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# Field investigations of deformations in soft surrounding rocks of roadway with roof-bolting support by auger mining of thin coal seams

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## Abstract

Coal auger mining is a promising technology used for excavating thin coal seams. The efficiency of auger mining is largely related to the stability of mine roadways in the influence zone of the coal-face. Roof bolting systems are promising in such conditions. An adequate choice of roof bolting parameters is only possible if one understands the features of the stratification of the rocks and stages of deformation of the array in auger mining. Modern monitoring methods of the condition of rocks are based on the use of mechanical benchmarks, sounding of the mine array and the use of optical devices. There are few studies concerning roadways with auger mining. The innovations presented in this manuscript are a determination of the research results of the in-situ processes of rock deformation around a roadway in auger mining which will help to better understand the features of deformation processes in the technological method and design an adequate support system. Some field studies were undertaken in order to investigate the geo-mechanical processes that can be observed while auger mining a roadway with fully grouted bolts of 2.4 m in length. The research included monitoring rock stratification with the help of mechanical telltales, the convergence in the roadway using contour benchmarks, measurements of altitude and rock falls, and visual observations. The presented results show that roof-bolting can be used to support the roadways for auger mining.

**Keywords:**

coal auger mining; bolting support; rock bolt; field monitoring; monitoring station

## 1. Introduction

The most favourable way of mining a seam, which enables a highly efficient use of deposits is longwall mining. The mining machine used in the system is a longwall shearer.

The shearers applied for mining thin seams are produced by the Chinese company Beijing Hot Mining Tech Co., Ltd., by the Spanish company Mackina-Westfalia, S.A. and by the Corum Group. All the above mentioned shearers, as well as static coal plows, work as traditional longwall systems which are the most commonly applied ones.

The systems of longwall mining as well as the machines are adjusted each time to the local conditions and can differ significantly from one another. However, all of them usually require mechanized longwall support, coal conveyors in order to transport coal along the longwall and a complex automation and control system, which requires high costs spent on the equipment and its maintenance. In addition, miners are needed to make the equipment work in longwall mining. At the same time, working in thin seams is extremely hard and uncomfortable. It is economically viable to use longwall mining systems while mining long excavation fields.

The technology of borehole underground coal gasification aims to ensure the obtainment of the capability to explore uneconomical coal reserves in difficult geological conditions, including thin seams. Compared to longwall mining, it is possible to reduce miners' labour and use uneconomical and unconditional coal reserves by using this technology. The products of gas combustion do not contain the oxides of carbon and sulfurous anhydrite. The final product of the production process technology of borehole underground coal gasification does not become coal, rather it is an element for further conversion, such as kilowatts of thermal, electric energy and chemical raw materials. However, the introduction of this technology requires fundamentally different equipment for coal mining, which makes it impossible to combine it with the work of a conventional mine. This technology is a promising one for developing new deposits, or excavating the remaining coal seams after mining. Its implementation also requires large capital expenditures.

Coal augers are a new type of mining equipment used in thin coal seams, making coal mining in roadway surfaces possible without support, which has a promising prospect of application (**Yang et al., 2017; Senyur et al., 2003).**

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The roadway of this technology will increase the recovery ratio of coal due to the partial extraction of non-commercial reserves and protective pillars (**Bondarenko et al., 2018**). This technology enables the excavation of unconditional coal reserves in coal pillars, near geological disturbances and old roadways, etc. As an independent type of excavation, auger mining is not economically viable, according to the authors, because it has very low daily coal production compared to longwall mining. The problem of this technology is insufficient safety due to mining seams with high methane content, a high percentage of coal dust, potential fires and explosive gas mixtures. This problem even led to the banning of auger mining in some countries. However, modern auger machines are much more sophisticated than 50 years ago and they use some technical solutions to address the above issues. Therefore, if one uses this technology at the same time as longwall mining, it will prove to be extremely viable. This is where the authors see the place for augering mining. This can be explained not only by the extraction of non-commercial reserves, but also by the low complexity of work, low costs of extracted coal, the absence of large capital and current costs for production.

However, the efficiency of augering mining is largely related to the stability of reusable mine roadways, some of which should be maintained for a long period in the zone of coal-face work influence (**Bondarenko et al., 2018**).

