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Review

Roof Fall Hazard Monitoring and Evaluation—State-of-the-Art Review

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Abstract: A roof fall hazard is still one of the major threats in the underground mining industry. Each such type of event always brings great risk to miners and causes serious interruptions in the process of rock excavation. In general, the possibility of roof fall hazard occurrence is directly related to the local geology, the presence of horizontal stresses as well as the type of excavation method and the efficacy of the utilized roof support. Due to the complexity of this process, it is important to continuously evaluate the roof fall risk, especially in long life-time places where a mining crew is often present. Within this article, a detailed review of the current methods of monitoring and evaluating roof fall risk was presented. Based on the extensive literature survey, different types of devices were described, and their advantages and disadvantages were pointed out. Furthermore, new trends in the area of roof fall risk monitoring were described and discussed.

Keywords: ground control; roof fall hazard; monitoring systems

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1. Introduction

The underground excavation of deposits located at great depths in most cases is associated with roof fall hazard occurrence, which is one of the undesired and hazardous effects of the loss of stability of the mine workings. Generally speaking, these phenomena depend on uncontrolled and sudden roof failure, and the falling of rocks toward the excavated space, which constitutes a lethal threat to mining crews. This risk is widely observed and reported in the mining and tunnelling industry in Poland [1–4], the USA [5–7], Australia [8], China [9–12], South Africa [12–14], and India [15]. The level of risk directly depends on the local geological conditions, presence of tectonic disturbances and faults, type of operation, distance from mined-out areas, and type of applied rock support [1,7–22]. Additionally, environmental conditions such as temperature, water presence, and overall humidity may affect the probability of roof fall occurrence [23]. In most cases, the phenomenon of roof failure is an unwanted event that is harmful to the mining crew and equipment [24]. Still, there are some exceptional cases in which roof fall is an occurrence that is not only desirable, but also forced in a deliberate way, which, paradoxically, aims at increasing the safety of exploitation [25]. Such a situation may be observed in the example of underground mining performed with the use of room-and-pillar mining systems with roof deflection and room-and-pillar mining systems with forced roof fall. Both mining methods are utilized in Polish underground copper mines and their basic assumption is that the stresses generated by overlying rock mass reach a level that always leads to the destruction of the pillars. Therefore, to achieve a good excavation rate, the technological pillars that are excavated in the first stage are cut to smaller, post-critical dimensions that allow them to slowly yield under the rock mass pressure [26]. This solution also has a second important advantage, in the form of the minimization of risk of pillar burst, due to the lack of ability to accumulate energy by pillars of remnant size (Figure 1). In such an approach, the workings are liquidated solely by roof deflection, or if necessary by partly filling empty space with waste rock.

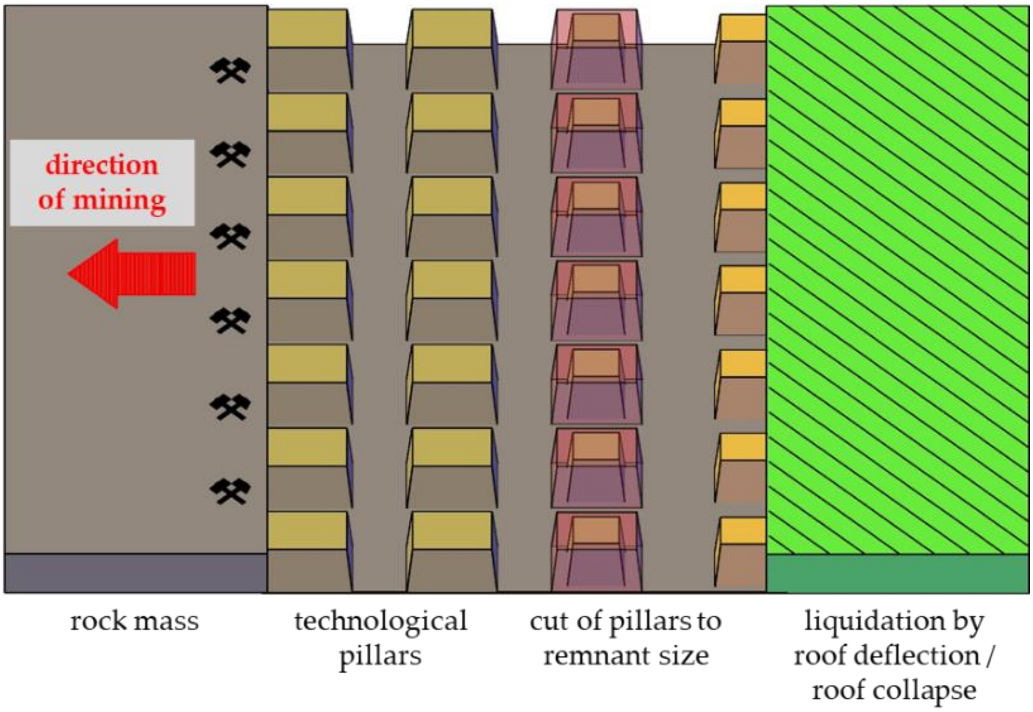

Figure 1. The schematic presentation of the room-and-pillar mining system with roof deflection.

The exact dimensions of the pillars and workings were adjusted to the local mining and geological conditions. At the moment, in Polish copper mines, there are over 20 variants of room-and-pillar mining systems that are fit to the local strength of the rock, height of the deposit, presence of tectonic disturbances, and the presence of a mined-out area in the surrounding of the analyzed mining panel.

According to data presented in [6,24], the room-and-pillar mining system, aside from its advantages, seems to be prone to the occurrence of instability within the direct roof stratum, and therefore more effort has to be put into monitoring and evaluating such phenomenon in mines utilizing this system. Still, roof falls are also often in underground mine excavation with the use of a longwall mining system. As Prusek pointed out [1], roof falls are also common in underground hard coal mines where longwall and board-and-pillar mining systems are utilized.

To highlight the scale of the threat, roof fall-related accidents have to be mentioned. As presented in [12], only in the last 5 years, as many as eight tragic roof failures causing 86 deaths have occurred in China. A similar situation may be observed in coal mines in the U.S., where according to the report published by MSHA [27] in 2006, roof fall caused seven fatalities, 278 non-fatal days lost injuries, and 150 no-days-lost accidents. Worrying data in this regard were also recorded in Polish underground mining. According to the data presented by the Polish State Mining Authority (PSMA) in the years 1994–2013, most deaths in the Polish mining industry were caused by roof falls. For this reason, 93 people have died in the mines during the period of 20 years [28]. Unfortunately, this statistic has not improved in the last years, even with the utilization of more sophisticated evaluation methods and monitoring systems. As reported in the most recent document prepared by PSMA [29], the total accident rate observed in Polish underground copper mines in the last few years related to roof falls varies between 168 and 204 per year (Figure 2). Taking all of the above-mentioned into consideration, it may be stated that the development of new and more reliable monitoring systems and risk evaluation methods is one of the key goals that have to be achieved in the mining industry to ensure the safety, continuity, and efficiency of underground operations. Reducing the risk of developing hazardous situations should always be the primary goal, especially when it comes to ensuring safety in a confined workspace like a mine, where quick escape options are usually limited. As a result, risk management methodologies have been developed and successfully applied in underground mining. The complexity of interactions between people, machinery, explosives, and the rock mass, in addition to the numerous unknowns and incomplete knowledge of the rock mass, contributes to the need for risk assessment and management.

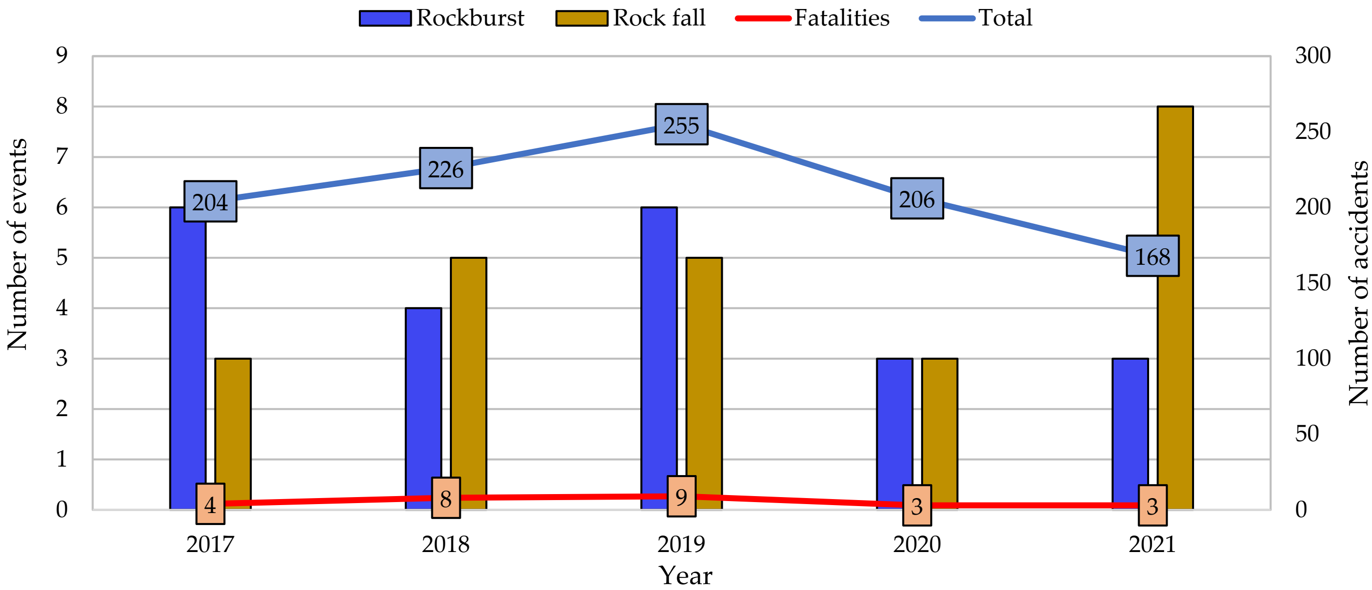

Figure 2. Number of accidents caused by rock falls and rockburst in Polish underground mines in the last 5 years.

