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Automatic Monitoring System Designed for Controlling the Stability of Underground Excavation

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Abstract. Ensuring the stability of mining excavations is a crucial aspect of underground mining. For this purpose, appropriate shapes, dimensions, and support of workings are designed for the given mining and geological conditions. However, for the proper assessment of the adequacy of the used technical solutions, and the calibration of the models used in the support design, it is necessary to monitor the behavior of the excavation. It should apply to the rock mass and the support. The paper presents the automatic system designed for underground workings monitoring, and the example of its use in the heading. Electronic devices that measure the rock mass movements in the roof, the load on the standing support, and on bolts, the stress in the rock mass, are connected to the datalogger and can collect data for a long of time without any maintenance, also in hard-to-reach places. This feature enables the system to be widely used, in particular, in excavations in the vicinity of exploitation, goafs, or in the area of a liquidated exploitation field.

Keywords: Stability of mining excavation, Rock mass monitoring system, Automatic integrated monitoring system, Support control, Rock bolt monitoring

1. Monitoring of underground excavations

Monitoring of the underground excavations is necessary for maintaining their stability. Monitoring not only provides information on the excavation actual condition; it also generates data for verification of the design assumptions and the final design of the working [1-3]. In numerous cases it was a basis for changes or optimization of the assumed support system [4-6]. Proper monitoring of the stability of underground excavation requires concurrent monitoring of the rock mass, and of the support.

Limiting monitoring to the rock mass only causes a lack of data of the load on the support, hence to what degree the support load capacity is engaged. On the other hand, monitoring of the support only precludes identification of the causes of load concentrations i.e., the magnitude of deformation and the intensity of fracturing of the rock mass around the excavation. Monitoring of the excavation may consist of the following measurements:

- convergence of the excavation (linear, peripheral),
- floor heave,
- 3D scanning,
- drillholes inspection by camera,
- stress changes in the rock mass,
- fracturing in the roof rock,
- load on the support (standing support, dowels and bolts, lining),
- deformation of elements of the support,
- stress in the support elements.

Carrying out monitoring of an excavation over a long time allows for determination of trends of rock mass deformation and loads on the support, which can be used for prediction of the behavior of other excavations in similar or specific (e.g. waterlogged rock mass, presence of fault) geological and mining conditions [7, 8]. Shen [9] stresses that the scope and other aspects of monitoring should be adjusted to the possible type of stability loss of the excavation e.g., beam failure, joint-controlled rock falls, roof sag, guttering and shear failure, skin failure, and rib spalling/failure. Skipochka et al. [10] and Mataev et al [11] indicates that it is possible to reduce production costs volume and increase production safety by optimizing the technology of the underground workings support system when simultaneously introducing rock mass monitoring.

Monitoring of roof fracturing and load on the support is particularly important for the design of rockbolt-type support [6, 9, 12, 13], in which case the hazard of sudden failure is much higher than in case of standing support. Majcherczyk and other authors [3, 4, 7, 8, 14, 15] recommend for the second case measurements of convergence or 3D scanning [16, 17]. Walentek [15] demonstrates in his paper that the support of excavation can be modified together with the advancement of the excavation based on convergence data received progressively, and then used to determine Ground Reaction Curve (GRC), Longitudinal Displacement Profile (LDP), and Support Characteristic Curve (SCC).

An additional parameter that can be monitored and may be used for the stability assessment of the excavation is the stress and its changes within the rock mass [1, 2, 9, 18, 19]. It refers particularly to the situation of the mining front getting closer to the excavation which induces additional stresses [1, 19]. In such cases, useful information may be also obtained from convergence monitoring [14, 20, 21], as well as from endoscopic inspection of boreholes [7, 20, 22, 23]. Endoscopic inspections and measurements show well the development of discontinuities in the rock mass caused by the increasing stress from the approaching exploitation front [5, 6, 14, 15, 20].

Convergence data may also be used for back analysis of the rock mass parameters that were affected by the advancing exploitation [21, 24].

Equally significant are measurements of load on the support as they show how the support load capacity is engaged by the rock mass in terms of magnitude, direction, and distribution. The tensional force measured in the rock bolts should not exceed the nominal rock bolt capacity specified by its manufacturer [2, 4, 5, 6, 7, 13, 14, 19, 15]. Standing support monitoring shows maximum or yielding load [4, 5, 14]. It should be noted that the direction of the load can be inferred from load sensors properly positioned on the perimeter of the support frame, or under the wall arches. Asymmetric load detected on the support signals improper work of the support i.e., no yield on joints, and plastic deformation of the frame [7, 19, 25].

All monitoring data are useful for preparation of the numerical model, and for the calibration of the initially assumed rock mass parameters and stress criterion [7, 9].

Certainly, monitoring of the excavation stability requires proper management. The management covers selection of the parameters to be measured, selection the suitable instrument for each parameter (in terms of accuracy, working range, dimensions, working conditions), number and positioning of the instruments, delegating responsibility of the instruments, measurements, and data processing to the qualified staff [26]. Lack of professional management may cause incompleteness or inaccurateness of data obtained at a high cost, as well as deficient interpretation.

A comprehensive interpretation requires data from a complex monitoring system that covers rock mass and support. Still, the data acquisition and interpretation can be arranged simply and expediently. To achieve that the instrumentation needs to be designed to fully depict the effect of changes of geomechanical situation of the excavation, and the data acquisition possible by just one readout unit. There are known similar monitoring projects in the mines [14, 19], yet most often comprising only single instrument; not an array of instruments combined with automated dataloggers [1, 2, 3, 4, 5, 7].

2. Monitoring of gate roadways

In the case of gate roadways, next to the exploitation panel, the monitoring of the excavation may serve several purposes:

- evaluation of sufficiency of the selected support type,
- observation of working of individual part of the support,
- evaluation of the effect on the rock mass and the support from the approaching longwall face,
- evaluation of the inter-reaction between rock mass and support at changing geological and mining conditions,
- testing of new technological solutions.

Access to the roadway and monitoring devices is safe and unrestricted in a situation where the roadway is still ahead of the exploitation front. Hence, the measurement can be carried out manually, and the devices can be serviced if needed. The situation becomes difficult once the excavation is behind the exploitation front. Often, they are fenced off due to safety reasons e.g., lack of ventilation. However, the monitoring data that can be obtained from them is particularly valuable for correcting further roadway designs. In such cases, automated monitoring is the solution.