Therefore, it is necessary to choose a reliable support of roadways, where an auger machine is located. Since the disturbance of the geomechanical state of a rock array using such a type of excavation is much lower than with longwalls (**Feng et al., 2015**), a frame support with a large metal capacity is not the most appropriate. For such conditions, the perspective supporting systems are rock bolts.

Roof bolting systems are the modern type of support that are a widely used mining practice world-wide to ensure the stability of mine roadways, such as tunnels, chambers, etc. The most widely used roof bolts are full resin bolts (**Wen, 2010**), with mechanical locks (**Korzeniowski and Skrzypkowski, 2017**), energy absorbing bolts (**Wen et al., 2016**) and non-adhesive fixing rock bolts (**Sakhno et al., 2018**).

When designing support systems in roadways, which are used in auger mining, the peculiarities of the mechanisms of the deformation of contour rocks and the redistribution of stresses in the rock array should be taken into account. The use of known experience for exploiting any systems in mining is impossible without an analysis of the specific conditions. This creates an interest in the studies on the adaptation of the well-known experience of roadway supports using roof bolts for auger mining.

Thus, an actually important scientific and practical task is to study the deformation processes in the contour rocks of the roadways supported with roof bolts, which are used in coal auger mining.

The basic laws of deformation of contour rocks around the roadways, which are supported with steel frames, are well-known. Recent research on the behavior of the rocks around the roadways, supported with the roof bolting systems, enables us to form an idea about stratification and the loading stages of roof bolts of various types. The modern methods of monitoring the stability of underground openings are based on the use of mechanical benchmarks, deep multi-point displacement detectors, sounding of the array and the use of optical devices, such as cameras (**Larson et al., 2000; Heritage, 2019; Ning et al., 2020**).

The observations of convergences of the main ventilation roadway with a combined support system "bolt-cable-mesh-shotcrete + shell" done in the Xin'an coal mine is in Pingliang city in China's Gansu Province are presented in the work (**Yang et al., 2017**). The grade level of the main roadway roadways is 700 m to 900 m. The surrounding rock of the main ventilation roadway is mainly composed of mudstone and sandstone with an inclination of 10 degrees. The roadway is excavated in the strata of sandstone. The cross-section of the roadway is an arch, with a width of 4.8 m and a height of 3.9 m. The monitoring results indicate that the convergence can be divided into two periods: (1) an active period and (2) a stable period. In the active period, the deformation increased greatly within the first 40 days after excavation. The main functions of the flexible support system are intended not only to improve the stress state of the surrounding rock but also to allow yielding and deformation to release the swelling strain energy and effectively reduce the support load. In the stable period, after an excavation of 40 days, the deformation slowly progressed and became stable.

The final roof subsidence, floor heave and wall-to-wall convergences were 60 mm, 40 mm and 120 mm, respectively. Such deformations characterize a good operational state of the roadway, even though it is carried out in strong sandstones. It is proven that the satisfactory stability of roadways can be maintained without using any steel support frames.

The results of complex observations of the roadway convergence and stratification of the rocks were published in the paper (**Niedbalski et al., 2013**). The measurements were carried out in the inclined drift Izn in the seam 358/1 at a depth of 900 m. The coal seam thickness was in the range of 2.3-2.9 m. The immediate roof of the roadway consisted of claystone and mudstone, above which sandstone occurred. The compressive strength of rock amounted to 46 MPa. The floor in the analyzed area consisted of claystone and mudstone. The roadway was not influenced by any exploitation pressures.

An analysis of the average values of height change over time for particular sections of the roadway with a frame spacing of 1.2 m and 2 coupe rock bolts on each frame indicates that in the first period of measurements (i.e. up to the 159th day), a systematic vertical convergence of the roadway occurred (up to the value of –52 mm). After this period, a minimization of convergence was observed.

Endoscopic measurements carried out in the inclined drift Izn for the borehole located in the roadway indicate that the range of fractured zones between the initial and the final measurement changed only insignificantly from 0.45 m to 0.90 m. The number of fractures also increased unimportantly (i.e. from 4 to 7) over a period of about a year and the total separation amounted to 18 mm.

Similar measurements in a roadway with a steel frame and a spacing of 1.5 m separation indicated the rate was more significant, and in the final phase of measurements reached 41 mm with the range of fractured zones being 4.4 m. This proves that in the conditions of a single roadway, additional roof bolting support significantly improves the durability of the roadway.