Within this paper, the current state-of-the-art (SoTA) in the scope of roof fall hazard monitoring and evaluation is presented. The methods and devices as well as the advantages and disadvantages of each solution are described based on the authors' experience and an extended literature review. Additionally, new perspectives and ways of further development are analyzed and described. The goal of this review is to make mining operators familiar with the technology that is currently used worldwide and may contribute to increasing the efficacy of geomechanical hazard prevention.

2. Indicators of Roof Fall Risk Development

Based on past research and experiences, it may be stated that roof fall is preceded by a number of indicators related to the disintegration of roof strata structure, changes in working geometry, and microseismic activity [30].

Every roof fall risk evaluation method requires the determination of the factors that contribute to the possibility of instability occurrence. As Ghasemi [31] pointed out, at the moment, several variables affecting roof fall risk are recognized and monitored. These variables include geology, depth of deposit, geometry of workings, horizontal and vertical stress levels, and type of support. According to the data presented in research works [13,32], the key factor affecting the risk of instability occurrence is the improperly chosen type of roof support. Furthermore, any defect in the roof support causing its poor performance is indicated (Figure 3).

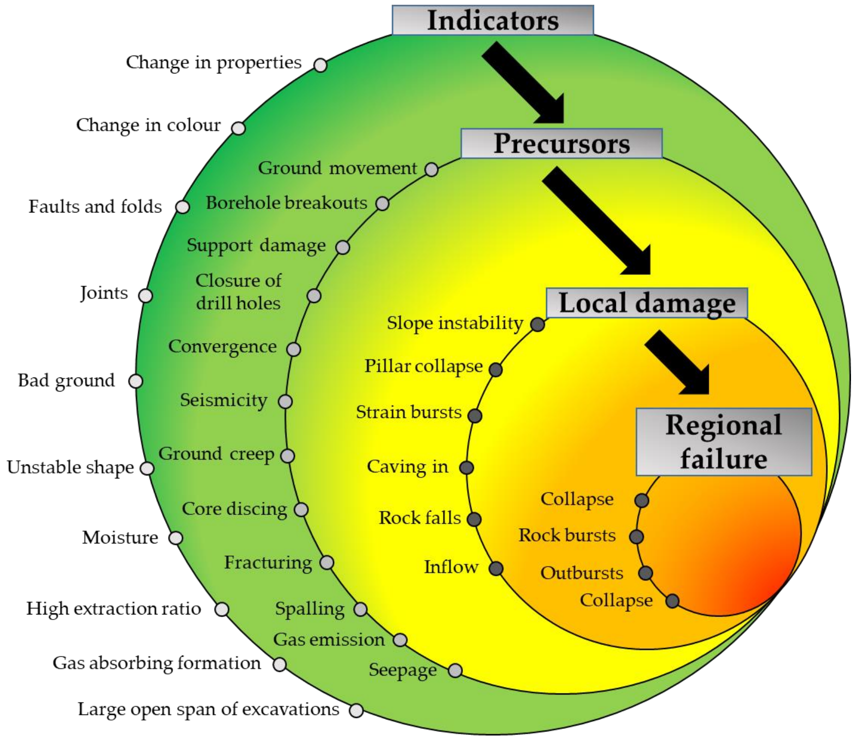

Figure 3. Indicators of the roof fall disintegration based on [33].

Taking into consideration the high complexity of geomechanical failure, there is a great necessity for the development of novel monitoring and evaluation methods that will focus on multi-parametric analysis. First, the reliability of monitoring devices should be increased by an improvement in terms of the data resolution and implementation of continuous monitoring and data acquisition. After that, as Małkowski and Juszyński pointed out in [24], it is important to implement the complex and sophisticated methods of multiparametric hazard evaluation. This goal may potentially be achieved by the utilization of real-time based statistical analyses or the development of the so-called Internet of Things (IoT), which will hopefully allow mine operators to provide far-reaching awareness about the current rock mass state with respect to the presence of people, machines, and external negative impacts such as mining-induced seismicity. In general, IoT is the implementation of Internet connectivity into existing monitoring devices and sensors. What is crucial is the fact that after connection, different devices may be linked and interact with others, and data gathered simultaneously from all sensors can be remotely analyzed. In the case of the mining industry, IoT is currently in the testing phase, but it may potentially be used as a tool that is useful for lowering costs and optimizing the extraction process. It also may be useful in terms of health and safety improvement and analyze the probability of natural hazard occurrence.

3. Monitoring Systems—Current SoTA

3.1. Borehole Monitoring

Control of the state of the rock mass and ground support condition by employing borehole cameras is one of the monitoring systems that are often used in underground mines [34–37]. Visual inspection produces valuable information regarding the rock mass quality in the roof layers described by parameters associated with the presence and character of discontinues such as cracks, joints, their directions, and distributions. The appropriate assessment of the rock mass in relation to the fracture structure, space distribution, and their alteration in time has an important impact on the selection and maintenance of the applied ground support [35,37,38]. It should be noted that by means of a borehole camera, apart from the simple visual inspection of roof layers, some of the rock mass quality parameters such as tunnel quality index (Q), the rock quality designation index (RQD), and rock mass rating index (RMR), etc. can also be evaluated [37,38]. The main elements of the borehole system can be seen in Figure 4.

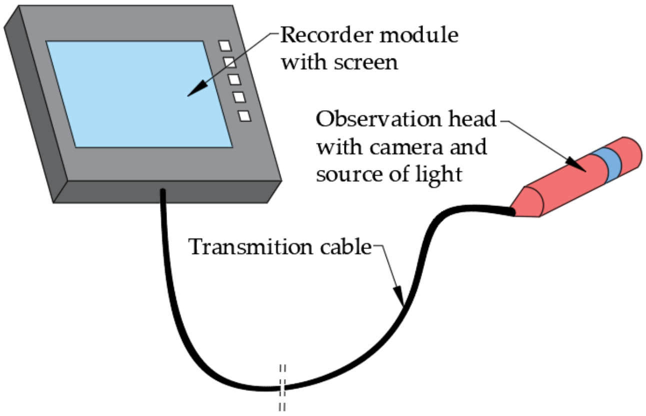

Figure 4. Scheme of the borehole camera system.

It can be stated that a borehole monitoring camera is a relatively low-cost device compared to other measurement systems. Unfortunately, this system also has some drawbacks. In most cases, it is manually operated, and in some conditions, this kind of equipment tends to get stuck in drill holes and can be lost; it is also time-consuming, therefore, can only be used locally. Additionally, it should be mentioned that a reliable assessment of the rock mass current state and potential behavior should be extended to the other monitoring methods [34,36,38,39]. For instance, this type of monitoring can be easily expanded with simple displacement indicators for roof strata-like telltales in which strings can stabilize at two or more levels. This indicator allows for the assessment of displacements into roof strata in time. A combination of these two simple systems can measure displacement, if it occurs, and determine what happens in the roof (e.g., the delamination process) [35]. Nevertheless, visual inspection brings direct and valuable information about the state of the rock mass in the immediate vicinity of the working.

3.2. Instrumented Rock Bolt

Rock stress is an inherent part of the underground environment. Generally, in the intact rock mass, there is a state of balance that ensures the stability of the rock structure. Underground exploitation changes this natural and stable state, which can lead to the overload of some areas and the failure of underground man-made structures (e.g., in the form of rock falls). Therefore, in many cases, there is a need to support rock structures to maintain their stability. One of the most widely employed type of ground support to reinforce underground structures to ensure their stability is rock bolt. For a better understanding of the huge scale of using rock bolt in the worldwide mining industry, yearly usage of this kind of support exceeds 500 million [40]. Looking into this number, it is natural that rock bolt, equipped with special sensors, are often used to monitor stress in the immediate vicinity of the working, notably the roof strata. Data gathered from this kind of rock monitoring system are very meaningful to ensure workplace safety [39–42].

Depending on the type of sensor, there are different types of instrumented rock bolt. The following sensors can be used with rock bolt [43–53]:

- electric strain gauges;
- vibrating wire;
- optical fiber;
- ultrasonic.

