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*Original Research Article*

# DEVELOPMENT OF A METHOD FOR TESTING A POWERED ROOF SUPPORT IN ORDER TO DETERMINE ITS OPERATING PARAMETERS

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Abstract

Monitoring of powered roof supports is an area for research. External factors have a significant impact on the operation of powered support in a longwall excavation, therefore the use of solutions that will counteract these factors is an area for improvement. The article presents studies related to the adaptation of the measuring and recording system for the geometric parameters of the section and its compatibility with the powered roof support. Each of the presented stages consisted of a series of analyses based on computer simulations using the finite element method (FEM), as well as bench tests and real-life tests. The tests included defining the geometric parameters of the powered roof support's work in the test site and the mining wall. These studies allowed for the development of guidelines for the monitoring system. The results and analysis allowed for the formulation of two crucial conclusions. The use of a measuring system is a tool that allows monitoring the geometric parameters of the powered roof support during the coal mining process. The system monitors the transverse and longitudinal inclinations of the canopy, base floor, shield and the lemniscate, as well as the operating height of the support. The structure of the powered support can also be improved to improve operational safety by installing innovative mounting brackets for the monitoring system. The holders will allow for safer and more precise installation of the sensors and will make calibration of the system easier.

Keywords: geometry measurement, powered roof support, work safety, longwall mining, monitoring

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## 1. INTRODUCTION

In mining, monitoring the operation of machinery and equipment is one of the key elements of a coherent concept of Industry 4.0 [1,2,3]. In coal mines, in addition to monitoring changes in the operation of machines using portable devices, measurement and control devices are used to monitor their work constantly [4,5,6]. The measurement method and its calibration are challenging for engineers and mining practitioners. Determination of measurement error depends on the technology mining companies use [7,8,9,15]. This aspect is of great importance in assessing technical condition and analysis of changes occurring in the working environment [9-12] and the assessment of movement performed by machines [13,14]. The technical solutions proposed by the market generate both advantages and disadvantages for mines [15,16,17,18]. Innovative solutions increase efficiency and work safety, which is an advantage but, simultaneously, increases costs [19,20,21,22]. Production burdened with too high costs is a barrier to ensuring the profitability of the work carried out and the viability of the mining plant [22,23]. An area that significantly limits the capabilities of the monitoring systems is the need for a database for processing extensive data collection by mining companies. This element influences how current measurements are monitored, predicted, diagnosed and archived [24,25].

The powered support is the main element of the longwall complex, which also consists of a mining machine and a scraper conveyor [26,27,28,29]. The operation of each of the machines constituting the longwall complex is dependent on each other [30,31,32]. The powered roof support protects the crew passage, supports the mining ceiling [33,34] and affects the mining machine's movement towards the unmined coal and the scraper conveyor responsible for coal transportation [35]. Figure 1 presents a view of the mining wall at the site of the crew's passage.

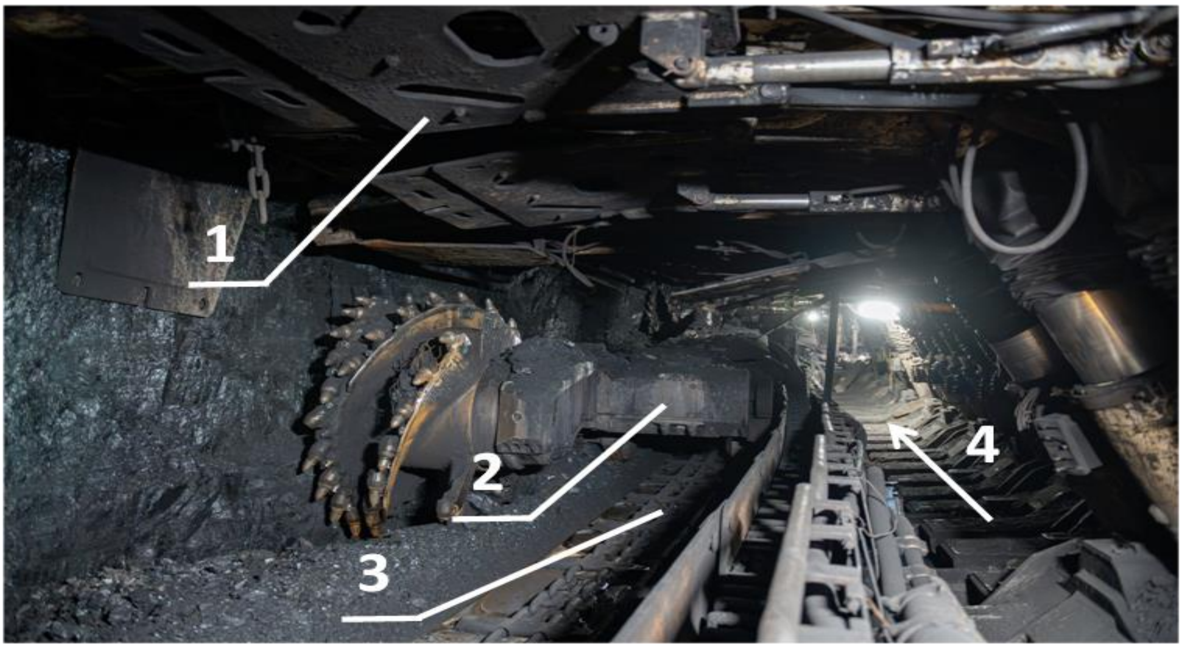


Fig. 1. View of the mining wall, where: 1 – powered roof supports, 2 – shearer, 3 – conveyor, 4 – crew crossing point

The process of mining coal is complicated. Constant supervision is necessary to ensure continuity of production. The market is mainly focused on monitoring pressure changes in the powered roof support's operation [36,37,38,39]. The operation of the support is greatly influenced by forces resulting from the load of the surrounding rocks and failures related to leaks in the support props [40,41,42,43]. Monitoring these phenomena will significantly affect the efficiency and safety of the powered support and will allow for a faster response [44,45]. If we enrich these measurements with geometric changes in the position of the powered roof support, it is possible to expand the area of research. Knowledge of such large data sets gives you the ability to determine in a broader aspect the powered roof support's operation cycle in real-life conditions [46,47,48].

Based on the study's results, the authors present the steps that made it possible to develop guidelines for a monitoring system that can work with a commonly used pressure monitoring system. The article characterises the work of the measuring and recording system. It determines the calculation method based on which the authors determined the angles of powered roof support for each element on which the sensor was built. The developed guidelines for the measuring and recording system and the construction of the powered roof support based on model, bench and actual tests will enable the implementation of a solution for monitoring the operation of the support in the production process.

## 2. MATERIALS AND METHODS

Determining the geometric values of the powered support operation is an important element of controlling the entire longwall complex. Information obtained from the support operation measurement system allows for the preliminary determination of the geological and mining conditions prevailing in the longwall excavation and its proper functioning. To illustrate the research, which formed the basis for the development of guidelines for the monitoring system, the authors developed a protocol (Fig.2).