Automated dataloggers read the instruments and store the results over a long time depending on memory size e.g., several weeks. Then the results can be downloaded to a portable computer in situ or remotely via telecommunication cable. Moreover, dataloggers can read the instruments at a preset frequency, usually from 1 to 12 hours, which allows for detection of minute changes in the rock mass and the support. Therefore, the example correctly designed monitoring station (Fig. 1) for stand-and-roofbolting support should comprise: multipoint extensometer (minimum 4-point) installed in the roof (marked in orange), load cell installed on the roof-beam of the standing support (marked in yellow), instrumented rock bolt with minimum 4 sensors (marked in red).

In addition, it is recommended to include in the station a biaxial stressmeter for monitoring of stress in the rock mass (marked in purple), and in case of gate roadways advised are load cells on wood cribs, concrete props, and other elements supporting the subsiding roof (marked in blue).

Of course, the station may be equipped with many other sensors e.g., load cells under the side arches, or convergence meters. However, the design of the station is limited by the number of transmission channels of the datalogger (marked in grey on the diagram). If necessary, two or three datalogger may be needed.

As an addition to the station, it is suggested to drill an investigation hole for endoscopic inspections and measurements of apertures of fractures during formation and maintenance of the excavation. Mechanical parameters of the rock types surrounding the excavation can be also obtained from the drillhole core.

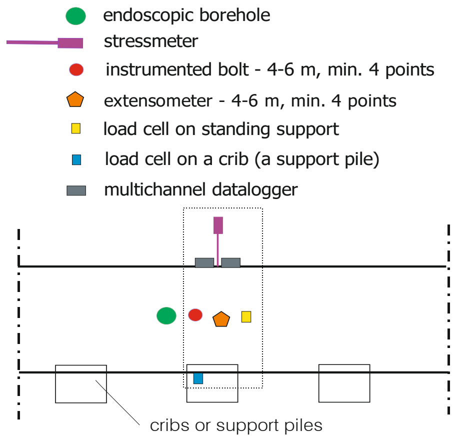

Fig. 1. Diagram of typical automated monitoring station in an excavation with stand-and-roffbolting support.

In this paper the authors present the monitoring system developed for detecting and recording rock mass movements, loads on the support, and loads on additional supports at the near-goaf zone. The system was installed and successfully used in a maingate PW-1 in “Pniówek” coal mine belonging to JSW (Jastrzębska Spółka Węglowa, free transl.: Jastrzębie Coal Company) in Poland.

3. Example of the monitoring system for gate roadway

3.1. Description of monitoring station

In the presented case the monitoring system has been developed for longwall roadway in a coal mine, where the roadway was maintained beyond the exploitation front for ventilation. Therefore, the assumption was that the system had to comprehensively monitor the stability of the excavation, and the readings could be regularly carried out in situ. For this purpose, the instruments for measuring movements in the rock mass and loads on the support were selected and configured that way that they could be read, and the reading stored, by one datalogger or readout unit.

Therefore, when designing the monitoring station, the following aspect had to be considered:

- selection of instruments that suitable for working in mining conditions,
- selection of instruments with measuring range suitable for the expected values,
- selection of instruments powered by the same voltage,

- selection of instruments ready to work as integrated system,
- ensuring the instruments received permit to work in compliance Polish mining regulations,
- ensuring the instruments received ATEX certificate for safe use in explosion hazard zone,
- design the number of instruments and transmission channels matching the capacity of the datalogger.

It appeared that the certificates from other countries issued for the instruments (e.g., by the US or Korea), stating their suitability for working in the mines, do not qualify them for use in Polish mining. Also, some of them did not comply with explosion protection requirements. Since the intended monitoring station was within a methane hazard zone, it was decided that the dataloggers would be protected in legally approved, spark-safe casings.

The objective of monitoring of the maingate PW-1 in coal mine Pniówek was a verification of two novel support systems for longwall roadway maintained behind the longwall front. The two new supports were installed along 200 meters sections each, and their behavior was later compared with the typical support used in the mine. Hence three sections of different support scheme were instrumented and monitored. In each tested section of the maingate PW-1 there were two stations installed comprising (Fig. 2):

- load cell installed on roof arch of the standing support,
- rod extensometer, 6 meter long and with 4 measurement levels,
- rock bolt stressmeter, 6 meter long and with 6 measurement points,
- load cell installed on wooden crib support,
- two biaxial stressmeters.

The stressmeters were installed in the walls at 90^0 to each other, in the boreholes inclined to the roadway axis, to enable the determination of changes of vertical and horizontal stress, hence the triaxial stress state.

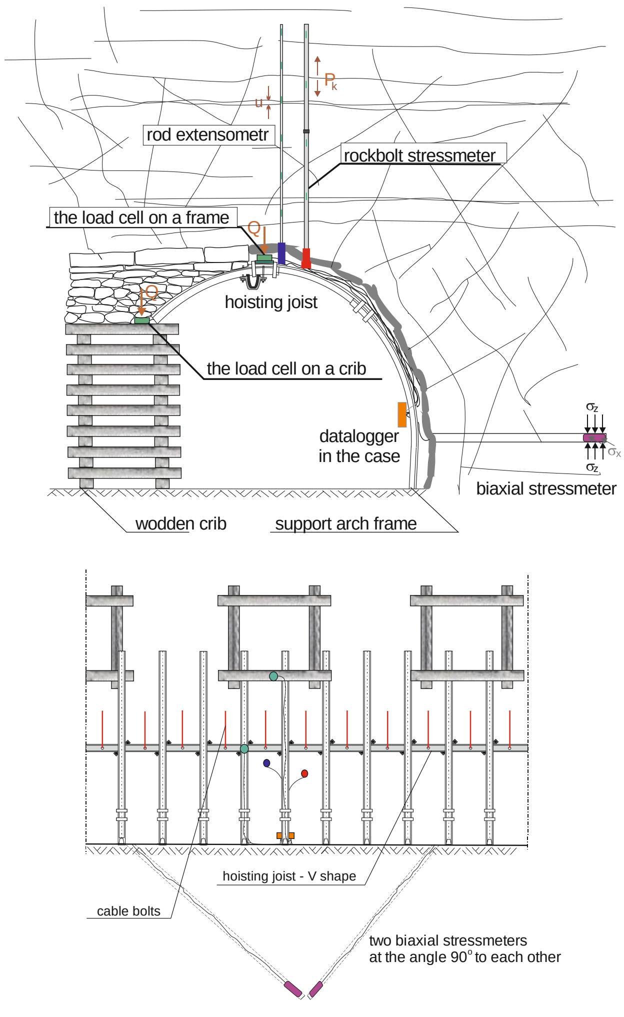

Fig. 2. Diagram of monitoring station in PW-1 maingate.