Instrumented rock bolt with strain gauges are based on an electric sensor that changes its parameters with bolt deformation. Strain gauges are installed along the rock bolt's rod in different configurations depending on the length of the rock bolt and the assumptions that are made. An exemplary solution, with three measurement levels and four points on each level attached in four positions 90° apart, is shown in Figure 5. In Polish underground copper mines, there is also a more cost-effective version of this rock bolt with three measuring levels.

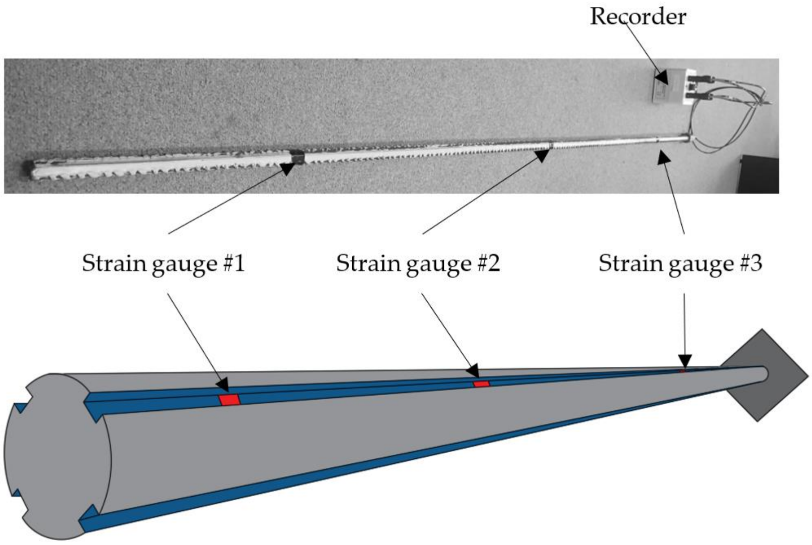

Figure 5. Exemplary scheme of instrumented rock bolt with strain gauges installed on the three measurement levels.

Generally, based on the measurement axial stress, the bending moment, displacement and shear stress can be determined. The drawbacks of this kind of solution are limitations in the resolution along the bolt and long-term stability; additional short base-length strain gauges can cover a small part of the rock bolt length. To avoid this shortcoming, long-base gauges can be applied [40,44,51,52]. With the use of a strain gauge-based instrumented rock bolt, the local roof fall risk may be determined easily by a comparison of the rock bolt's rod strength and axial tension force generated by the rock mass pressure. Such an approach was tested in Polish copper mines, and the results indicated that rapid roof fall hazard increased a few days before failure (Figure 6).

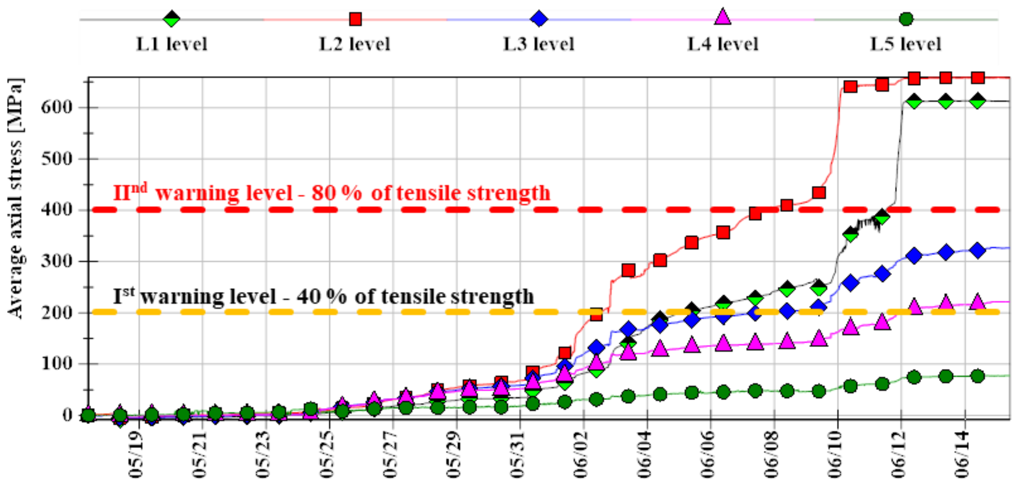

Figure 6. Example of the axial stress measurement performed with the 5-level instrumented rock bolt.

Another type of sensor is based on the vibrating wire. In this method, the stress level is linked to the natural vibration frequency on the wire, which changes in relation to the tension value. This type of sensor is long-term stable, reliable, and is characterized by high accuracy. However, the vibrating wire gauge is fragile and can be damaged even before reaching its capacity limit. This kind of device can only measure the axial stress [40,47,48,53]. An exemplary concept of measurement by means of vibrating wire is shown in Figure 7.

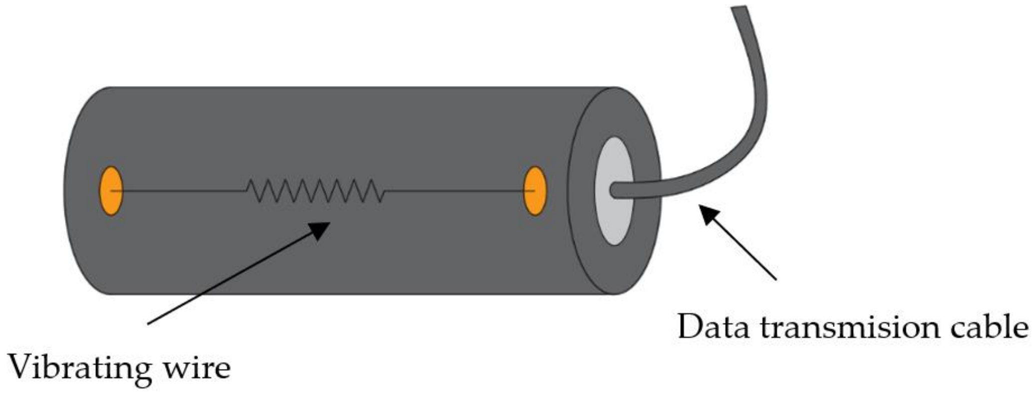

Figure 7. Scheme of the vibrating wire strain gauge [44].

In the last few years, strong attention has been paid to an instrumented rock bolt equipped with optical fiber sensors. This kind of sensor measures the parameters of the light that travels through the optical fiber. There are many different types of devices that employ different light technologies (i.e., fiber Bragg grating (FBG), and distributed optical strain-sensing (DOS)). There are many components that are crucial for correct working of the system based on the optical sensors, consisting, in general, of the following elements: source of light, receiver, modulator, processing unit, and optical fiber. This method can measure the axial loading, share loading, and bending moment [40,44,47,54–57]. There are some important advantages of fiber optical sensors (e.g., real-time, reliable, distributed measurement, high sensitivity, and corrosion resistance). It is worth mentioning that this technology can also be used with cable bolts. However, it should be stated that sensors based on optical fibers have limited strain measurement and are fragile, therefore, they should be properly protected from damage [40,55,56]. Depending on the sensor type, the length of the measuring line may exceed 1000 m and the spatial resolution reaches millimeters [55,56]

Apart from the technologies mentioned previously, another type of sensor should be presented, namely instrumented rock bolt with ultrasound sensors, which can measure load changes and deformation. Rock bolt are the path for ultrasonic wave transition itself, hence the meaningful advantage of this kind of technology is that there is no need to install any elements along the rock bolt, and the sensors are assembled at the exposed end of the bolt, therefore, they are relatively cost-effective. There is also potential for a large-scale monitoring system with clusters of rock bolt [40,43].

3.3. Optical Fiber-Based Monitoring Systems

Systems that use optical fiber sensors can also be employed to monitor geotechnical parameters not only by means of instrumented rock bolt. A proper design system can also monitor rock deformation in underground structures (e.g., workings, roadways, chambers, etc.). Monitoring can be built on the base of separate lines of fibers or as a spatial grid (Figure 8). This kind of system can also be used to even monitor massive structures (e.g., tunnels, mine still pillars, chambers, etc.) [55,58–60].

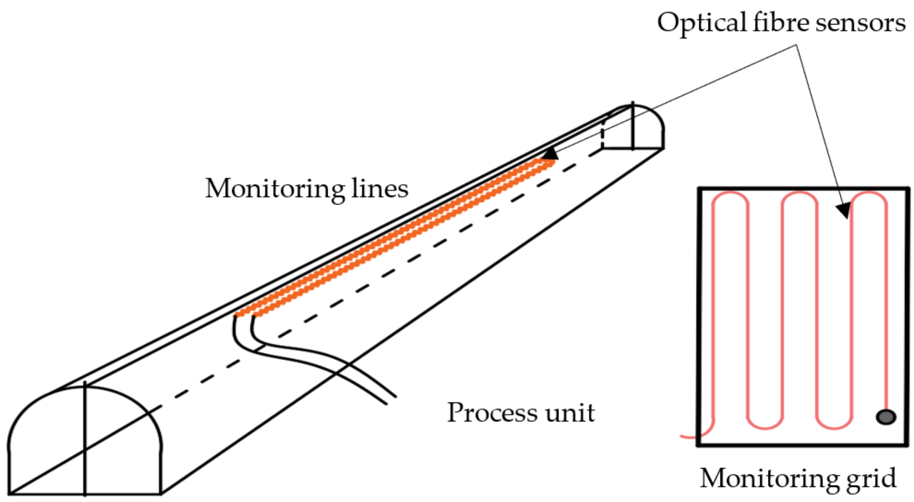

Figure 8. Scheme of different types of monitoring systems using optical fiber sensors.