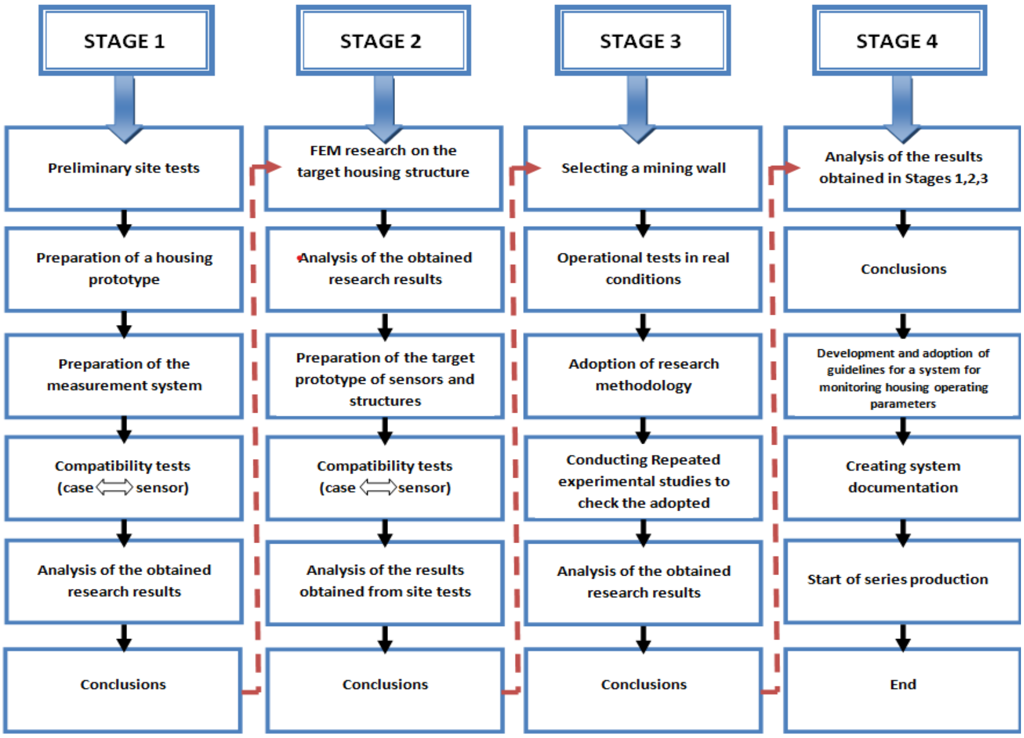



Fig. 2. Methodology of the procedure – research

The first stage (Fig.2.) of the research included laboratory tests. For the purposes of conducting the research, a prototype of the measurement system was constructed to conduct preliminary analyses of compliance with housings used on the market. The analysis excluded the collision of sensors with individual housing elements and their installation location. This stage included, as part of preliminary site tests, the use of a prototype of a powered roof supports equipped with hydraulic control, on which the sensor prototype was mounted on magnets. These activities initially determined the compatibility of the sensors with the housing. The first assumptions set by the research team were met. This allowed us to move on to the next stage.

The second stage (Fig.2.) focused on model simulations (FEM). Before starting the FEM analysis, a geometric and kinetostatic analysis was performed based on a flat model of the section. Then, the 3D model was made and used for strength analyses. A computational area has been defined in the form of a computational grid. Strength analyzes included determining the elasticity and plasticity limits of individual elements of the powered roof support.This method made it possible to exclude places on the powered roof support most susceptible to deformation and damage during operation.

After the analysis, the team started preparations for the target measurement system. The prepared target measurement system was made of intrinsically safe materials and permanently adapted to difficult conditions in mining. With the system ready, its installation on the powered roof support could be commenced, taking into account the previously performed analyses, in order to determine their compatibility. For this purpose, specialised mounting brackets have been prepared. The innovative holders prepared eliminated errors related to assembly, reduced measurement errors and eliminated assembly using magnets.

On the basis of the analysed data, the team chose a wall for testing in real-life conditions (Fig.2.). The choice of the test wall was crucial from the perspective of testing the system in the most difficult conditions of exposure to mining hazards. High risk of roof rockfall, dust, water and vibrations are selected factors that could have a significant impact on the system's operation. Testing in the wall was the third stage of work on the measuring and recording system. The measurement results from real-life tests and previously performed analyses allowed the team to determine the research methodology for implementing the solution. The course of activities carried out determined the final method of research, which will enable the definition of guidelines for the monitoring system.

In stage IV (Fig.2.), the guidelines were finally defined, and the technical documentation for the developed system was created.

It was necessary to determine the angles between the powered roof support elements to determine its geometric parameters. Sensors were thus used, which, based on MEMS technologies, allowed us to narrow the acceleration measurement. The angle on specific areas of the powered roof support's operation could be given thanks to the acceleration measurement. The acceleration value measuring method is shown in Figure 3 and the formulas below [49].

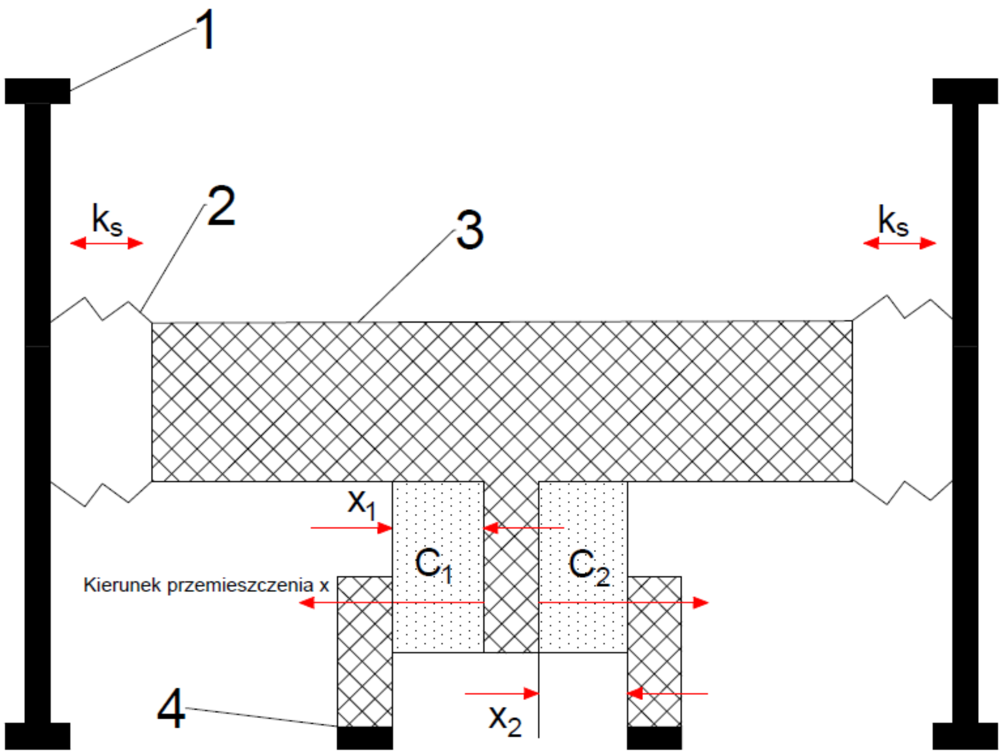



Fig. 3.Structure of MEMS accelerometers, where: 1 – base, 2 – spring, 3 – movable mass, 4 – fixed plates, C – capacity difference, $x_{1.2}$ – deflection value, $k_s$ – spring constant

The capacity of the flatbed condenser can be determined by the formula [50-52]:

$$C_0 = \varepsilon_0 \varepsilon_r \frac{A}{d} = \varepsilon_A \frac{1}{d} \; [F] \tag{2.1}$$

Where:
A - cover's surface [m$^2$],
d - distance between condenser's covers [m],
$\varepsilon_0$- appropriate electric vacuum permittivity [F/m],
$\varepsilon_r$ - relative electrical material permittivity from which the insulator cover is made [F/m].

The difference in capacity C1 and C2 (Fig.3) determines the value of the deviation of the suspended condenser covers. Adopting air permittivity $\varepsilon_A$ [F/m] between the condenser covers and the reference frame is as follows:

$$C_1 = \varepsilon_A \frac{1}{x_1} = \varepsilon_A \frac{1}{d + x} = C_0 - \Delta C \; [F] \tag{2.2}$$

$$C_2 = \varepsilon_A \frac{1}{x_2} = \varepsilon_A \frac{1}{d - x} = C_0 + \Delta C \; [F] \tag{2.3}$$

If $a = 0\ [m/s^2]$ capacity $C_1$=$C_2$= 0 [F], because $x_1 = x_2$ [m]. If, on the other hand, the displacement of the inertial mass x is different from zero, then:

$$C_2 - C_1 = 2\Delta C = 2\varepsilon_A \frac{x}{d^2 - x^2}\ [F] \tag{2.4}$$

Measuring capacity differences, $\Delta C$ you can read x by the equation:

$$\Delta C x^2 + \varepsilon_A x - \Delta C d^2 = 0 \tag{2.5}$$

$$x \approx \frac{d^2}{\varepsilon_A} \Delta C = d \frac{\Delta C}{C_0}\ [m] \tag{2.6}$$

It follows from the relationship that the displacement of a given mass is proportional to the capacitance difference ΔC. The capacity of the condenser is measured through two appropriately modulated voltage waves passed through the condenser. Comparing this data with the original modulating waveform, we obtain a voltage proportional to the difference in the capacity of these condensers. Hook's law [53] states that a spring exerts an elastic force $F_s$ proportional to the deviation x (Fig.3) from its initial state ($F_s$=$k_s$x), where $k_s$ (Fig.3) is the spring constant). It is sufficient to base these dependencies on Newton's Second Principle of Dynamics [54], to obtain the relationship between inclination and acceleration:

$$a = \frac{k_s}{m} x\ \ [m/s^2] \tag{2.7}$$

$\frac{k_s}{m}$this is a constant resulting from the structure of the accelerometer, and the value of the inclination x – as described – determined by the analogue processing system to the form of a voltage signal. For reference, it is worth noting that in the example accelerometer, the inertial mass is about 0:1g, the minor detectable change in capacity is about 20aF, and the distances between the condenser covers are about 1:3m.