Moreover, in five of the six stations installed there were investigation holes drilled for endoscopic inspection of development of fracturing since completion of the excavation.

Fig. 2 shows one of the two new support systems tested – with V-profile joist, fixed in the roof along the axis of the gallery with strand bolts, where the excavation borders with goafs supported with wood cribs.

3.2. Monitoring of rock mass

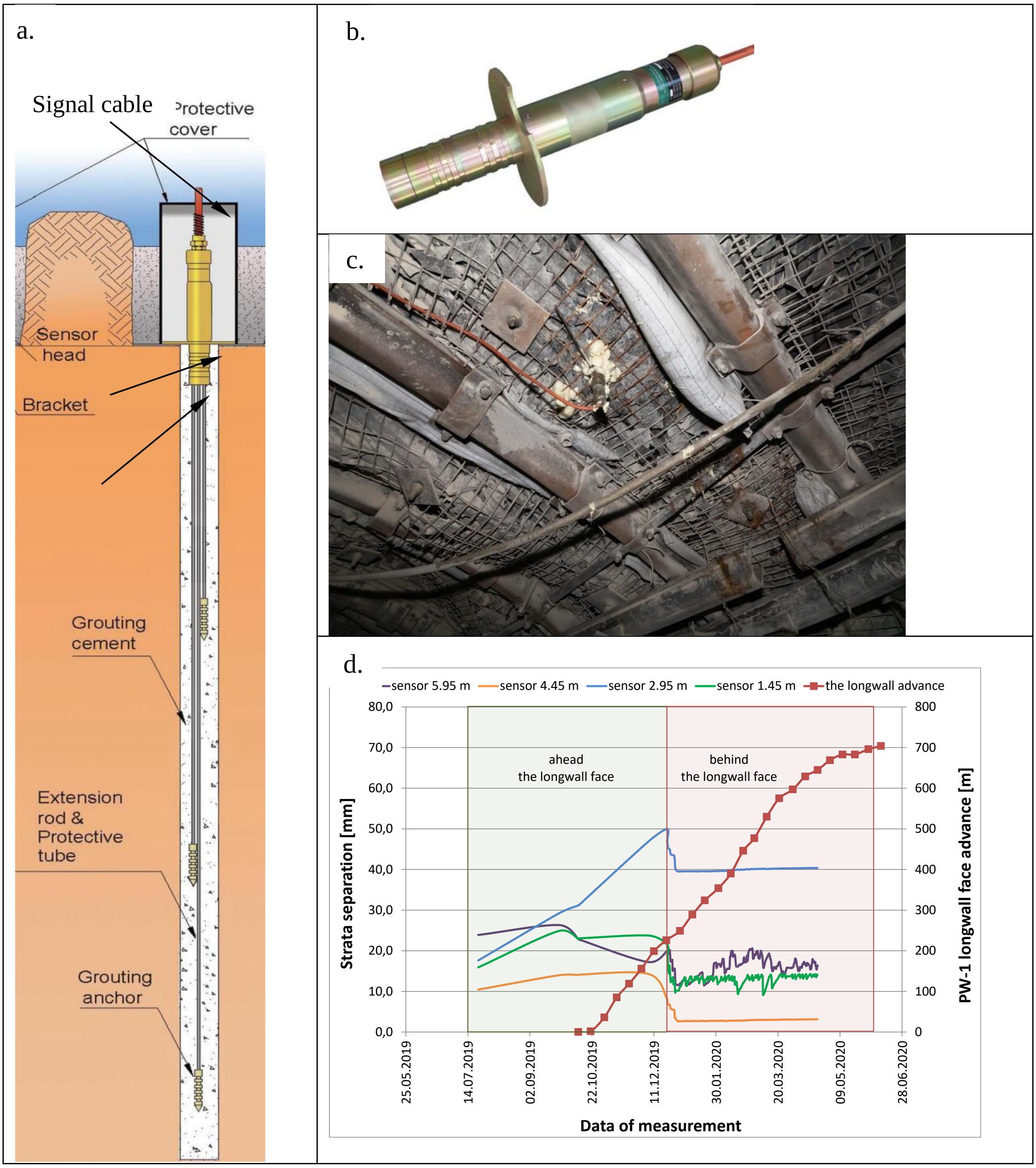

Fig. 3. Rod extensometer MPBX model 1390, a. general view and installation diagram [27], b. extensometer head, c. extensometer grouted into the roof of the gallery, d. readings compiled as graphs.

Rod extensometers with vibrating wire sensors model 1391 by ACE Instruments Co. Ltd were selected for the presented research case for monitoring the development of fracturing within the roof rocks. Extensometers consist of 6 mm diameter polyethylene pipes connected to the reference head equipped with

6 vibrating wire transducers. Fiber glass rods ended with grouting anchor are inserted into the pipes. Once the anchors are grouted at designed levels the rods transmit the anchor movements to VW transducer (Fig. 3a). The distance of the anchors to the reference head can be decided to suit the purpose and the conditions. In this case the anchors were positioned and grouted at 5,95 m, 4,45 m, 2,95 m, and 1,45 m distance from the reference head.

Reference head is made of stainless steel and alloys (Fig. 3b). It is used to set the initial tension on the VW transducers (i.e. zero reading). It also contains a temperature sensor that allows for temperature correction of VW transducer readings. The extensometer was grouted in full length using resin-type glue Verpensin (Fig. 3c).

Figure 3d shows results of readings of one of the sensors that were carried out both before and behind the front of the longwall panel. Visible on the graph is a drop of aperture values which is linked to the passing by longwall and developing collapse of roof, hence subsiding of the roof rocks onto the standing support of the roadway.