3.4. Roof Deflection and Delamination Measurements

Displacement monitoring of the roof strata is commonly performed by means of different types of extensometers [43,48,50,61–64]. In many cases, these are very simple and reliable devices that allow for monitoring of the roof. The working principle is very simple, namely, distance measurement is carried out between points where one of them is located and stabilized in the point in the roof, and is treated as stable over time, and the second one is moveable and is located at the collar of the borehole [47]. There can be more than one stabilized point, hence, the spatial resolution of measurement can be improved (multi-point extensometer) and therefore a more accurate location of roof delamination can be determined. There are also instruments available with automatic warning systems (e.g., auto warning tell-tale extensometer (AWTT)) [65]. A sketch of three-level mechanic extensometer can be seen in Figure 9.

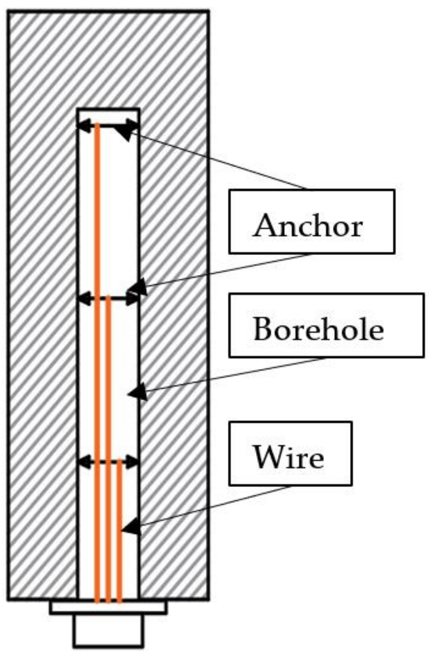

Figure 9. Scheme of the three point extensometer.

Distance measurements can be performed by many methods (e.g., magnetic, electric, optic, mechanic, etc.) [61,62]. One example of an extensometer is a multilevel sonic probe extensometer (magnetic), which can monitor dozens of levels with an accuracy of

<0.5 mm [61]. Deformation of the roof layers can also be monitored by inclinometers. Some of the laser devices are able to measure with a resolution of 0.02 mm/m [63].

In recent literature, there have also been attempts to analyze roof fall hazards with the use of roof deflection monitoring systems. According to the very detailed research described by Stolecki and Grzebyk [66], deflection of the roof occurs in the course of the destruction process of the roof strata. Therefore, a relevant long-term continuous monitoring of this process was executed by a newly developed inclinometric network. This network was built with the use of numerous autonomous sensors for the continuous tracking of roof deflection with a built-in module for wireless data transmission (Figure 10).

Figure 10. Inclinometric sensor with a wireless data transmitter.

This system allows for the recording of changes in the spatial position of the inclinometer rigidly attached to the grouted rock bolt installed within the roof strata. Tests performed by the authors proved that the phenomena of roof collapses are strictly determined by the occurrences of the roof rock destruction preceding them. A similar conclusion may be drawn based on the result presented in [67,68].

Up until now, all preliminary test sites have been located in underground copper mines in the Lower Silesian Copper District in Poland. The collected database of roof deflection and the correlation of results with actual mining and the geological situation in the analyzed area allowed for the development of a so-called criterion to assess the stability of roof layers (Figure 11). This criterion illustrates the stages of roof destabilization as a function of time and the size of the slope angle change.

What is important is the fact that the criterion to assess the stability of the roof layers was tested in underground conditions and according to the preliminary analyses, allowing us to indicate the increase in roof strata failure occurrence a few days before the unwanted event (Figure 12).

3.5. Geometry of Underground Workings

Apart from the above-mentioned monitoring methods of underground structures, there are other ones that are used more and more frequently, namely geometrical mapping. This can be achieved by means of radar, laser, or photogrammetric-based systems [69–75], the deformation of workings, tunnels, chambers, etc. to yield meaningful data regarding the behavior of the rock mass in time. These data can also be used to both build more accurate 3D models and to verify the results of the numerical modeling of rock mass [71]. A laser scan, which produces a cloud of points that represents the surface of the rock, can also be the source of data regarding the occurrence of discontinues and their parameters such as size, orientation, and density [75].

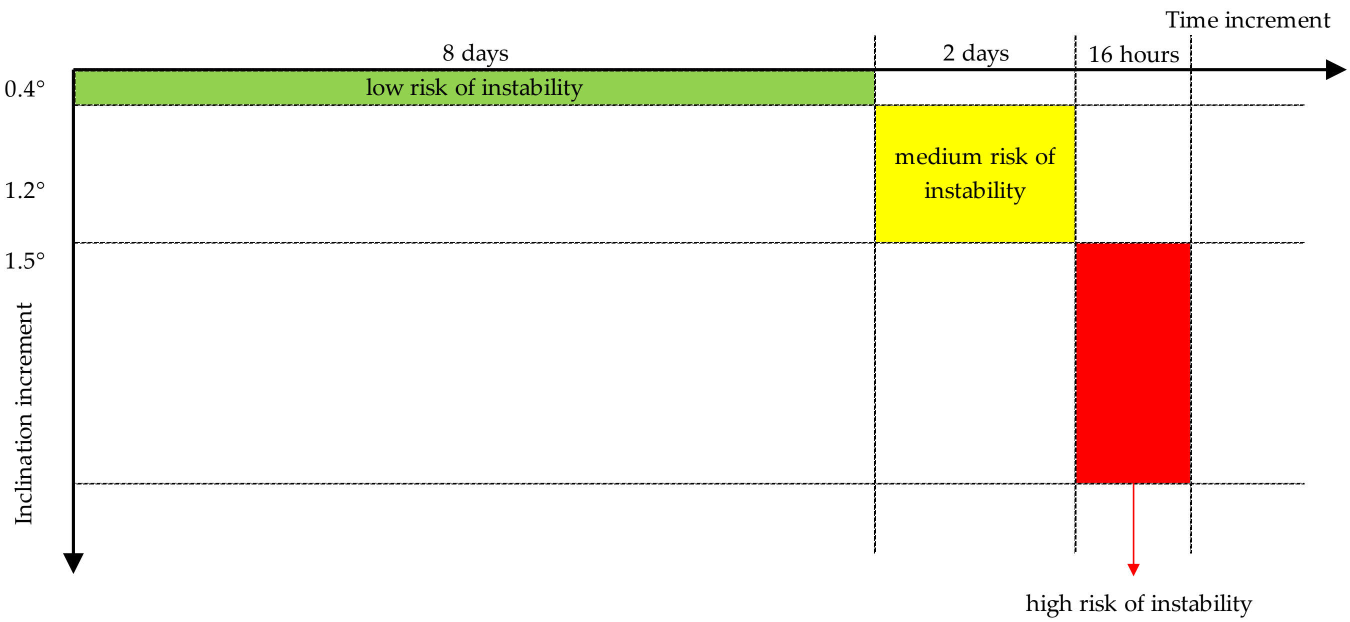

Figure 11. Graphic representation of the criterion to assess the stability of the roof layers.

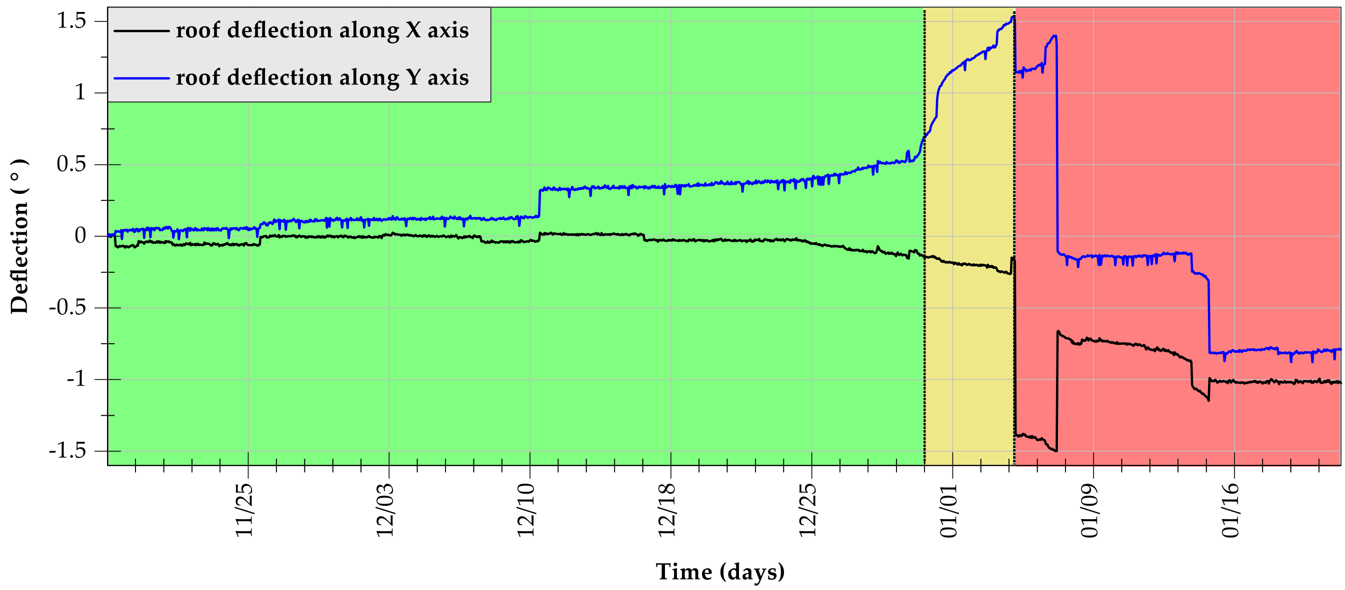

Figure 12. An exemplary case of ground failure prediction with the use of an inclinometric sensor.