Accelerometers measure the acceleration resulting from the Earth's motion and gravitation. Acceleration occurring during the movement is measured by sensors. The working angles of the housing elements are determined based on these values. The tilt angles determined by the system sensors are shown in Figure 4 and using the following formulas [55,56,57].

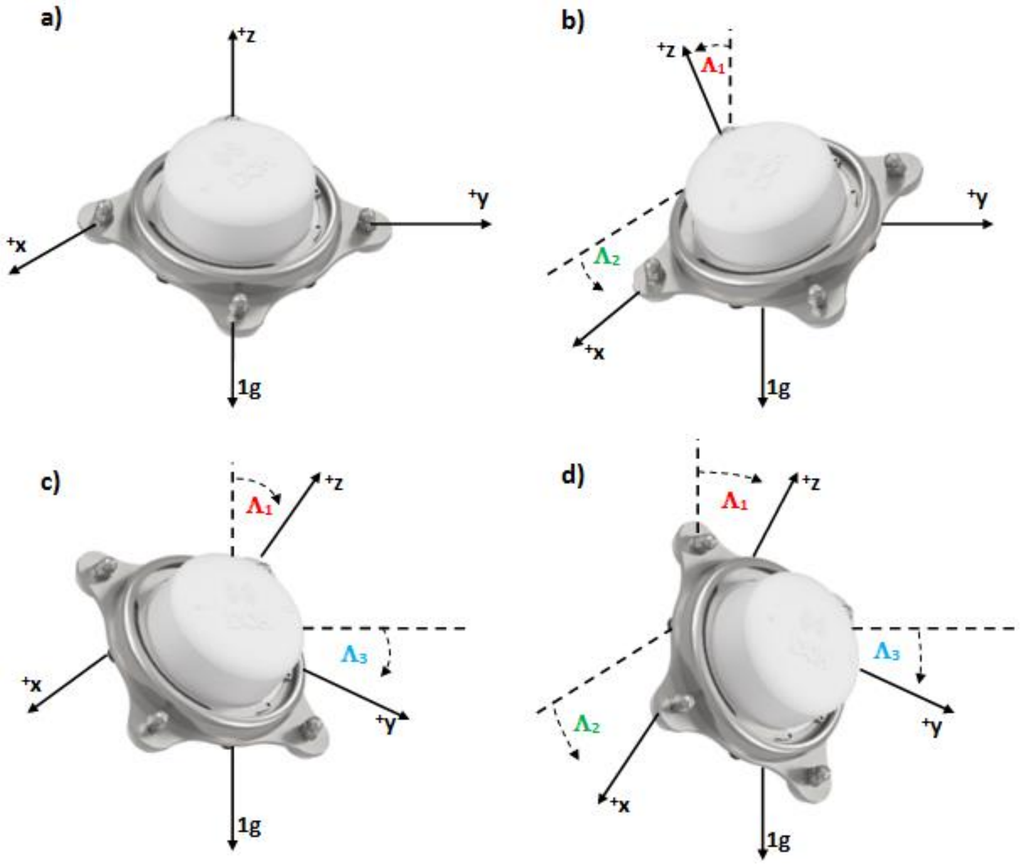



Fig. 4. Sensor slopes, where: **a)** reference position, device with axes x, y (field 0g) and an axis perpendicular to the horizon (field 1g), **b)** Λ2 angle between the direction of gravity and the z-axis Λ2 angle between the horizon and the x-axis of the accelerometer, **c)** Λ3 angle between direction and Y axis, **d)** inclination angle in three axes x, y, z

The angles of inclination are determined using the following formulas [52]:

$$\Lambda_1 = \arctan\left(\frac{\sqrt{a_x^2 + a_y^2}}{a_z}\right) [°] \tag{2.8}$$

$$\Lambda_2 = \arctan\left(\frac{a_x}{\sqrt{a_y^2 + a_z^2}}\right) [°] \tag{2.9}$$

$$\Lambda_3 = \arctan\left(\frac{a_y}{\sqrt{a_x^2 + a_z^2}}\right) [°] \tag{2.10}$$

Where:
Λ- angle value, [°]
$a_y$- Earth's acceleration value in the Y axis, [m/s$^2$]
$a_x$- Earth's acceleration value in the X axis, [m/s$^2$]
$a_z$- Earth's acceleration value in the Z axis, [m/s$^2$]

The use of MEMS accelerometers requires meticulous calibration. Calibration required leveling of the sensors. Leveling was performed at the time of their assembly on the structural elements of the housing. In the first phase of measurements, the system performs an angular cut-off α of the machine inclination, defining its inclination at point 0 (Fig. 5).

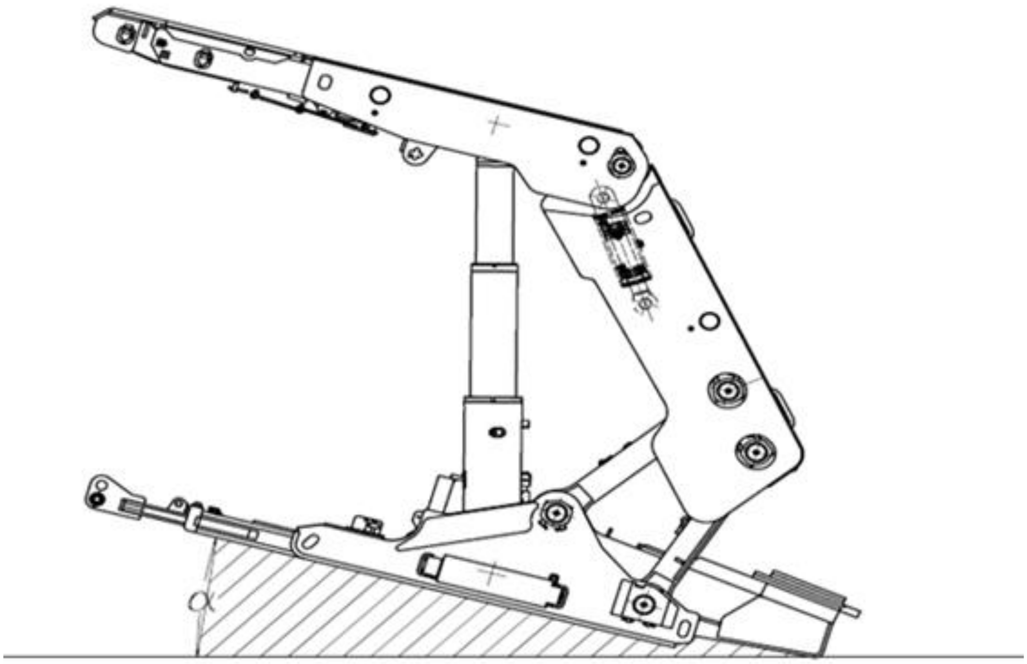



Fig. 5. The angle α cut-off.