Sound extensometer measurements were carried out at the Moranbah North Central Queensland Coal Mine (Australia) (**Shen et al., 2003**). The roadway of a rectangular shape, 5.2 x 3.2 m in size, was mined at the bottom of the seam which was 5.5 m thick. The support of the roadway was with roof bolts of 2.0 m in length. The probes were installed in the wells which were drilled from a parallel roadway into the roof of the monitored roadway before mining it. The analysis of the graphs given by the authors suggests that the stratification of the rocks to a depth of 4.5 m was already observed in one day after mining the roadway. It was discovered that the roof-bolted array is stratified as a single block. The vertical deformation of the roof was 17 mm in a month after mining the roadway at station 1 and it was 51 mm at station 2.

Similar extensometric research in the roadway which is supported with roof bolts of 2.0 m in length at the coal mines of the Teralba Colliery (Australia) (**Frith et al., 2017**) indicates that stratification of the contour rocks depends on the previous stretch of the bolts. With a small preliminary load (2-3 t), stratification occurs sequentially from the contour of the roadway depth into the array. In this case, the vertical deformations get bigger in proportion to the depth. The deformation of the contour rocks has a fading character with a slowing-down of the vertical deformation rate 21-27 days after mining the roadway. Outside the zone of influence of coal mining, the deformation of the contour rocks at a depth of 0.5 m was 45-47 mm, and 51 days after mining the roadway it was 117 mm. The zone of stratification is limited to a depth of 2.3 m. The increase of the previous tension of the roof-bolts up to 8-9 t leads to a significant reduction of vertical deformation in the contour zone at a depth of 0-0.5 m. The overall convergence of the contour was about 40 mm. Almost the same vertical deformations were recorded at a depth of 0.5 m. The depth of stratification did not decrease significantly, which was up to 2.0 m.

The research which was done at the Quiang Coal Mine (China) (**Yu et al., 2016**), at a depth of 886 meters in conditions of weak rocks showed that according to the graphs, the influence zone of the longwall face is about 30 m long. The general deformations in the same line with the roadway reach 600 mm and their rate at the distance closer than 25 m exceeds 4 mm/day. The vertical convergence in the roadways outside the influence zone of the longwall face was 766 mm in 183 days, and the horizontal convergence was 1,102 mm. The deformation rate was at least 3 mm/day. The deformation nature of the roadway contour while monitoring was different, so the rock falls were not localized at the intersection in the same way. According to the authors, this is due to the change in the component ratio of the stress field.

The field studies in the Jangxi Province coal mine in China attempted to detect the areas of rock destruction around the roadway. The observations were made at # 603 tailgate on the seam B4 which was 2.8 m thick at a depth of 806 m. The geological structure of coal-measured strata is relatively simple. The immediate roof of this roadway is siltstone with a thickness of 8-10 m, and the main roof with a thickness of 2-4 m is an interbed of siltstone and fine sandstone. While the immediate floor is mudstone with a thickness of 2-4 m, the main floor of sandstone is 12 m in thickness (**Yuan et al., 2018**). The gate roadways have to be tunneled along the unstable gob before finishing the #602 roadway face. In the roadway there was a failure of bolts and cables, and localized roof fall. The deformation of a single sidewall was up to 300-700 mm.

The observation of the rock stratification was carried out by photographing the state of the cracks in the boreholes. The results show that the damage depth of surrounding rock reaches nearly 8 m. The failure depth of the roof is 8.3 m, of the sidewalls is 7.2-8.0 m, of the top corners 5.0 m. Such deep stratification causes significant deformations in the contour of the roadway and cannot be restrained by frame supports.

The field observations of the state of rocks around the roadway, which were conducted at a depth of 641 m using extensometers and geophysical equipment, are presented in the work (**Šňupárek and Konečný, 2010**). In the contour of the roadway, 4 radial holes were drilled at a depth of 7 m. The tests were carried out within 6 months from the start of tunneling. The measurement step along the well is 10 cm. The results showed that in 2-3 months, the process of destruction around the roadway stops outside the longwall influence zone. The zone of stratification into the roof reaches 2.5 m, in the sides it is 1.8-2.0 m and in the upper corners of the roadway, it is 1.5-1.9 m.