It should be stated that scanning systems provide millimeter accuracy with centimeter spatial resolution or even millimeters in the case of laser scanners [69,70,75]. In the case of radar systems, it even has sub-millimeter precision and a resolution of tens of centimeters, with the measurement in a real-time manner with data updated two times per minute [69]. Despite the advantages, there are still some important limitations of these technologies, for instance, even though current lasers are very fast (e.g., some scanners are able to scan hundreds of thousands of points per second), the scanning process can take a long time [70]. It must also be kept in mind that mining conditions can be very harsh and many of them can negatively affect the laser scanning process (e.g., poor light conditions, dust, humidity, water, mobile mining, etc.) [76]. Nevertheless, these monitoring methods are very promising and still under rapid development. It should be stated that radars and laser scanners are also used with drone technology, which allows the use of these methods remotely [70]. The exemplary 3D model of the underground workings' deformation is presented in Figure 13.

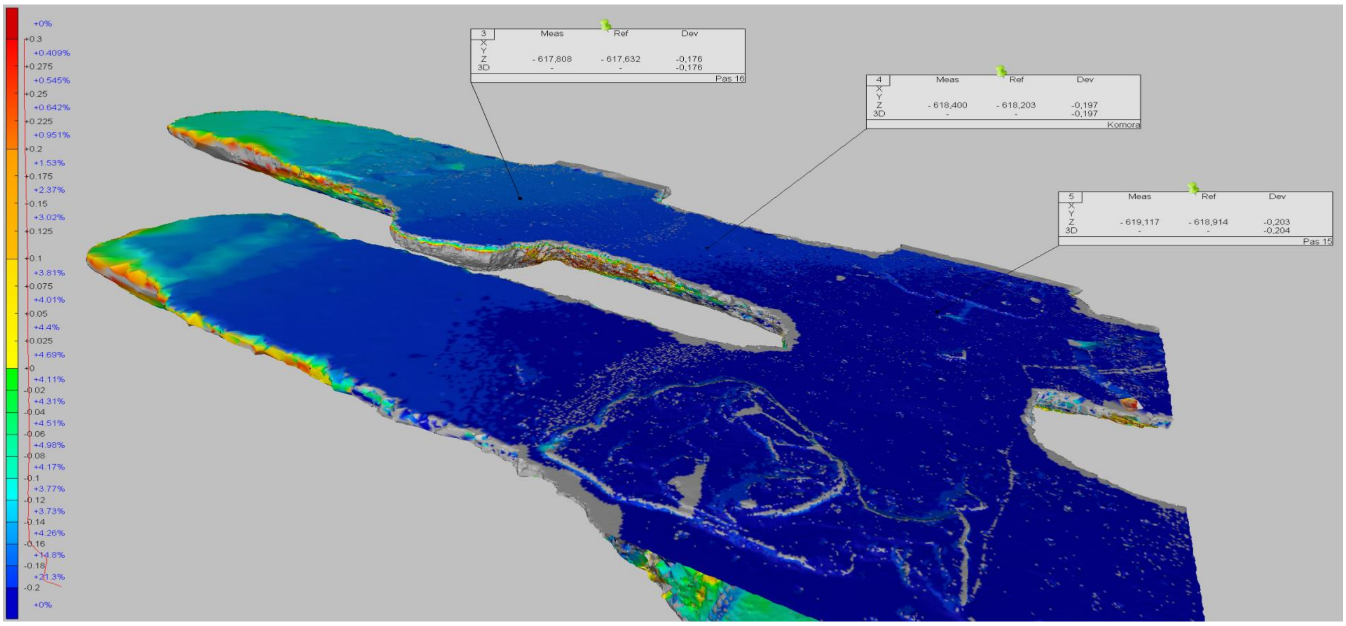

Figure 13. A spatial model of the mine workings was generated using laser scanning [21].

4. Analytical and Numerical Risk Evaluation

In most cases, continuous monitoring with the use of the devices described in Section 3 allows the local risk of ground failure to be indicated. Due to the limitations of the recent technology, reliable stability monitoring of spatial underground workings is currently very challenging. However, some improvement in this matter has been recently observed due to the rapid development of numerical and statistical methods of ground hazard evaluation with the use of information about local geology, data from monitoring systems, and the description of historical cases of ground failure.

4.1. Numerical Modeling

The development of numerical methods in rock engineering has progressed very rapidly in recent years. Aside from the development of new computational methods, more reliable solutions allowing for a better description of the factual rock mass states are continuously being improved. The most common and currently applied numerical methods for underground excavation design, according to Barla [77], are presented in Figure 14.

Continuum methods	Discontinuum methods	Hybrid continuum/ discontinuum methods
• Finite element method (FEM), • Finite difference method (FDM), • Boundary element method (BEM).	• Discrete element method (DEM), • Discontinuous deformation analysis, DDA, • Particle flow method, PFC.	• Hybrid FEM/BEM, • Hybrid DEM/BEM, • Hybrid FEM/DEM, • Other hybrid methods.

Figure 14. The most commonly used numerical methods in the evaluation of the stability of underground workings.

The biggest advantage of numerical analyses is the possibility of determining the stress field and deformation in the surroundings of the mining excavation [78]. Due to the many years of the development of computational codes, it may be stated that the finite element method (FEM) is still the most commonly used. As pointed out by Pytel et al. [79], 3D FEM-based numerical modeling allows for roof stability to be determined in both the static and dynamic load condition. Still, the reliability of analysis strongly depends on the quality of the input data and has to be continuously validated with in situ monitoring results in the form of the stress and displacement distribution within the roof strata or the characteristics of seismic source and recorded waveforms in the case of dynamic analyses. What is important is the fact that due to the rapid development of hardware and the implementation of new more efficient codes into the most popular numerical software, it is possible to determine the roof stability in large underground areas, which is of the highest importance in the stage of planning underground excavation and periodical geomechanical risk evaluation in existing mining panels [79–84]. An exemplary distribution of safety factors within the immediate roof strata is presented in Figure 15.

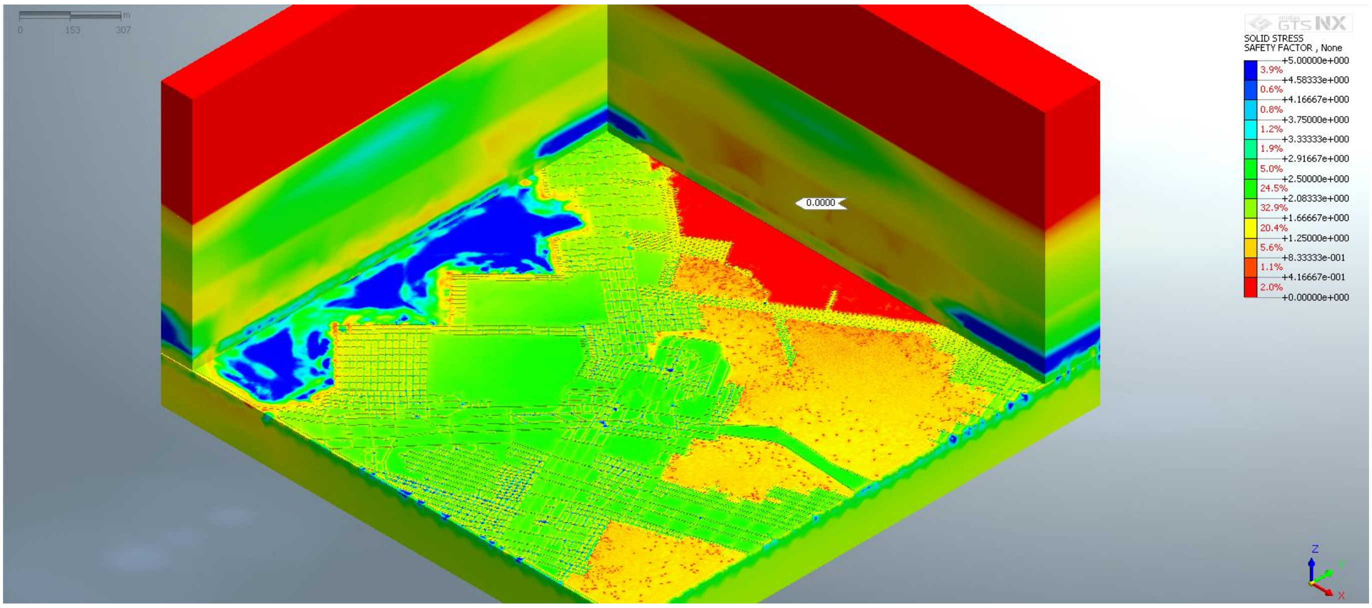

Figure 15. Distribution of the SF values within the immediate roof strata in the selected mining area (size of the model 2 km × 2 km × 1.5 km).