You can determine the parameters of the output signals generated by the accelerometer: the output component and the gain. The height range of the individual elements with trigonometric functions on which the sensors were installed was determined by knowing the angle and geometric properties of the powered roof support structure. Heights were determined using the formula:

$$H_n = l_n \cdot \sin\sphericalangle \, [m] \tag{2.11}$$

Where:
$H_n$- measured height, [m]
$l_n$- length of the section element, [m]
sin∢- angle of the section element.

To determine the total working height of the longwall support, the total value of the three heights of the basic working elements of the powered support was required, defined by the formula:

$$H_{total} = H_1 + H_2 + H_3 \text{ [m]} \tag{2.12}$$

Where:
H1- total height measured for the length of the cap piece and the angle, [m]
H2- total height measured for the length of the shield and the angle, [m]
H3- total height measured for the length of the lemniscate and the angle, [m].

The adopted procedure allowed the authors to determine the total height of the casing on the test stand and in real conditions. (Fig.6)

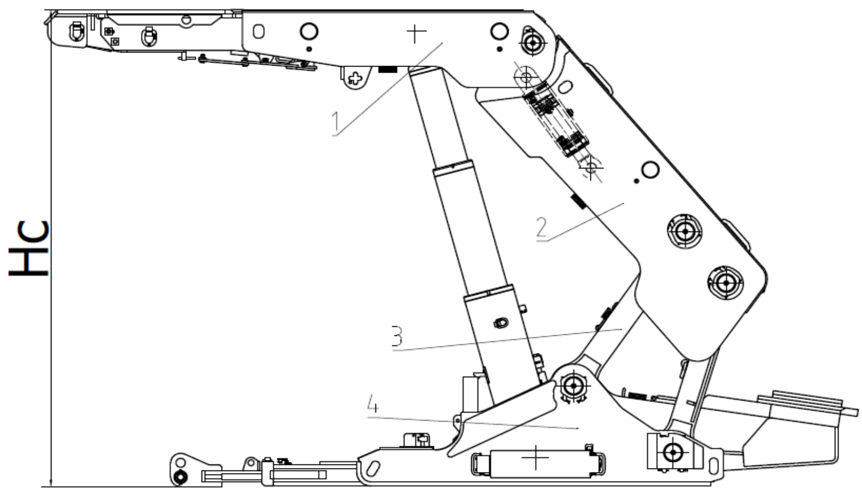



Fig. 6. The total height of the support, where 1 - canopy, 2 - shield, 3 - lemniscate, 4 – base floor, Hc - total height

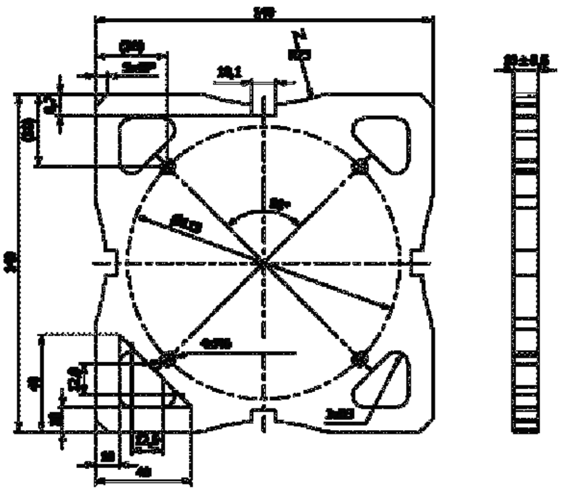
## 3. RESULTS

The adopted calculation method, an integral part of the MEMS technology, made it possible to construct a prototype of the measuring and recording system. Before testing in real-life conditions, the measuring system required analysis based on computer simulations, the purpose of which was to determine the places of its installation. Collisions with basic support elements were excluded, the final location of the sensor installation site was determined, and the places with the greatest stresses were diagnosed. In accordance with the developed research method, bench tests were conducted, which were the basis for undertaking tests in the mining wall. These tests led to determining the final sensor mounting points in the wall support.

### 3.1. Bench testing

The bench tests provided the basis for developing guidelines for the powered roof support monitoring system.  The next stage included testing in real conditions. The task was completed with the help of specialised mounting brackets made for this purpose. The innovative mounting brackets were designed to take into account the geometry of the supports elements. Fig. no. 7 presents an innovative mounting bracket 42mm thick, 140mm wide, and 140mm high and specifies other geometric parameters.

a)



b)

c)

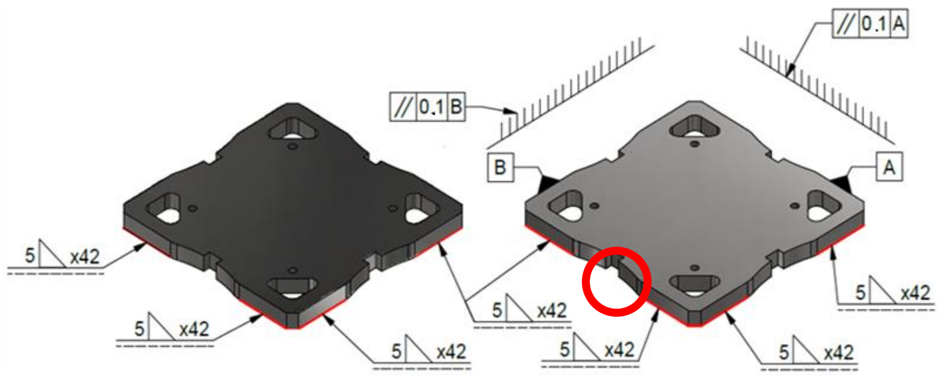



Fig. 7. Innovative mounting bracket, where: a – geometric parameters of the sheet, b – view of the mounting sheet on the test stand - lemniscate, c – parameters of sheet mounting

The brackets require installation. Correct installation of the brackets is crucial for system calibration. Leveling the sensors that make up the measuring and recording system allows for much more accurate measurement and easier installation.

The next step in calibrating the measurement system was to install the sensor cover in which the system sensor was installed. For this purpose, the innovative mounting brackets had special indentations (Fig.7, (c)), (Fig.8), so the arrangement of the sensor could be possible following the instructions of the designers. The method of manual calibration of the sensor is shown in Fig. 8.

Fig. 8. Device for manual sensor calibration

Based on the analyses and bench testing, the authors determined the mounting points of the brackets with the sensors of the measuring system. Fig. 9 shows a view of the test stand with innovative mounting brackets built into the wall support structure.

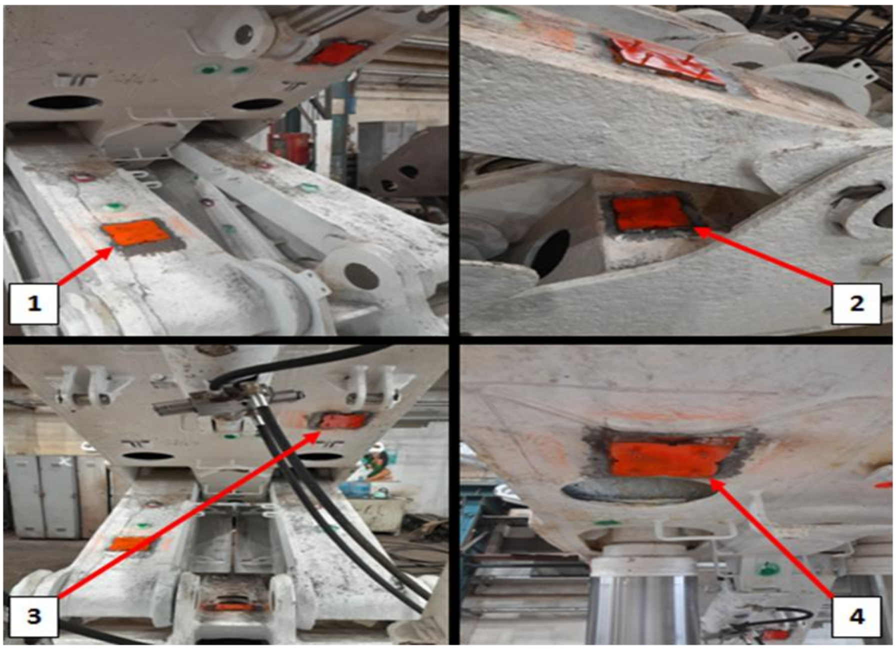



Fig. 9. Innovative mounting brackets on the test stand, where: 1 - lemniscate bracket, 2 – base floor bracket, 3 - shield bracket, 4 - canopy bracket

The location of innovative grips is the basis for calculating the geometry of the wall support operation. Monitoring the operation of the support elements allows determining its height and the transverse and longitudinal inclination. Figure no. 10 shows changes in the height of the support operation at the test station.