The geological conditions for the mining of seam 385, which is 1.33-1.8 m thick at a depth of about 950 m at the Bogdanka Mine (Poland) are similar to the mines of the Ukrainian Donbas. The research on deformation of the rocks at contour and depth stations was carried out while mining longwall 1 / VI / 385 (**Herezy, 2015 b**) and 2 / VI / 385 (**Herezy, 2015 a**) in conveyor roadway 2 / VI

/ 385, which was used repeatedly while mining the second longwall. It was found that the stratification of the rocks, even outside the influence zone of coal mining, exceeded the depth of the deepest benchmark that was located at a depth of 6.0 m. The deformations of rocks within the stratification zone were of a variable character. The activation of the rock deformations was observed at a distance of 100-150 m from the longwall, which is the influence zone of coal mining. The displacement of the depth benchmarks at a distance of 6 m from the roadway contour reached 80 mm about 60 m from the front of the longwall. This indicates that the radius of the destruction zone around the roadway significantly exceeded the specified depth. The deformation of rocks in the re-used roadwork at a distance of 20-30 m from the longwall while mining the second longwall panel is 10 times bigger than at the time of mining the first one. The total stratification of the rocks at the depth of laying cable bolts amounted to 12% of the length of the bolts.

The research on deformation of rocks was also carried out at the contour stations in conveyor roadway 2 / VI / 385 (**Herezy, 2015 a**) that was used repeatedly. The roadway was supported by an arch support. The maximum vertical deformation at the contour stations was 2,010 mm, the minimum was 980 mm, the horizontal maximum one was 650, and the minimum one was 250 mm. According to the given graphs, both vertical and horizontal deformations when close to the longwall get activated at a distance of about 100-150 m and increase by the degree of dependence. The author defines three characteristic deformation zones ahead of the longwall front: 1,300-300 m, 300-100 m, 100-0 m with a deformation of 0.03 mm / m, 0.125 mm / m, 0.55 mm / m, respectively.

Thus, the analysis of the field observations in various coal basins of the world shows that, in general, the deformation of the roadway contour has a fading character. The active phase of the deformation and stratification in the roadways takes a period of about 30-45 days after mining the roadway. In this case, the stratification zone according to the vertical deformation of the mechanical benchmarks reaches a depth of 2.0-2.3 m, while the stratification zone, which was detected using an ultrasonic method, was about 4.5 m deep. The rate of deformation at this stage is 4-4.5 mm/day. The growth of the destruction zone of the rocks around the roadway slows down.

In the zone of active influence of the longwall face, which is for varying conditions between 30-100 m, the rate of vertical deformations of the contour exceeds 4-5.5 mm/day, the depth of stratification is over 6.0 m, the total deformation of the contour exceeds 800 mm. The area of destruction increases. In the zone of the repeated influence of the longwall face, there is an activation of the deformations in the area of the same length, but the absolute values of deformations are more significant, and according to some data are more than 10 times larger than that.

The research results of the stratification of the rock mass around the mine roadways obtained in the works listed above do not differ in essence from the classical concept of the occurrence of the zone of inelastic deformations around the roadways, which was proposed by Labass (**Xie et al., 2018**). According to his studies, the maximum stratification of the strata caused by the excavation or the proximity of the longwall is observed on the contour of the roadway. The stratification of rocks decreases when the distance from the contour of the roadway increases and outside the zone of influence of the roadway approaches zero.

A large number of studies have been conducted in solitary roadways, chambers and roadways in the zone of influence of longwalls. In spite of this, there are not enough supported studies of the roadways while auger mining. The geomechanical processes around such roadways are different from the situations listed above. Understanding the features of the rock stratification and deformation stages of the mine array is necessary for the correct choice of the supporting parameters. Therefore, the contribution of this work is the investigation of the in-situ processes of rock deformation around a roadway while auger mining. It will enable a better understanding of features of deformation processes to help design an adequate support system.

## 2. Methods

In this section, the description of the site and geological condition of experiment is presented. The measurements and observations were made on the conditions of the conveyor roadway of the northern longwall of seam $k_8^{н}$ at a depth of 450 m at the Dobropolskaya Mine, Ukraine.