Biaxial stressmeters – model 1375 made by ACE Instrument Co. Ltd. were applied for monitoring of changes of stress around the excavation (Fig. 4a). The probe contains an array of three VW sensors directed along a plane perpendicular to the probe axis, and at 120^0 to each other, hence measuring stress perpendicular to the probe axis and in three directions. The probe, as it is in the extensometer, has an in-built temperature sensor. The probe is made with stainless steel and watertight. The probes were inserted into the holes to around 10 m depth and grouted with cement (Fig. 4b).

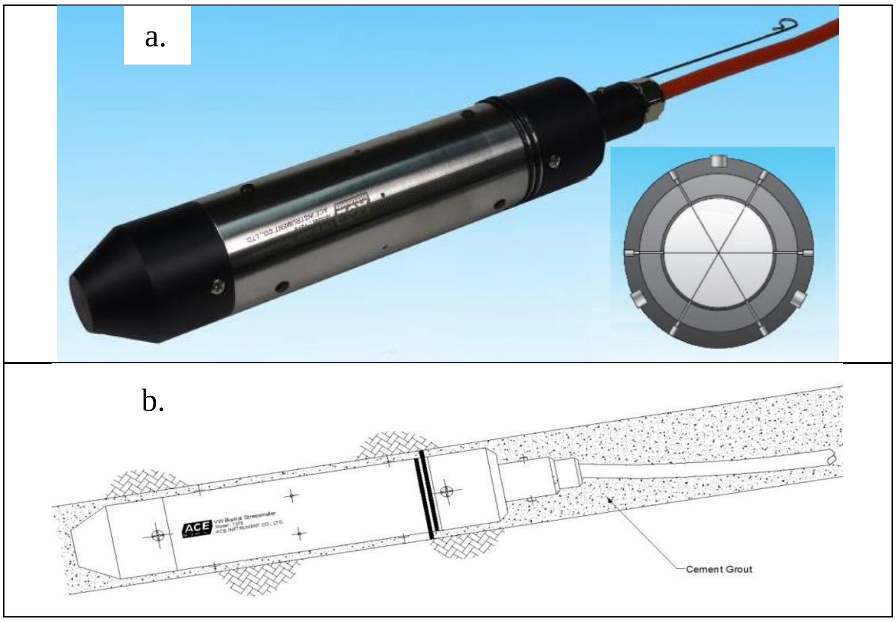

Fig. 4. Biaxial stressmeter, a. general view, b. way of application of the probe [27].

Figure 5 shows stressmeter installed in the wall of the excavation. Visible is the vent tube used for grouting the sensor in the rock.

Biaxial stressmeter allows for determination, not only the stresses in directions perpendicular to the meter axis, but also the tilt angle of the resultant vector of principal stresses. Figure 6a shows the chart of changes of vertical and horizontal stress versus position of the longwall front. The stresses increase together with the approaching exploitation front, and, in case of vertical stress, reach around 1.6 MPa when the longwall is at 100 m distance. Figure 6b demonstrates the method of determination of the resultant of principal stresses, while Figure 6c shows the tilt of the resultant vector. The graph confirms the observations in the excavation that the principal stresses resultant vector is tilted from vertical, in this case of about 60-75^0, and the tilt value is not invariable.

Despite the stressmeter position was around 0.9 m above the floor of the excavation it was damaged by the heaving floor when the longwall was at approx. 110 m distant from the monitoring station.

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Fig. 5. Biaxial stressmeter installed in the wall of the excavation. Visible is the vent tube used for grouting the sensor in the rock.