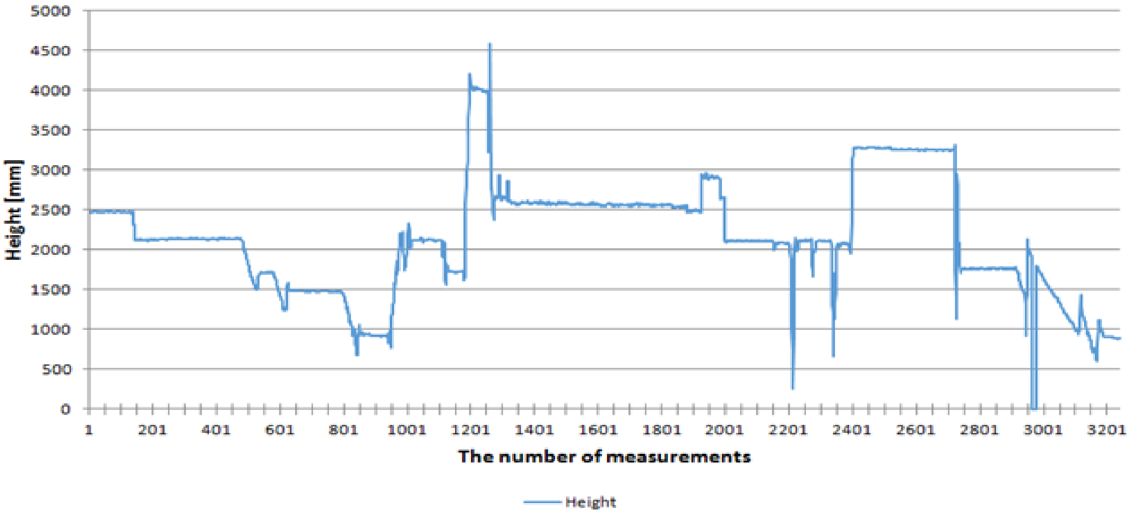



Fig. 10. Chart of changes in the working height of the housing on the test stand

The graph shows the height of the powered support during the system tests. The variable work cycle reflects the actual conditions of its cooperation with the longwall complex and the rock mass. The powered roof support was controlled in the range of 4200 mm-750 mm. The installed measuring system with mounting brackets has been adapted to 5 powered roof support sections built into the mining wall. The measuring system communicated wirelessly using sensors, a converter, an underground computer and the network infrastructure of the mining plant. The purpose of installing the system was to determine the efficiency of the system under real-life conditions. Sensor mounting locations are presented in Fig. 11:

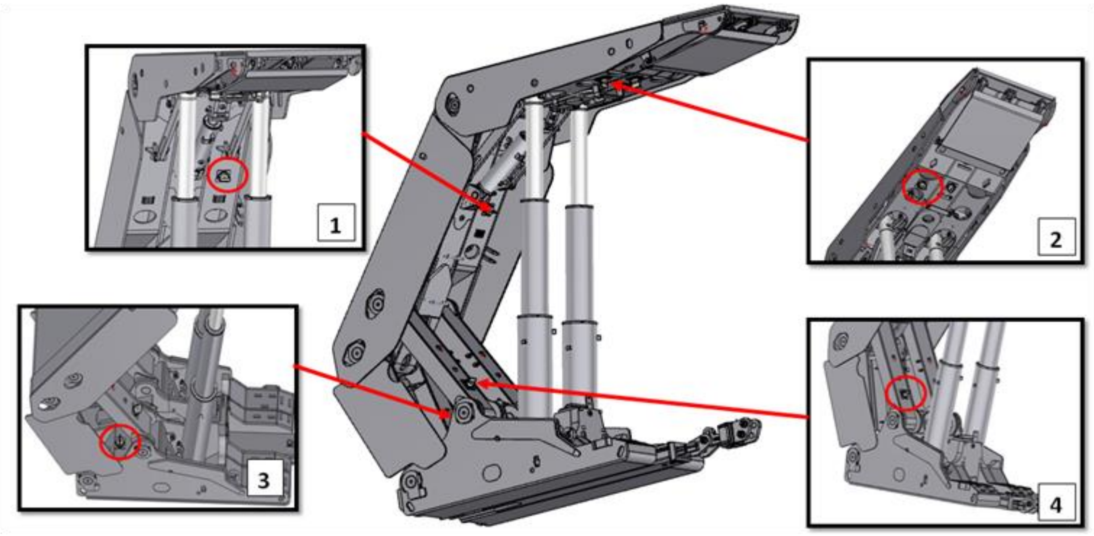



Fig. 11. Monitoring sensor locations, where: 1- shield sensor, 2- canopy sensor, 3- base floor sensor, 4- lemniscate sensor

### 3.2. Operational research – experimental

The success achieved during the bench tests allowed for conducting tests in real conditions. The stage of tests in real conditions consisted of installing a measuring and recording system in the mining wall. There were 96 sections in the longwall excavation. Five of them were monitored. Three were located next to each other, i.e. 34, 35, 36, and two more were scattered, i.e. 60 and 70. The sensors communicated wirelessly. The adopted guidelines and the method of installation are shown in Fig. 12.

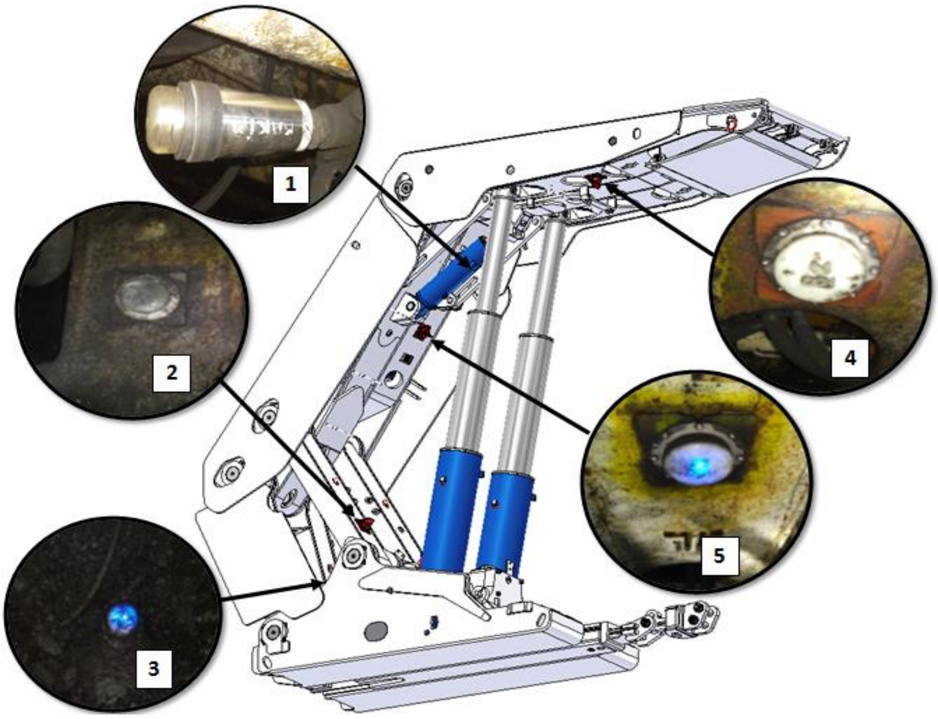



Fig. 12. Test stand with: 1 - memory card in the sensor, 2 - lemniscate sensor, 3 –base floor sensor, 4 - canopy sensor, 5 – shield sensor

The measurement data was collected over a period of 66 days. The data was saved on a memory card installed in the pressure sensor, as shown in Fig. 12. The graphs present measurement data from 3 days (Fig. 13-18), which illustrate the slopes of the tested sections and heights (Fig. 19-21).