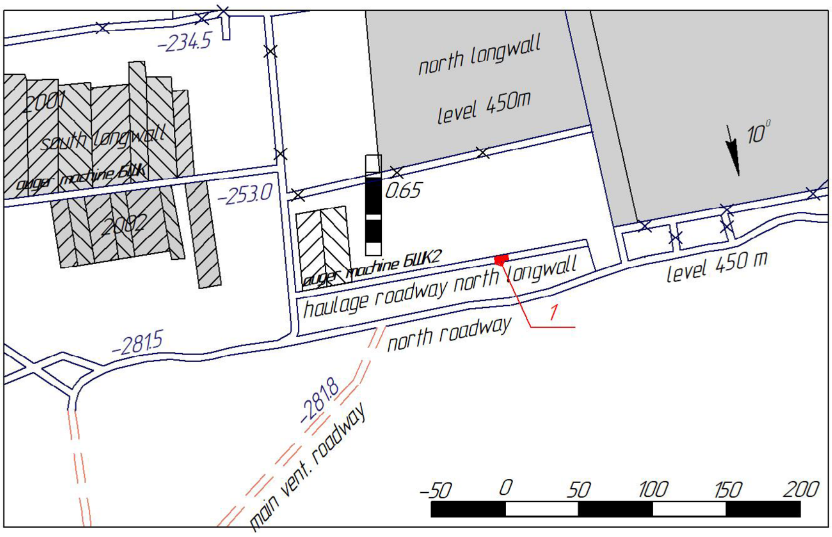
### *2.1. The engineering status*

The conveyor roadway was designed for auger mining excavation. The excavation was done using a BShK-2DM auger mining machine. The length of the roadway was 270 m, the length of the wells was 50-70 m.

The site grade level was +182 m, the roadway level was - 280 m, and the grade level of the roadway was 462 m. The roadway was horizontal, therefore the dip length of the coal face was 462 m. The arrangement of roadways on seam $k_8^{н}$ is shown in **Figure 1**.

The roadway had a rectangular cross-sectional shape. The height of the roadway, while mining, was 3.3 m, the width was 4.8 m. The roadway was supported by roof-bolting with a bolt density of 0.77 bolts/m$^2$. Full resin bolts with a length of 2.4 m were installed under a steel beam with SVP-22. The metal mesh was installed under the steel beam. The support step was 1 m. In one row, two wooden supports were additionally installed under the beams.

The detailed parameters of the primary support system of the “mesh-bolt” are shown in **Figure 2**. The same




1 – Deformation monitoring station
**Figure 1:** Mine plan on seam $k_8''$

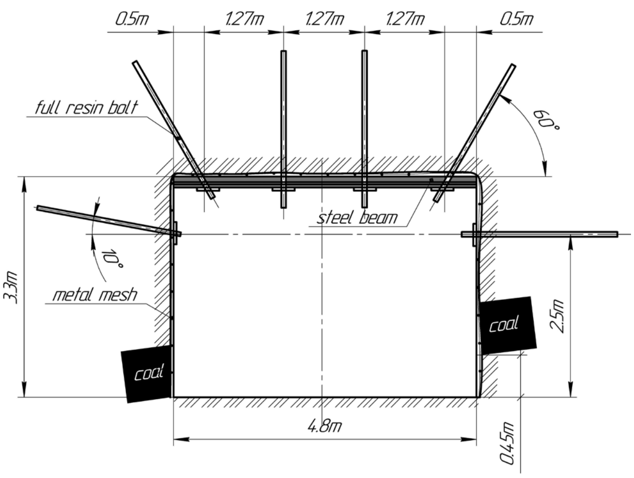



**Figure 2:** The primary support scheme

| Column | Lithology | Thickness (m) | Geologic description, uniaxial strength σ,(MPa) |
|---|---|---|---|
| | sandy mudstone | 7.2 | black gray, bedding in the lower, σ=30 MPa |
| | mudstone | 1.9 | black gray, bedding in the lower, σ=27-29 MPa |
| | coal $k_8^i$ | 0.63-0.70 | semibright coal, banded structure, fractured, σ=8-12 MPa |
| | sandy mudstone | 2.4 | gray, thin isinglass-stone interbed, σ=28-32 MPa |
| | sandstone | 3.5 | bright grey, horizontal bedding, σ=32-37 MPa |

**Figure 3:** Strata histogram and geologic description in this research work

figure can be used to evaluate the relative location of the roadway and the coal seam.

## *2.2. Rock mass properties*

The coal seam had a complex structure with a division into two packs of thin mudstone (thickness 0.01 m) interbeds. The surrounding rock of the roadway is mainly composed of mudstone and sandy mudstone with an inclination of 10 degrees, and the detailed strata histogram is illustrated in **Figure 3**.