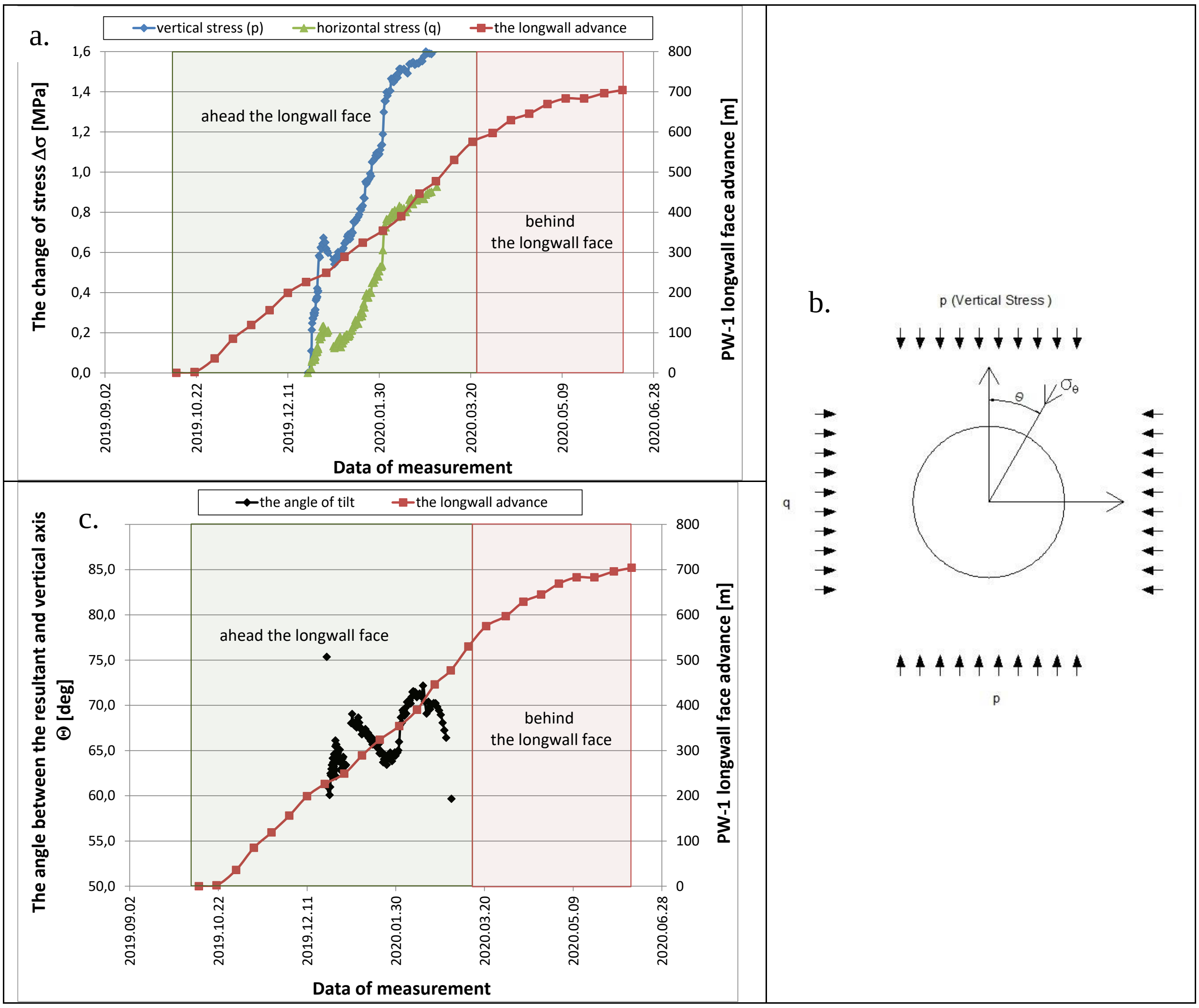


Fig. 6. Evaluation of stress in the rock mass at station no 6 during PW-1 longwall advance, a. chart of changes of stress, b. diagram for determination of the change of the resultant vector of principal stresses, c. change of tilt angle of principal stresses vs. advancement of the longwall.

3.3. Monitoring of support

For monitoring of load on the frame of the standing support the sensors had to be compatible with the datalogger. Therefore, the selected devices were vibrating wire type load cells, model 1102 made by ACE

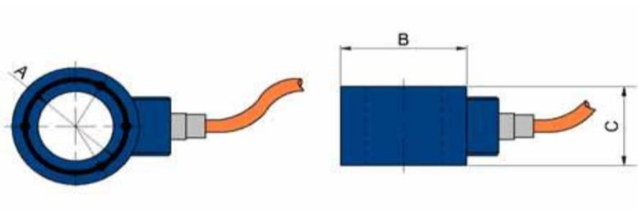
Instrument Co. Ltd.; 3-wire, specified for load up to 40 T. By the manufacture's specification the load cells of 1100 series are designed for measurement of load on concrete or steel structures (Fig. 7). It was also assumed that having all the measuring devices from one manufacturer, and built on the same principle, would be advantageous for assembling them into the system. Due to a broad range of load capacity, it was possible to use load cells 1100 series for monitoring both the load on support frames and wooden cribs.

To achieve a good contact between the frame of the support and the rock, the load cell was placed on the roof arch of standing support (Fig. 8) on a purpose-made pad that allowed for wedging it into the V-profile and preventing slipping of the load cell from it.

Fig. 7. Dynamometers (load cells) of 1100 series from ACE Co Ltd. [27].

Tab. 1. Parameters of load cells of 1100 series by Ace Co Ltd.

Load cell model	**1102**	**1103**	**1105**	**1110**	**1115**	**1120**
Max. Load [T]	40	80	140	140	140	200
Dimension A [mm]	38.5	50	100	125	75	100
Dimension B [mm]	72	88	138	158	122	150
Dimension C [mm]	80	80	80	80	80	80
Cross-sectional area [cm^2]	29.07	41.18	71.03	73.34	72.72	98.17



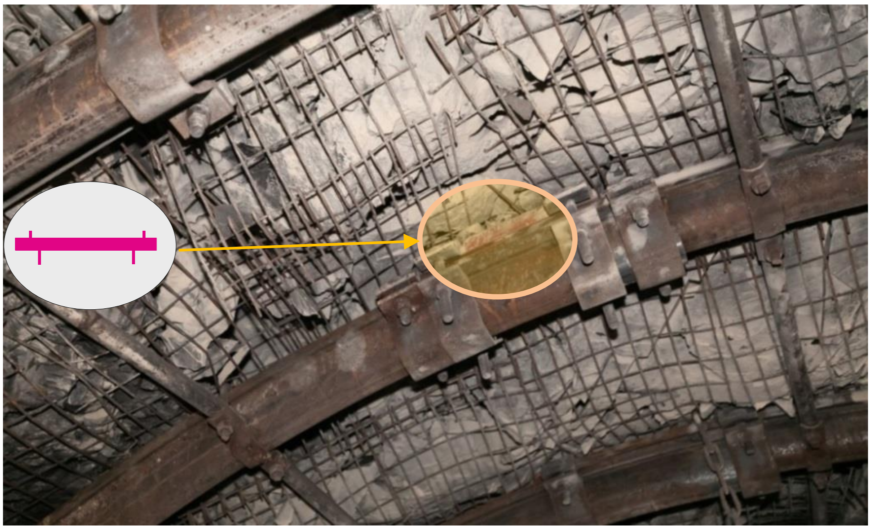


Fig. 8. Load cell type Vibrating Wire installed on a steel plate on top of roof arch in maingate PW-1.

An example of load recorded on the load cell installed between the rock and the roof arch of yielding support in roadway PW-1 versus longwall advancement is shown in Fig. 9. Despite combined standing and rock bolt support installed, visible is an explicit drop of load on the roof arch coinciding with the relaxation of the roof rocks exactly along the longwall face.