There are also numerous analyses of underground working stability performed with the use of the FDM method [85–87]. An example of the underground chamber stability analysis with the use of FLAC 3D software is presented in Figure 16.

With the increase in the software and hardware capabilities in methods of underground structure, design has evolved rapidly and more notice is being paid to discontinuum models that theoretically allow for the evaluation of the stability of fractured and highly jointed rock mass subjected to static and dynamic load conditions. Discontinuum methods may be used in analyzing the complex process of rock mass fracture and the complex interaction between seismic waves, and the roof supports rock masses during different types of load [88]. An example of the use of the DEM method for the purpose of rock bolt support performance in the enforcement of fractured rock mass is presented in Figure 17.

According to [77], even more advanced numerical models may be prepared by combining different simulation methods. A good example of combining different methods was presented in [89,90], where a hybrid approach FDM/DEM with the use of combined FLAC and PFC developed by the Itasca Consulting Group, Inc., USA was used. Such an approach allows for the prediction of rock fracturing around underground excavations driven in the anisotropic rock mass, and finally determines its stability and effective support methods. The hybrid approach is also suitable for the determination of rock bolt patterns and spacing. The results are also important from the point of view of roof support loading capacity, which is the base information necessary to ensure the stability of the underground excavation.

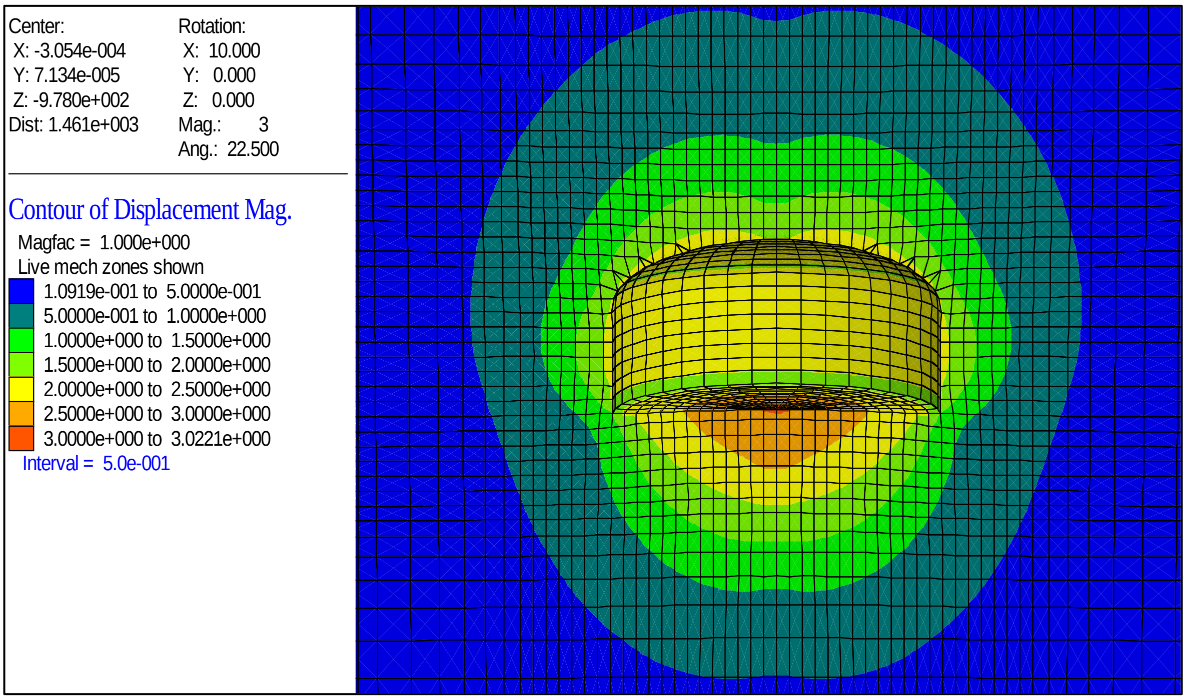

Figure 16. The contour of the displacement magnitude excavated in the rock salt chamber.

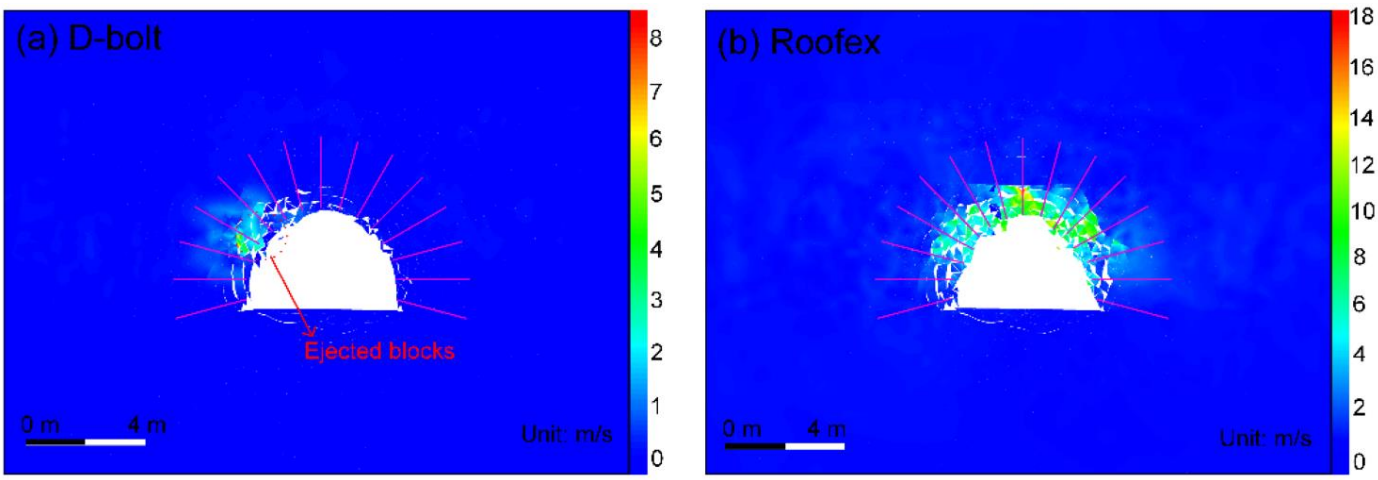

Figure 17. Simulated velocity distribution of the ejected rock mass along the tunnel supported by different types of rock bolt [88].

4.2. Machine Learning and Artificial Neural Networks

Artificial neural networks (ANNs) are mathematical tools that allow for the identification of complex relationships between variables in the form of correlation, patterns, and clusters that exist in a collected database [91]. A neuron accepts an n input data and processes the data to present a single output according to the scheme presented in Figure 18.

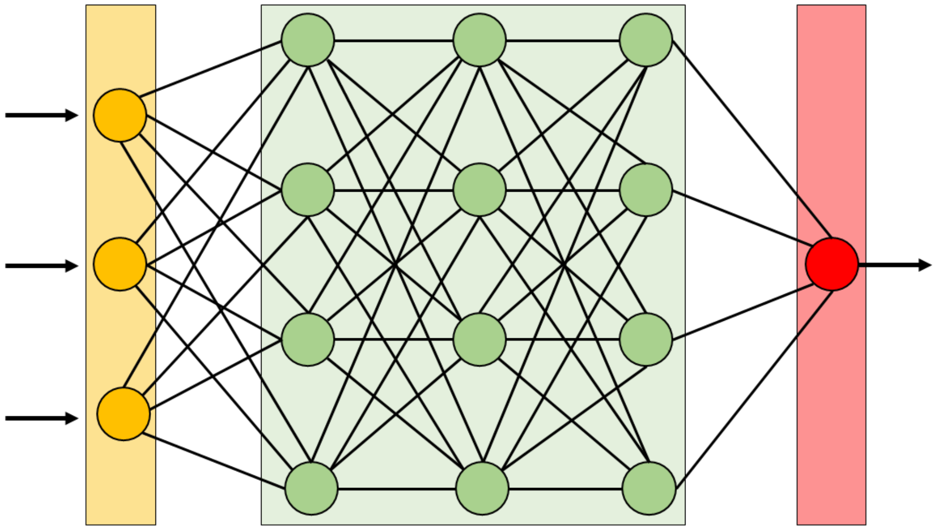

Figure 18. An artificial neural network.