## *2.3. Instrumentation and monitoring*

The choice of the research method was determined by the following considerations. The existing physical and technical methods, implemented with the help of extensometers and sonars (**Larson et al., 2000; Heritage, 2019**), are based on the principle of interpreting some measured physical parameters into others. For example, based on the analysis of changes in the velocities of waves that go through the mine array and the changes in their trajectory upon contact with rocks, as well as the reflection from different layers, a conclusion concerning the stratification of the strata is made. This approach enables you to quickly take measurements and it does not require high costs for the equipment of monitoring stations. However, the sensors of the devices that are used for the above mentioned methods are very sensitive to geological conditions, especially to moisture. They also have low sensitivity to the type of interlayer contacts and require fine tuning of the measurement range to filter out noise. This causes certain measurement errors. For the general understanding of the mechanism of rock destruction, such methods are quite satisfactory, but they cannot be applied for an accurate analysis of stratification.

The optical devices used in endoscopic studies (**Yuan et al., 2018**, **Xie et al., 2018**) describe the structure of rock destruction inside the borehole fairly accurately. However, over time, the walls of the borehole, in which the optical probe is placed, get deformed due to the destruction and displacement of rocks around the roadway. It is difficult to carry out sounding of the walls in the same borehole for a long time. At the same time, drilling a new borehole for each single measurement is not only expensive but you also have to drill another borehole in a new place. Thus, it is rather difficult to accurately track the stratification dynamics in a specific place. For a single measurement, optical ones are considered to be the most accurate method. However, it cannot be effective for frequent measurements.

The method of measurements using mechanical benchmarks does not have the above mentioned disadvantages. This is a way to directly measure deformations. By fixing the distance between the fixed benchmark, the roadway contour and each depth benchmark, it is possible to draw a conclusion about the stratification of rocks. Undoubtedly, some measurement errors are inherent in this method too. The error can be minimized by repeating each measurement at least three times. According to the authors, this method is the best one for frequent measurements in the same boreholes. Since the solution of the researched problem requires taking into account the dynamics of deformation processes in the rock mass, it was chosen for measurements in the studies given further. A similar method is also used by other researchers (**Niedbalski et al., 2013**). A distinctive feature of our experiment is the small distance between benchmarks and frequent measurements.

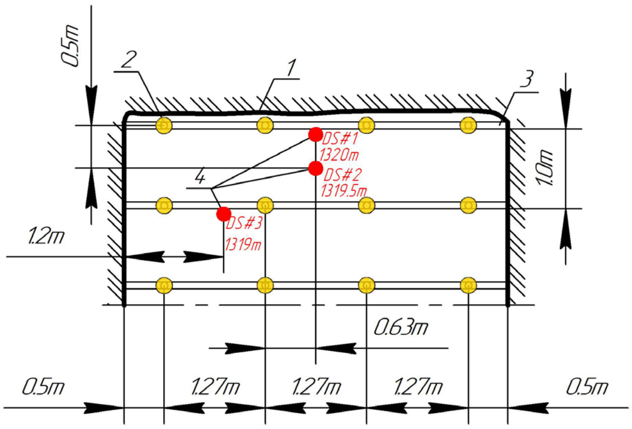
A comprehensive approach that included in-situ observations of the mine at the mechanical telltale, observations at the contour monitoring stations, instrument measurements of the altitude and area of the rock fall, visual observations by means of drawing sketches, and taking photos of the roadways was used as an in-situ research method.

The measurements were made at special monitoring stations that were built in the roadways. Each measurement was repeated three times, and the results were recorded in a record book. The arithmetic mean was taken for calculations and analyses.

A complex measuring station was built for monitoring the condition of the conveyor roadway of the northern main longwall of seam $k_8^i$ at a depth of 450 m at the Dobropolskaya Mine, which included three mechanical telltales (DS # 1, DS # 2, DS # 3) and two contour stations (KS # 1, KS # 2). The stations were built directly in the roadway face. The observations were made while mining the roadway and excavating the seam.