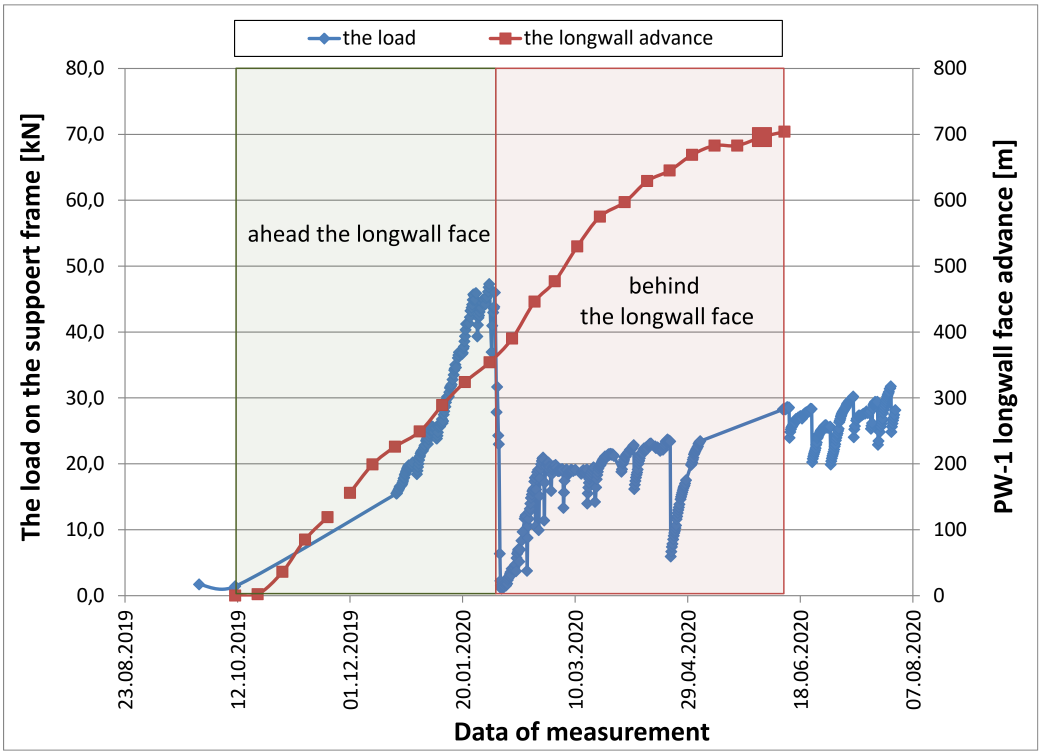


Fig. 9. Readings of load cell installed between rock and roof arch of yielding arch support in maingate PW-1 versus longwall advancement.

Monitoring of load on the rock bolt support was accomplished by introducing 6-levels, instrumented rock bolt stressmeter – model 1350 made by ACE Instrument Co. Ltd. The instrumented rock bolt comprises sections with vibrating wire sensors. These sections, maximum 8, can be distributed along the steel rod which is compressed or tensioned together with rock mass.

There is temperature sensor in the rock bolt head. For the purpose of measuring load on the installed rock bolt support the 6 meters long instrumented rock bolts were selected (Fig. 10a). This length allows for 6 measuring points at around 0.75 m intervals. For this project, the measuring points were fixed into the rock bolts at 0.75 m, 1.50 m, 2.25 m, 3.78 m, 4.25 m, and 5.78 m (Fig. 10b).

Such a long rock bolts, longer than the height of the excavation, require the final assembling of two pre-assembled sections during the installation. These two sections must be connected mechanically with a threaded coupler when inserting to the drill hole (Fig. 10c).

Before the coupler is used, the rock bolt sections have to be joined properly with male and female electrical sockets ensuring connectivity with vibrating wire sensors (Fig. 10d). The instrumented rock bolt grouted with cement into the roof of the excavation is shown in Fig. 11.

Fig. 12 shows an example record of load on the instrumented rock bolt. It appears on the graph, that the loads increase before the approaching longwall face, up to 215 kN on the level 3.75 m. The distribution of the load on the measuring points varies because it depends on what level the rock mass starts discontinuing. After the longwall face passes by the load on the rock bolt still increases.

In the case presented on Fig. 12 the coupler between upper and lower sections snapped due to bending and excessive rock movement still when being ahead of the approaching longwall face. As a result, the three upper sensors were disconnected, and the record is incomplete since the longwall position 15 meters to the station.

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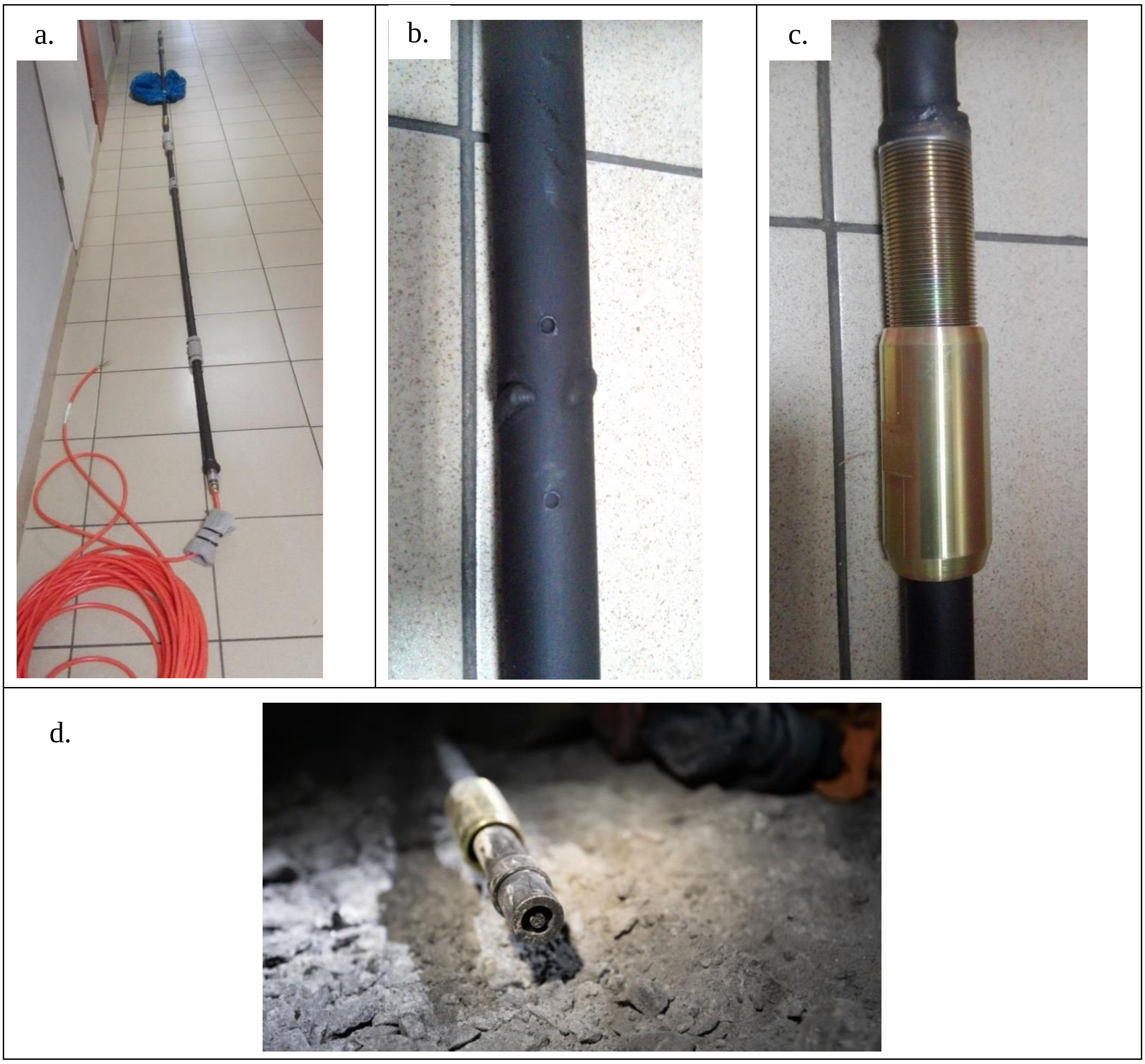

Fig. 10. Rock bolt instrumented with Vibrating Wire sensor, a. general view, b. section of the rock bolt with the Vibrating Wire sensor, c. coupler for rock bolt sections, d. socket for connecting rock bolt sections.