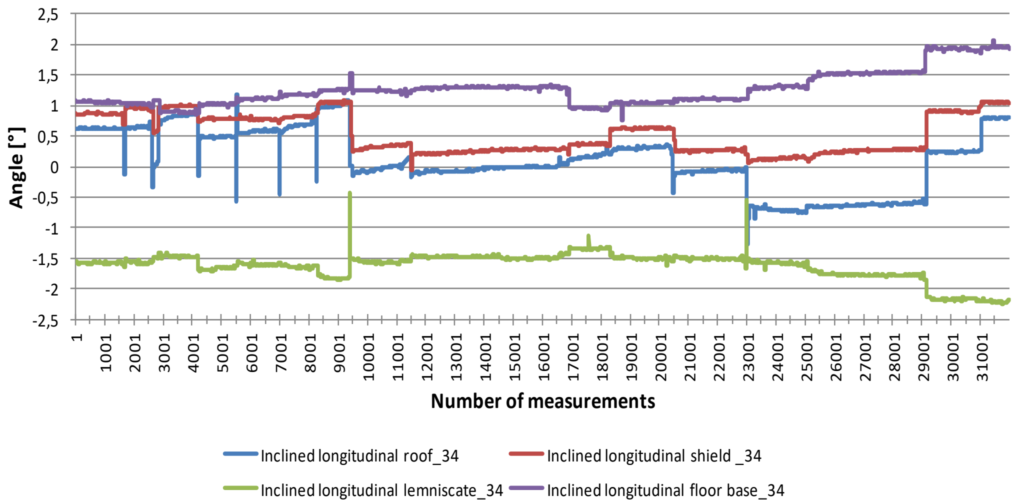



Fig. 13. Longitudinal slope of section 34

Figure No. 13 presents the longitudinal slopes of the basic elements of the powered roof support. The inclination values of these elements are insignificant because they result from the inclination of the longwall excavation. The slope in the wall is on average about 2 - 4º. The illustrated slopes of the elements on the graph confirm these assumptions. In the graph, the longitudinal slopes range from -2° to 2º.

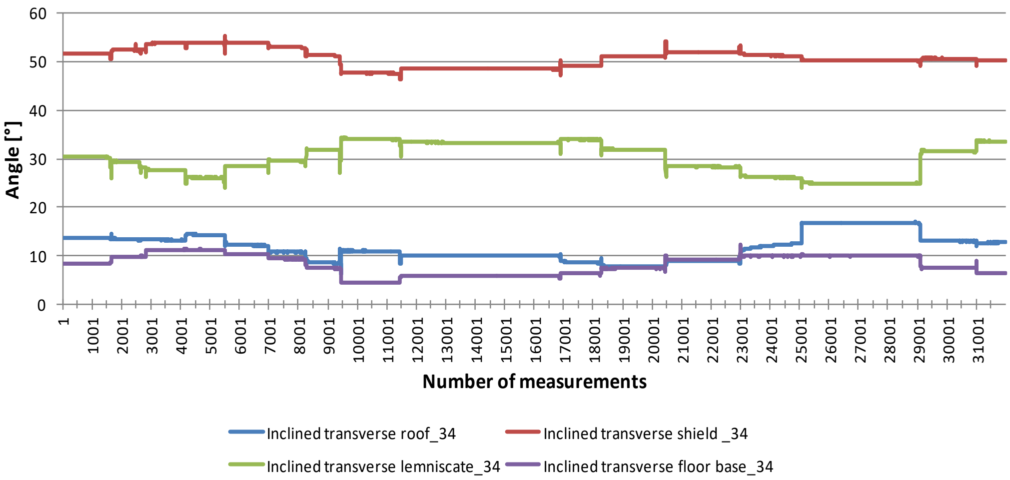



Fig. 14. Transverse slope of section 34

Figure 14 shows the transverse slopes which range from 5º to 55°. The transverse inclination of the roof and floor base varies from 5º to 18°. In the measurement areas in the same sample they are similar, as this results from the correct control of the powered roof support, i.e. its parallel operation. The course of the lemniscate and shield inclination lines on the graph results from the walking movement of the powered support.

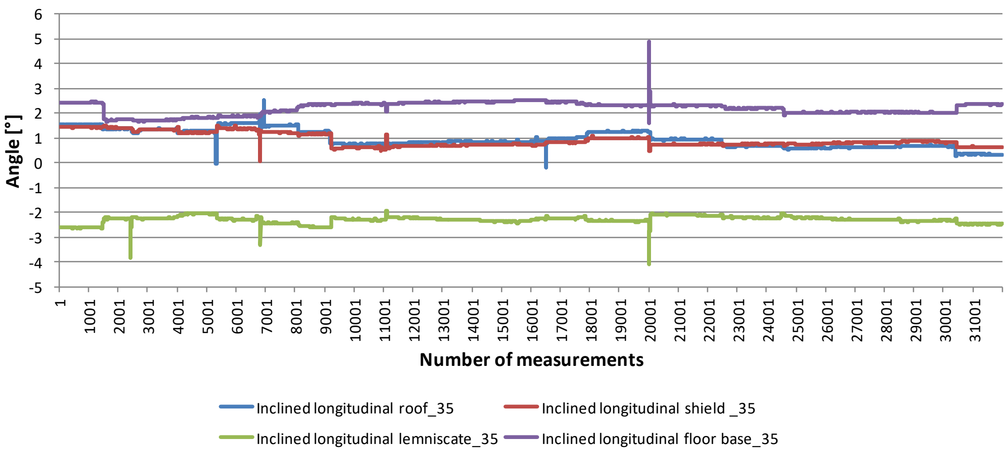



Fig. 15. Longitudinal slope of section 35

Figure No. 15 presents the longitudinal slope for the tested powered roof support No. 35 in relation to the time course illustrated in the form of measurement tests. The inclination range for the three monitored housing elements (roof, shield, floor base) is from 1º to 2°. Deviations in the range of -2° for the lemniscate may be due to unevenness of the floor in the longwall excavation.

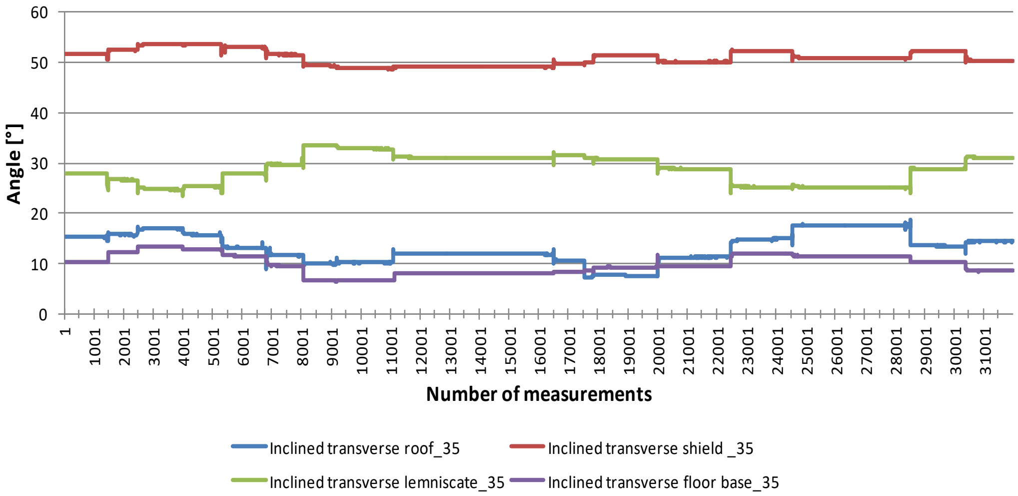


Fig. 16. Transverse slope of section 35

Figure 16 shows the transverse slopes of the housing elements. Also in this case, the phenomenon of parallelism of the operation of the roof and floor base elements occurs. Transverse slopes range from 6° to 53º.