In recent years, roadway stability based on neural networks has developed very actively [92]. An example approach proposed by Mahdevari et al. [93], based on the development of an artificial neural network with the use of a multilayer perceptron network, allowed them to achieve a satisfactory level of fitting between the predicted values and observed roof displacement, reaching R^2 = 0.9109. The study included a number of parameters describing the rock mass strength, which were used as an input of the model including uniaxial compressive strength, tensile strength, cohesion, angle of internal friction, Young's modulus, shear strength, density, slake durability index, and rock mass rating. The output value was roof displacement measured with a dual height telltale. As was pointed out by Zhang et al. [92], the approach proposed in [93] seems to be one of the first reliable research aimed at the use of AI in the stability prediction of underground workings. Still, it was concluded that the quality of the output data strongly depends on the number and quality of the input factors. As Małkowski and Juszyński [24] pointed out, there are numerous recent examples of the use of an ANN in underground engineering in which the connection between the input and output data is not clearly defined. Some approaches were based on tracking rock mass fractures and the correlation of results with geological structure and the rock mass parameters [94–96]. There have also been numerous works concentrated strictly on the parameters of rock layers in the direct surrounding of the underground space [94,97–100].

A very detailed and sophisticated study was prepared in 2021 by Małkowski and Juszyński [24], who based on the AAN analysis developed and proposed the roof fall hazard index for underground copper mines located in the Legnica-Głogów Copper District, Poland. As a result of detailed analysis, four stages of rock mass propensity to failure were determined and the correlation between the output values of the roof fall hazard index and target reached the level of R = 0.85, which is very promising. Additionally, the evaluation of roof fall hazards was satisfactory due to the correlation between targets and the outputs at the level of R = 0.90 (Figure 19).

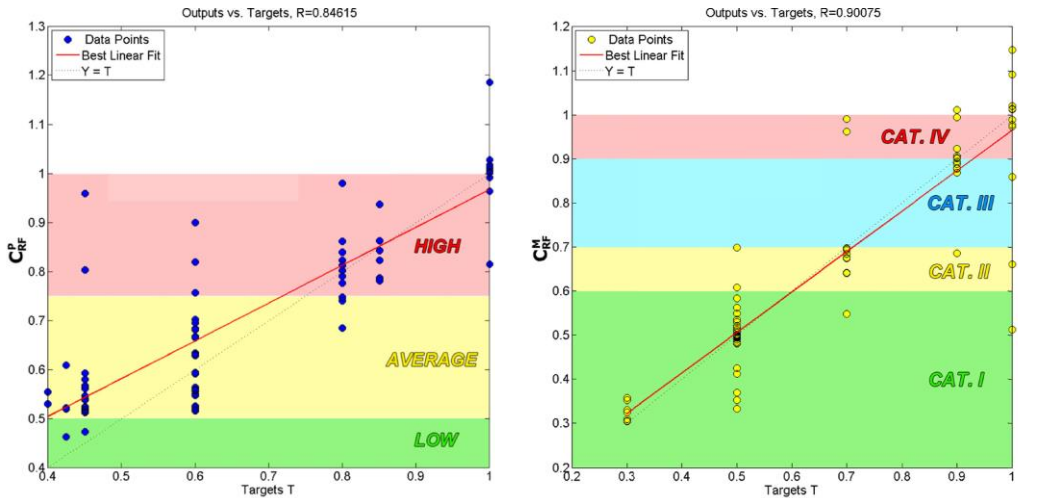

Figure 19. Evaluation of rock mass propensity to failure based on developed roof fall hazard index (**left**) and evaluation of roof stability—categories of roof fall hazard (**right**) [24].

5. Innovative Solutions under Development

With the implementation of development actions according to Industry 4.0, the digital transformation of the mining industry may also be observed. It assumes inter alia integration of novel, more reliable technologies including the Internet of Things (IoT), cloud computing and analytics, big data analyses, and the implementation of machine learning and artificial intelligence (AI) into the excavation and underground working maintenance process (Figure 20).

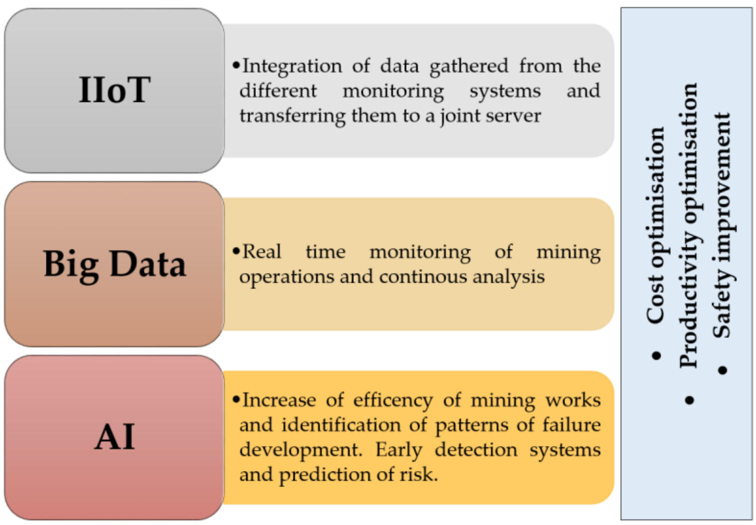

Figure 20. Key directions of mining digitalization according to Industry 4.0.

However, this kind of comprehensive solution fit to the particular site are still under development. Some preliminary conclusions are presented below.

5.1. IoT in the Mining Industry

The implementation of IIoT in the mining industry will be the base of a more complex evaluation of the whole exploitation process. This is why there are numerous mining projects related to the development and testing of new digitized methods in underground sites worldwide. All of these activities are aimed at improving the extraction efficiency, increasing the safety of the mining crew and equipment, and transforming from preventive to predictive decisions. Some successful examples of the implementation of IIoT in mining are presented in Table 1.

Table 1. Successful cases of IIoT implementation in mining [101].

Mining Company Name	Description	Benefits
Rio Tinto—Koodaideri iron ore project, Australia	Rio Tinto's Kookaideri project in Australia is set to build the world's first "intelligent mine" where all assets are networked together and are capable of making decisions in microseconds	Based on continuous monitoring the real-time decision are made what led to optimizing of production process
Hecla Mining Company—Casa Berardi mine, Canada	The mine introduced Newtrax's Mobile Equipment Telemetry in order to better manage machine downtime.	Daily operation of machines' time increased
Hindustan Zinc's Sindesar Khurd (SK) mine, India	Newtrax MET integrated with the Sandvik OptiMine digital platform to track and receive data from the entire underground operation including drills, loaders, trucks, and other equipment.	The effectiveness of production process increased
Goldcorp—Porcupine Gold Mine's Borden site, Canada	With a Ventilation on Demand system, Goldcorp can automatically adjust underground ventilation by controlling fans remotely through a centralized digital interface on the surface.	The operation's electrical consumption was reduced by 50% what significantly reduced cost.
Glencore's Matagami Zinc mine, Canada	Newtrax's Mobile Equipment Telemetry provides mine operations with essential data from interconnected assets and equipment.	The average tonnage of ore hauled in each trip has risen by about 10%.

Unfortunately, most of the successful cases of IIoT implementation in underground mining are related to machine monitoring and an increase in production efficiency. Things seem to be more complicated in the case of the prediction of a natural hazard, whose nature has not been fully recognized yet. Nevertheless, some actions have been already undertaken in this regard.

Based on an understanding of recent scientific and technological advancements, a general direction of further development may be set. One of the promising activities related to the improvement in roof fall monitoring and evaluation in underground conditions is being developed within the EU co-founded project with the acronym illuMINEation. Within the scope of this project, the innovative cost-effective roof stability monitoring system, supported by the Industrial Internet of Things (IIoT), was developed and tested in real underground conditions. As pointed out in [102], wherever there is a mechanical excavation taking place, rock mass instability poses a problem. The installation of rock bolt as well as the use of other support systems such as cable bolts, steel mesh, and shotcrete, can solve this problem. However, because rock mass is a complex natural material, it is challenging to generalize the solution. There are a number of methods for choosing the right type of support [103]. The behavior of rock mass can be predicted using geological data in conjunction with bolt deformation data and potential local or regional instabilities [104]. Joint orientation and positioning with the deformation value measured by rock bolt in the mine area revealed potential weak spots in the rock mass as input data for evaluating rock mass stability. In addition to value, bolt measurements can identify movement. Therefore, extended research on the development of a cost-effective roof fall monitoring system has been conducted. The low-cost sensors allow for significantly increased coverage of the mine area, and instead of a few monitoring posts, almost all rock bolts can be equipped with measuring devices at virtually no extra-costs compared to the standard bolt. What is important is the fact that all measurements are supported by machine learning methods and big data analysis systems, which allow for forecasting movements in the rock mass once sufficient data are available.