Fig. 11. Instrumented rock bolt installed in the roof of maingate PW-1. Visible is the end of the packer used for grouting.

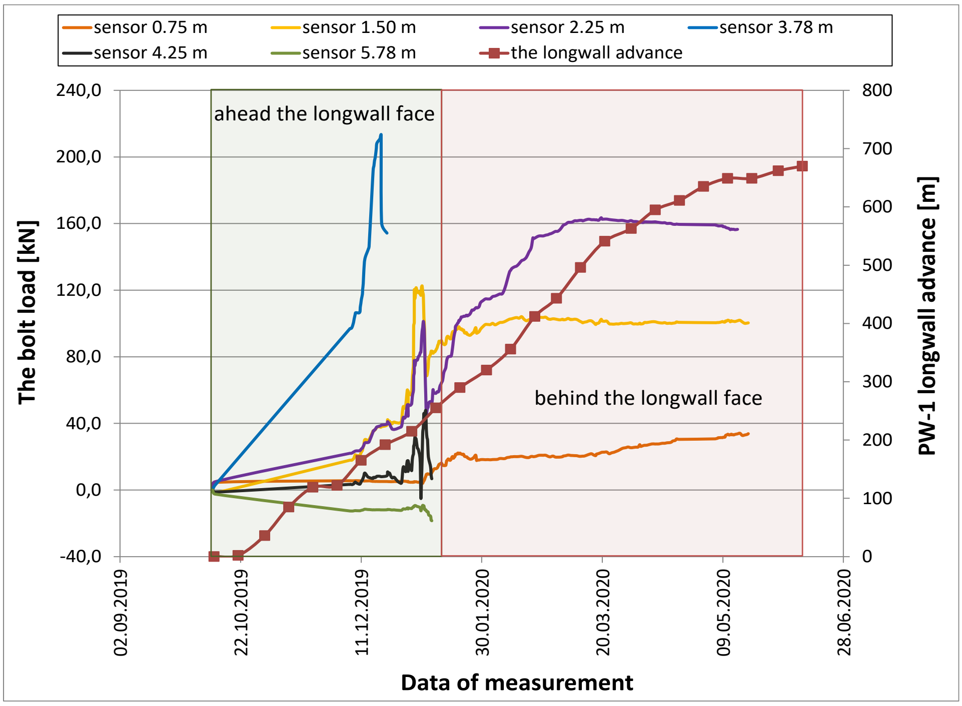

Fig. 12. Distribution of load along instrumented rock bolt in roadway PW-1 (station no 2) versus longwall face advance.

Because the roadway PW-1 was maintained behind the longwall face, the monitoring continued, and additionally included load on wood cribs. For this purpose, the vibrating wire load cell of 200 T capacity, model 1120 made by ACE Instrument Co. Ltd. was applied. The specified parameters of this device are given in Tab. 1. Even though there were no values of load on the wood cribs available from previous experience, yet assuming theoretical capacity of the wood cribs 160 T, the range of the selected load cell 200 T seemed sufficient and with good margin. Fig. 13 shows the monitored wood crib structure.

In practice, it appeared difficult to position the load cell under the rock rubble that way to correctly measure the load on the whole area of the wood crib. The load cell was placed on the roadway side of the crib, where the load was not representing the overall load on the crib.

Fig. 13. View on the monitor wood crib behind the longwall face PW-1.

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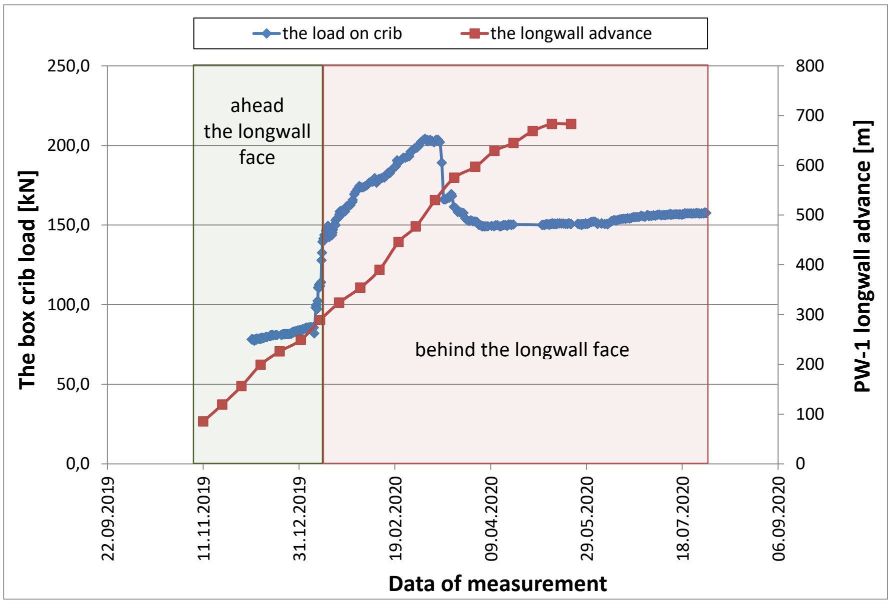

Fig. 14. Load on wood crib built in roadway PW-1 vs. longwall face advance – monitoring station no 2.

The readings show that the load on the wood cribs was not remarkably high (Fig. 14). It did not exceed 210 kN (21 T). In this case, the short, cantilevered section of the subsiding roof did not exert high load on the installed wood cribs. However, it needs to be pointed out that the load cells were installed on the roadway side of the crib where the load was lower and not indicative to the whole load from subsiding roof on the wood crib.