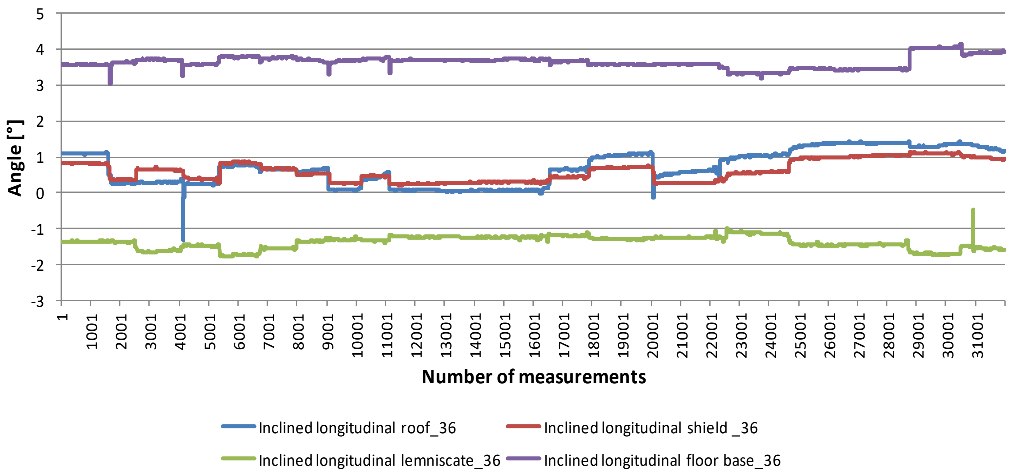


Fig. 17. Longitudinal slope of section 36

Figure No. 17 shows the longitudinal slopes for the tested section No. 36. The slope in this case ranges from -2° to 4º. A phenomenon that is repeated in each tested section for the longitudinal slope is illustrated by the overlap of the slope lines for the shield and roof elements.

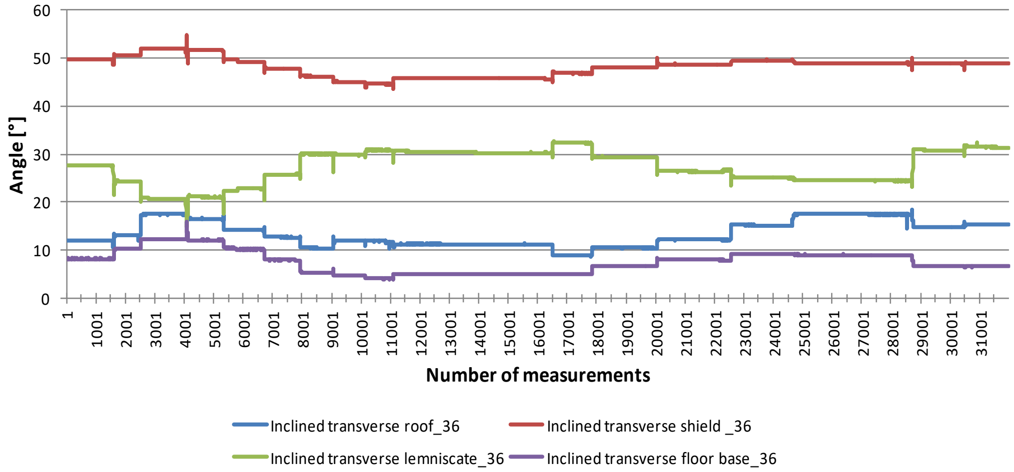



Fig. 18.Transverse slope of section 36

Figure 18 shows the cross slope for casing no. 36. Its operating range in relation to the transverse inclination of the roof and the floor base was from 5º to 19°. For the lemniscate from 20º to 32°, infarct shield from 45º to 52°.

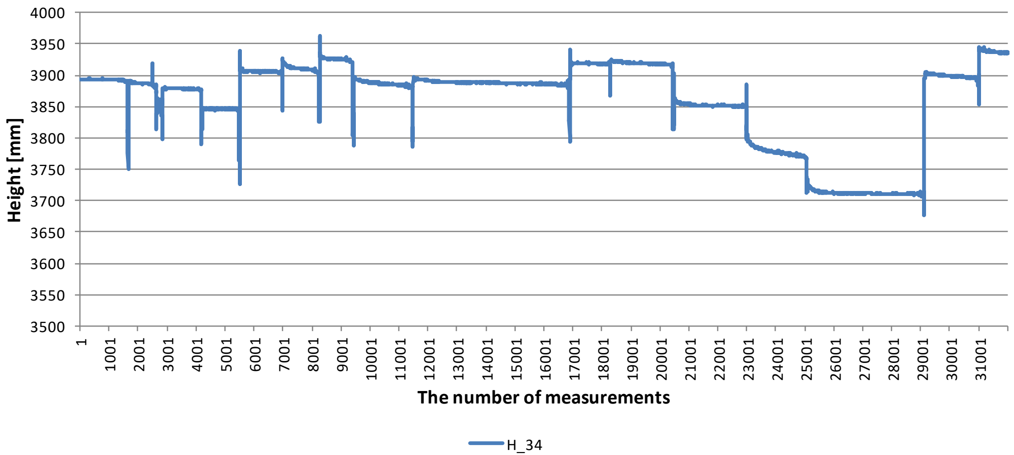



Fig. 19. Height of monitored section 34

Figure 19 shows a graph of height versus measurement samples, which constitutes time lines. The height changes are between 3700 mm and 3900 mm. The height changes presented are due to the operating cycle of the powered roof support.

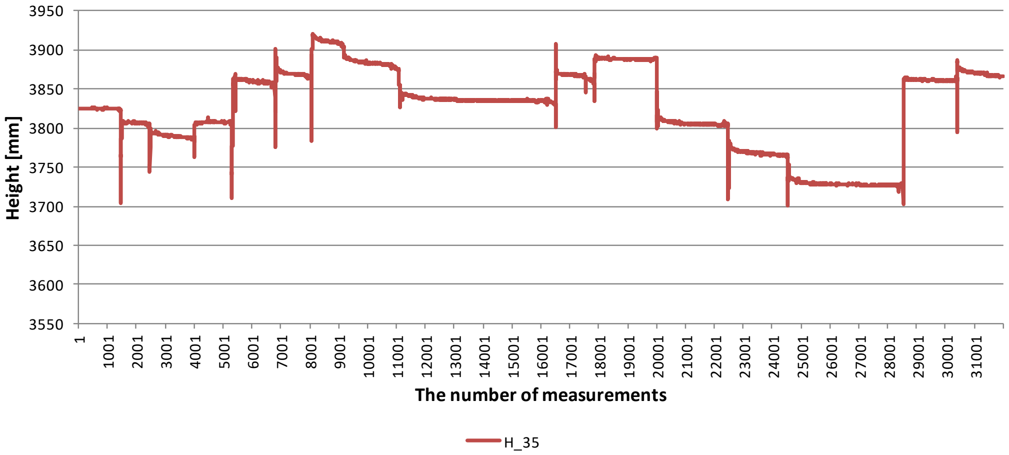



Fig. 20. Height of monitored section 35

Figure 20 presents the height variables for the tested section no. 35. The height for this support during the tested period ranged from 3725 mm to 3925 mm.

