 and the inability to start the data transmission by the wi-fi module, it was decided to remain in the data recording mode on the SD card. This was related to the need to enter the headframe each time in order to collect data. The next time for the system review and data collection was February 21, 2017. The inspection did not show any problems, the transmission devices worked well and the inclinometers were in the range of A or B measurement accuracy [8]. During the next review carried out in June 2017, it was found that the data from the SD cards can not be read and the display with data is not working. Later attempts to recover data in professional companies have confirmed the burning of cards and data loss. The technical service showed that the system was damaged due to overheating caused by significant overvoltage, not necessarily from the power grid (for example as a result of a lightning strike). In both recording devices (on both headframes) all semiconductors have been damaged. The failure limited the possibility of analysis to the period from Nov 1st, 2016 to Feb 21st, 2017. The system resumed its work in January 2018.

5 Summary

The basic problem of the system turned out to be its durability. The system between February and June 2016 crashed, resulting in a loss of data from this period and a long-term service. The defect would be detected faster and less data would be lost if the observations were sent via the wi-fi module. Currently, work is underway to strengthen the transmission system and secure the system against voltage changes. The inclinometers themselves are currently subjected to laboratory tests on the influence of temperature, shocks and the time needed to fully stabilize the stabilization reading after transport and installation.

In the period in which data was correctly recorded on the SD card, two significant incidents were recorded, causing excessive declinations. In the case of a headframe located above the Saint Kinga shaft it was the period from December 28, 2016 to January 8, 2017. From the information provided by the Wieliczka Salt Main, it appears that during this period works related to the exchange of ropes were carried out, which would have caused the displacement of the head itself. A similar event, however unrelated to the setting of ropes, took place on the headframe over the Daniłowicz shaft on November 28-30, 2016. The cause of such inclinometer was not identified and the readings returned to the previous trend after a few days.

These events confirm the previous comments regarding the Regulations (from 2002 [3] and 2017 [2]), in which the axis of the headframe is defined. Studies clearly indicate that the head and the stem of the headframe behave independently of each other, so it is impossible to determine the axis of the entire object. The authors invariably propose the delimitation of the problem of verticality of the guides and the stem of the tower as one element, and the verticality of the rope descending from the rope wheels to the shaft as the second and independently deformation of the headframe as a building object.

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