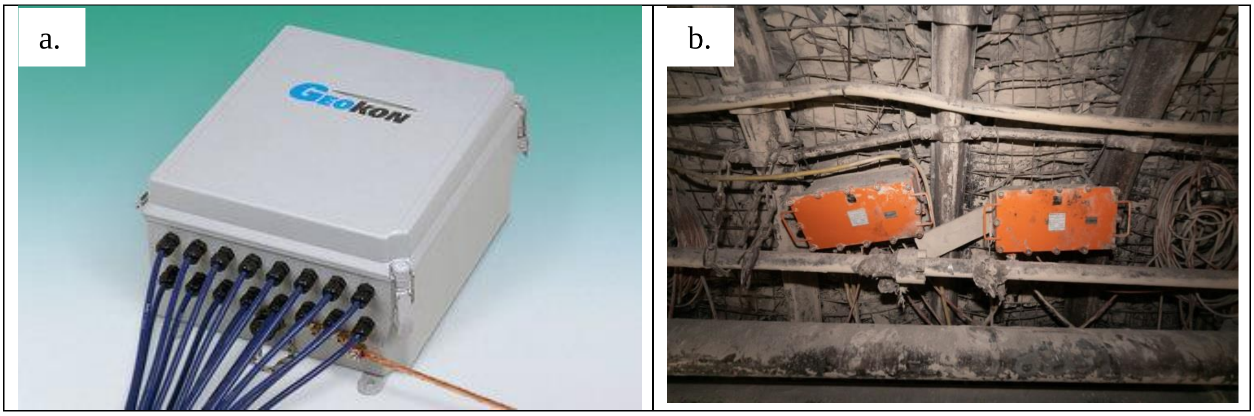

Fig. 15. 16-channel datalogger from Geokon, a. general view [28], b. two dataloggers in casings installed in monitoring station in roadway PW-1.

All readings were taken automatically by 16-channel datalogger from Geokon (Fig. 15a). Because of a large number of needed transmission channels, in each station there were two dataloggers installed, therefore, there were 12 such devices in total in the excavation. Due to the present hazard of methane explosion, as a safety measure, each datalogger was housed in intrinsically safe casing OS253/15/0/B which complies with ATEX requirements (Fig. 15b).

In addition, the dataloggers were not powered from their own batteries. Instead, they were connected to the mine's power grid which would allow for automatic power cut off in case of detected increase of methane content, fire, or other hazardous situation.

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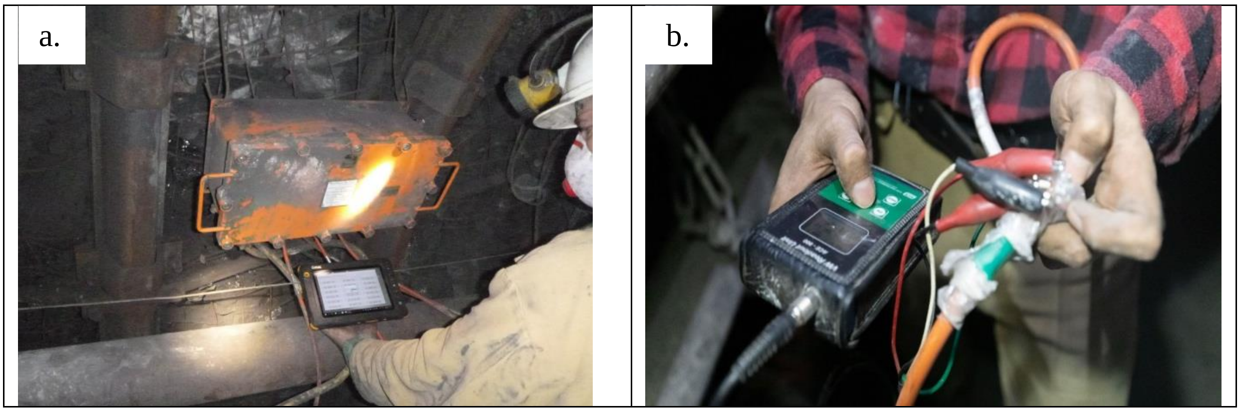

Fig. 16. Acquisition of data from sensors installed in maingate PW-1, a. downloading data from datalogger to tablet computer, b. reading the instrument with the use of portable readout unit.

Measurements were carried out at 6 hours intervals set on the automatic datalogger and then downloaded to the tablet computer (Fig. 16a). Until the automatic data logging system was in place the instruments were read by portable readout unit (Fig. 16b) and providing that way the initial set of reference readings.

It needs to be highlighted that the developed system has the capacity to transmit the data to the mine supervisor control room, either on the given exploitation level or on the surface, via the existing telecommunication network.

4. Summary

Efficient control of stability of the underground excavation requires simultaneous geotechnical monitoring of the rock mass and the support. Monitoring of rock mass should be carried out by extensometers or convergence meters. Whereas behavior of the support should be monitored by load cells placed on support frames, in concrete lining, or by tensometers or vibrating wires built-in rock bolts. It is recommended that the extensometer and instrumented rock bolt readings are spread over several levels. Comparison of that way obtained data with geological and mining charts is a basis for reliable evaluation of the efficiency of the support selected for the given geological and mining conditions.

In case of excavations close to exploitation fronts, or maintained close to the goafs e.g., for ventilation, the most suitable is automated monitoring system. It allows for instruments readings at discretionary set intervals. In such conditions, it is advised carrying out monitoring of load on the additional support like wood cribs, concrete props, etc. In the case of excavations affected by the exploitation, valuable information is provided from monitoring of stress changes within the rock mass which reflect the abutment pressure. Most often these changes are estimated only, while the design of reinforcement of the existing support depends on these values.

In this paper, the authors presented the first case of maingate in coal mines in Poland in which a fully integrated and automated system of rock mass and support monitoring was installed and functioned both ahead and behind the longwall front. The recorded readings explicitly show an increase of stresses before the exploitation front and a decrease behind it. Of course, this effect is well known in general, yet it is rarely quantified by direct measurements for given geological and mining conditions.

The experience gained from maingate PW-1 can be used in further monitoring projects, primarily to eliminate technical and organizational mistakes. The developed system can be advantageous for research projects e.g., on the stability of roadways with rock bolts, innovative support types, or other new technological solutions for mining.

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