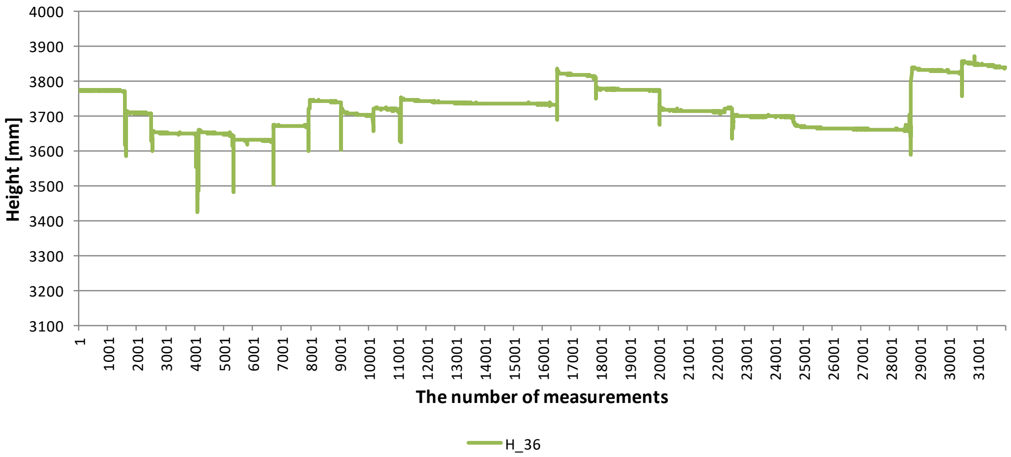



Fig. 21. Height of monitored section 36

In Figure 21 the heights of the tested section were lower than in the previous sections, ranging from 3625 mm to 3850 mm. The tested supports were located next to each other, therefore the range of working heights is similar. The changes that are noticeable result from the method of controlling the support by the operator or difficult geological and mining conditions.

## 4. DISCUSSION

The research results constitute a database for the analysis of phenomena occurring in the wall excavation and the wall support operating cycle. These conditions change with every next meter of the wall excavation. During operation, monitoring systems can be used as a tool for continuous monitoring of changes occurring during mining. The presented results show the inclination of the elements during the actual work of the section.

Graph no. 22 presents the heights of the monitored sections in the wall excavation.

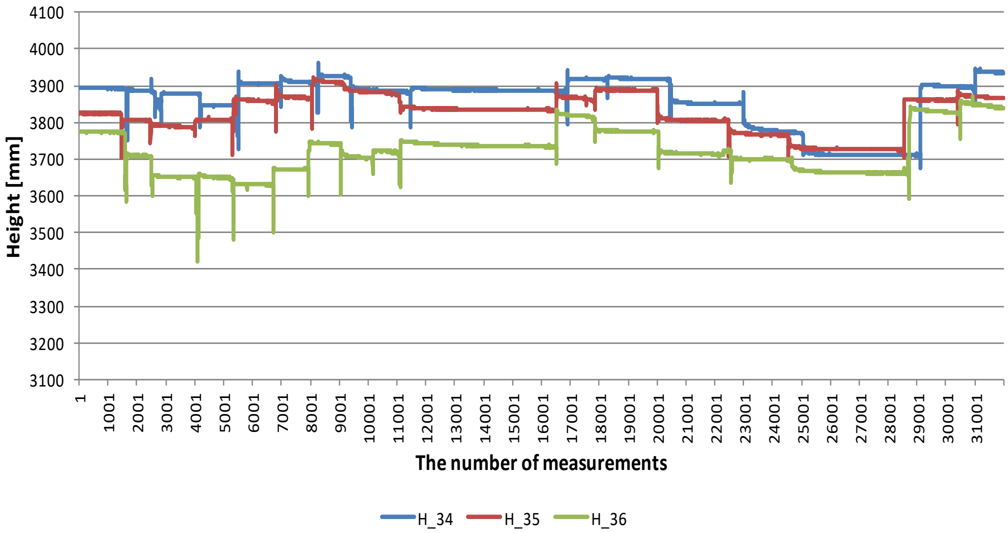



Fig. 22. Height of the three sections tested

The height diagram shows the work cycle caused by the movement of the longwall support towards the coal. This process consists of several stages that are related to its work cycle - hauling, moving towards the uncut coal and another expanding. The expansion allows the scraper conveyor to move in the direction of the unmined coal and to secure the excavation roof. Graph No. 22 shows the duty cycle and height changes during the casing movement. Using these values, we obtain a continuous overview of the operation of the entire longwall complex in relation to the design assumptions at the planning stage of the selected seam. The solutions presented in other studies indicate monitoring only the pressure value, which provides insufficient information about the operation of the entire casing and the interpretation of external factors influencing its operation. The proposed system enriched with geometric parameters extends the scope of data that allows for much more detailed analyses [58,59]. Other solutions are based on systems communicating by wire [59,60,61], the proposed system communicates wirelessly. The presented analyses are subject to discussion - to what extent the values obtained from the support monitoring system in terms of geometry and pressure parameters in the support props, which result from the pressure of the roof rocks, enable the prediction of the threat of tremors or rock falls in the longwall excavation.

## 5. CONCLUSION

Monitoring the operation of the wall support requires constant analysis of data obtained from the system. The information sent from the wall excavation is a result of external phenomena and the human factor. It is important to correctly interpret these phenomena in relation to the visualization of the system. For this purpose, not only the system is needed, but also experience in this area. If the obtained data is correctly read, it is possible to determine the work cycle of the wall support and monitor the work of the longwall complex.

The system allows you to determine the inclinations of the basic housing elements, their height and the pressure in the stands. The geometry of a longwall excavation is complicated. The way the deposit is deposited, the stage of the longwall excavation, the ceiling conditions, hazards or waterlogging affect the dimensions of the wall and consequently the operation of the support. Responding to these

factors in a preventive manner can significantly affect the efficiency and safety of machines and people. Using a monitoring system provides such opportunities, as constant supervision of the work of the wall support allows for reading symptoms of threats resulting from the exploitation of the wall.
The wall support is a basic element of the wall complex. Its monitoring will significantly affect the work of the entire complex. Therefore, conducting research in this area is the basis for defining factors that affect its work and the compatibility of the measurement system with its structure. The element of compatibility of sensors with the housing was significant for the quality of measurements obtained from the conducted research and ultimately the production process.

The article contains information on the methodology of the research conducted to determine the operating parameters of the wall support and the compatibility of the system with the structure. The longitudinal inclination of the monitored elements is between 2° and 4°. The transverse inclination was significantly different. This is due to the powered roof support design. The transverse inclination for the foot piece was from 4° to 11°, for the cap piece from 9° to 20°, the lemniscate from 20° to 35°, the shield from 47° to 53°. Using the data obtained from the system, we were able to determine the angles of the section and determine its height range. The height range of section 34 ranged from 3920 mm to 3700 mm, section 35 from 3710 mm to 3910 mm, section 36 from 3620 mm to 3880 mm. The differences in the specified parameters are influenced by the human and environmental factors. The human factor depends on the method of controlling the support in the production process and its operating phases during hard coal extraction. The environmental factor is related to the external conditions in the wall. This is influenced by the surrounding layers, which generate stresses affecting its elements.

The article presents the results of the research and the results of its implementation, which aimed to develop guidelines and adapt the system to difficult environmental conditions. Guidelines for the operation of the monitoring system:
- Sensors constituting the measurement and recording system should be located on the roof, floor base, lemniscate and shield.
- Innovative mounting brackets should be used to mount the sensors.
- The installation locations were designated taking into account the places most exposed to the impact of external forces in real conditions.
- The measuring system used provides geometric data (transverse and longitudinal inclination, height) and pressure changes from the actual operating conditions of the powered roof support.
- Using the handles used, significantly precise measurements were obtained.
- The obtained data provided the authors with knowledge on the practical application of the measurement system for work in production conditions.
- The system used was approved for operation on the basis of the created technical and operational documentation and certification.
- The sensors have been located to ensure easy access during service work related to failure or replacement of the power battery.
- The installation of sensors took into account the influence of construction elements on the communication quality of the measurement system.
- The sensors are visible to the crew for much better visualization of light signals indicating the operating status of the powered roof support.

Practical use of the system in conditions of sensor density in the wall excavation leads to significant changes in work, reduced downtime and increased safety of the crew. The demand for the amount of data obtained from the operation of machines and devices in the wall excavation increases the quality of supervision over the crew. The system used is one of the elements which, provided it is correctly interpreted and the crew has the experience, will significantly increase the efficiency and safety of the longwall system. Additionally, the system used in the research has an open interface that allows for the extension of measurement capabilities to include other parameters. Enrichment with vibration measurement of support elements could constitute an innovative direction of measurement of the operation of powered roof support. These possibilities allow for its wider use in other industries and constitute an area for development and research in this area.

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