Bolts with a measuring system in place have the ability to show changes and signal sensor damage, if it is present. Therefore, it may be stated that intelligent rock bolts are simply regular bolts with extra equipment that aids in the detection of potential instabilities and damage within the rock mass as well as showing changes in deformation and other additional information, depending on the type of sensor device. With the help of further analysis and other variables that can be calculated from the data already collected, it will be possible for us to determine the state of the rock mass. The scheme of the newly developed rock bolt prototype to measure roof bolt deformation is presented in Figure 21.

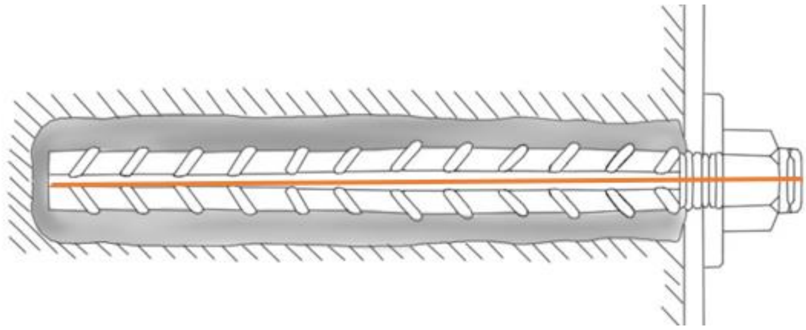

Figure 21. Rock bolt with an integrated sensor developed within the scope of the IlluMINEation project.

5.2. Novel Cost-Effective Solutions

When analyzing the innovative solutions that are still under development, cost-effective devices should also be mentioned. The development of low-cost sensors with reliable accuracy may bring many advantages to the quality of the obtained data, mostly due to the increase in the coverage level. An increase in the network density may be the basis of drawing conclusions about the potential risk not only locally, but also on a global scale in particular mines. In the scope of ground control monitoring devices, micro-electro-mechanical systems (MEMS) seem to be one of the most promising ones due to their great accuracy in static and dynamic conditions, and robustness, which makes them suitable for use in a harsh underground environment. At the moment, MEMS-based devices are widely tested in mining seismology. As highlighted in [105], data about ground motion recorded with MEMS-based accelerometers may be effectively applied for systematic observation of near-field strong ground motion. In Figure 22, the comparison of PSD of the noise recorded by a mine seismometer and cost-effective MEMS accelerometer is presented.

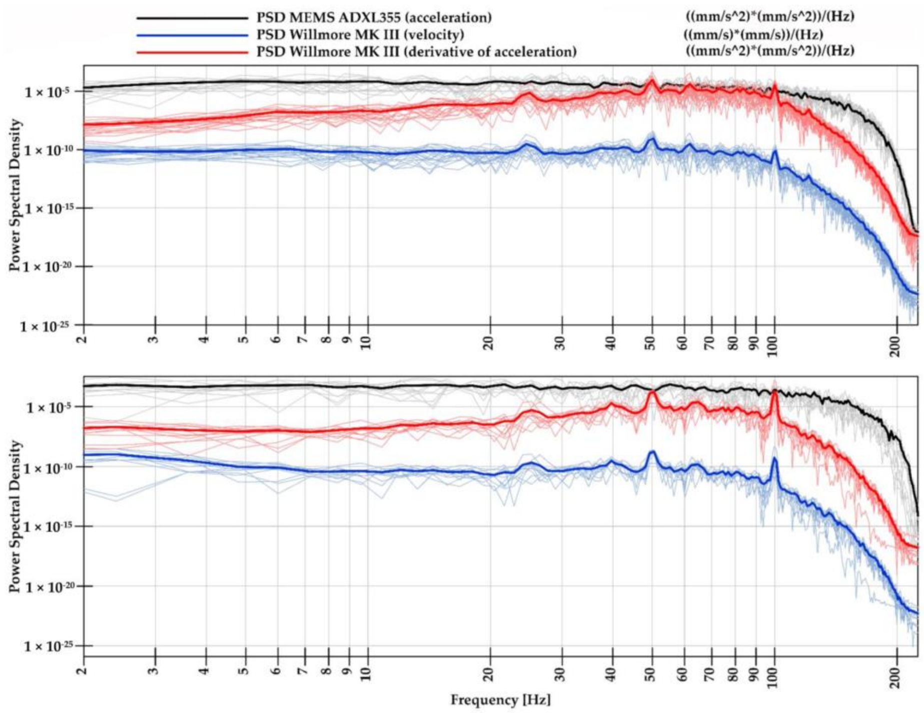

Figure 22. The PSD of noise was recorded by a mine seismometer and MEMS accelerometer in the horizontal (**top**) and vertical (**bottom**) directions [104].

There are also MEMS-based inclinometers that make it possible to significantly increase the quality and resolution of data regarding roof deflection in Polish underground copper mines.

6. Conclusions

The efficient prevention of roof fall hazards in underground mines requires the implementation of the continuous learning process, which has to be developed according to the main principles of measure, diagnosis, and treatment. Additionally, it is crucial to implement these risk management rules into safety systems used in underground conditions. This entails learning about the capabilities and limitations of the existing monitoring systems, their combined use, and how they can be installed and run efficiently. Moreover, one of the goals of the integrated learning process is to transfer the experience gained by engineers and miners over the course of their careers to an objective platform that can be contributed to and accessed by anyone. Thus, the IIoT platform plays an important role in constructing this experience by storing, reporting, and analyzing events. The IIot platform can be successfully implemented when every bolt is covered with a sensor, and it is only viable if the sensors are extremely low cost. This dense network of bolts would provide high-resolution data coverage. On this basis, new and improved algorithms for data analysis can be developed as well as a better understanding of the response behavior of the rock mass as a result of excavation activities (Figure 23). This concept must be robust and simple in order for it to be applied successfully in real life. It should cover the basic installation of the monitoring system, data transmission, data storage, data analysis, data visualization, protocol storage for events that occurred, set measures, and its back analysis.

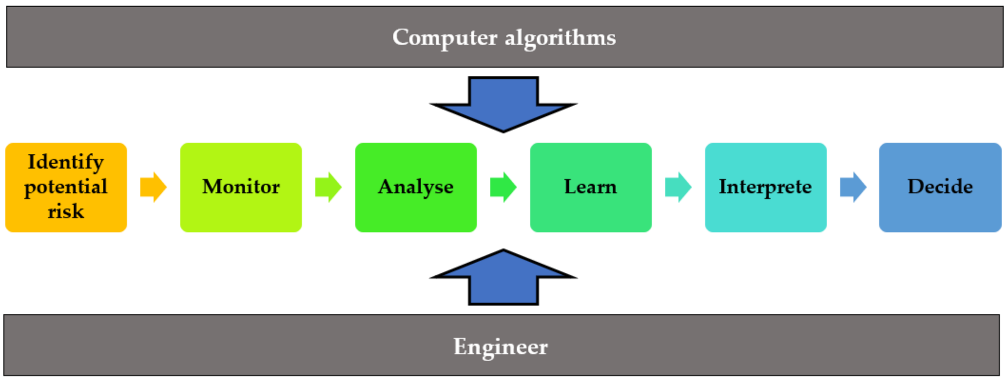

Figure 23. Key aspects of successful roof fall hazard risk management.

Future development requires the integration of different types of monitoring systems and continuous real-time evaluation of the hazard based on the collected data. An increase in the reliability of measurement systems will undoubtedly turn into the development of new, more reliable risk evaluation and prediction methods. It will be also the basis for the development of a more detailed and accurate numerical model that may positively affect periodical geomechanical risk assessment and the planning of underground excavation in challenging geological conditions. Still, at the moment, all these actions are related to many challenges, mostly technical. For example, the rapid evolution of numerical modeling tools in rock engineering allows for the preparation of a very accurate representation of the real, in situ conditions and thus forms the basis for the prediction of rock mass behavior in different load conditions. Discontinuum and hybrid modeling seems to be the most promising and are gaining importance every year, but due to the lack of precise information about rock mass, the discontinuity characteristics may also lead to significant errors, jeopardizing the safety of mining excavation.

An IIoT-based approach, aside from the visible advantages, also has to be further developed. At the moment, one of the biggest obstacles is related to the technological limitations of mine infrastructure. In order to properly implement large-scale IIoT, mining operators have to provide a sufficient data transfer capacity for simultaneous data collection and transfer between devices. Another important challenge is the resolution of data from mine monitoring systems. Due to the high costs of installation and maintenance, monitoring networks such as seismological, ventilation, or piezometric network are limited to a reasonable minimum. The implementation of low-cost devices to regular use may bring tangible benefits in the form of an increase in mine coverage with monitoring devices without a visible increase in costs. Summarizing the rapid development of technology and the intensification of works related to the development of mining technologies year by year will undoubtedly be associated with an increase in the accuracy of the monitoring and prediction of geomechanically hazards in mines. The simultaneous application of multi-parametric data analysis, statistical methods, and new cost-effective devices, already at the testing stage, will bring many benefits in terms of recognizing the characteristics of the rock mass and preparing more accurate models of the destruction of the rock mass. Therefore, further work is needed in this area.

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