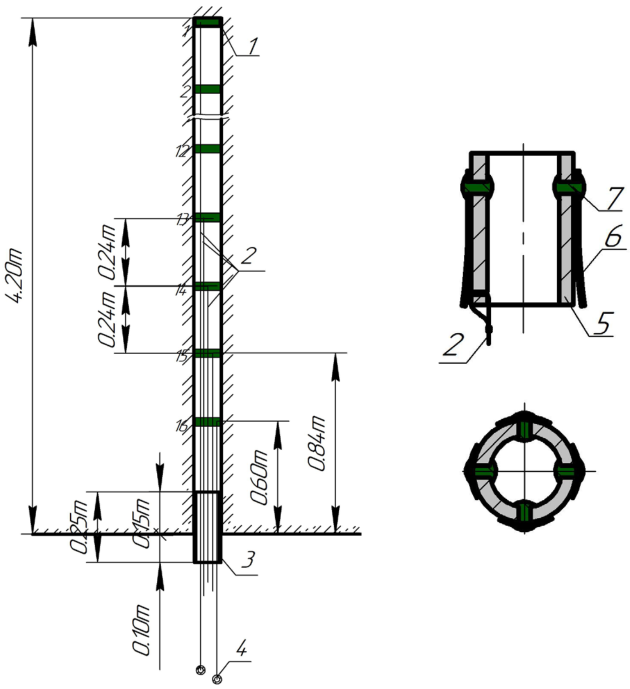
The telltales were vertically installed in the central part of the roadway. The first mechanical telltale is at the intersection of the roadway near the bolt beam (picket 132) between the bolts, the second one is between the rows of bolts at the center of the intersection (picket 131 + 9.5), and the third one is at a distance of 10 cm from the second bolt along the bolt row (picket 131 + 9), 1.2 m from the side of the roadway (see **Figure 4**).

For equipping the mechanical telltale, a bore-hole of 27 mm in diameter and a length of 4.4 m was drilled in the roof of the roadway. Each telltale contained 8 depth benchmarks (see **Figure 5a**). The benchmarks were installed in the bore-hole with the help of a telescopic rammer. Each benchmark was a piece of a steel pipe of 40 mm in length, on which a steel strip was fixed on four




1 – face, 2 – bolt, 3 – beam, 4 – monitoring stations

**Figure 4:** The layout of the monitoring stations



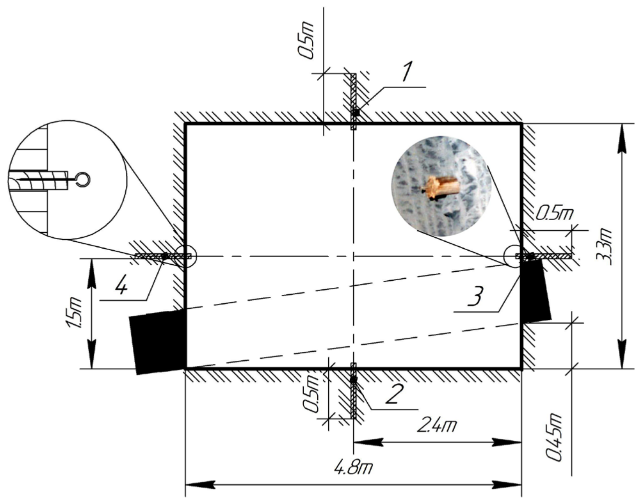

a) b)

1 – depth benchmark, 2 – wire of depth benchmarks, 3 – conductor, 4 – measuring ring, 5 – piece of steel pipe, 6 – bolt, 7 – rivet

**Figure 5:** Mechanical telltale (a) and the construction of the depth benchmark (b)

sides using rivets, which served as a bolt (see **Figure 5b**). A wire rod was stretched from each benchmark, at the end of which a ring with the number of the benchmark was fixed. The breakdown of the benchmarks (bolts) was carried out by moving them to the side of the mouth using the wire.

The benchmarks were installed successively, with the wire of the pre-set benchmarks inside the installed benchmark. At the mouth of the well, a conductor with a length of 0.25 m was installed. After this, an initial measurement of the distance from the bottom of the conductor to the ring with the number of each benchmark was made. The rod was stretched with the help of a rubber thread with a wire hook, which went through a measuring ring. The opposite end of the thread was connected to the plummet. The deformations were detected by measuring




1, 2, 3, 4 – benchmarks

**Figure 6:** Scheme of contour monitoring station

the difference in distance between the ring and the conductor. The measurements were made using a tape measure (measurement error tolerance of ± 0.5 mm).

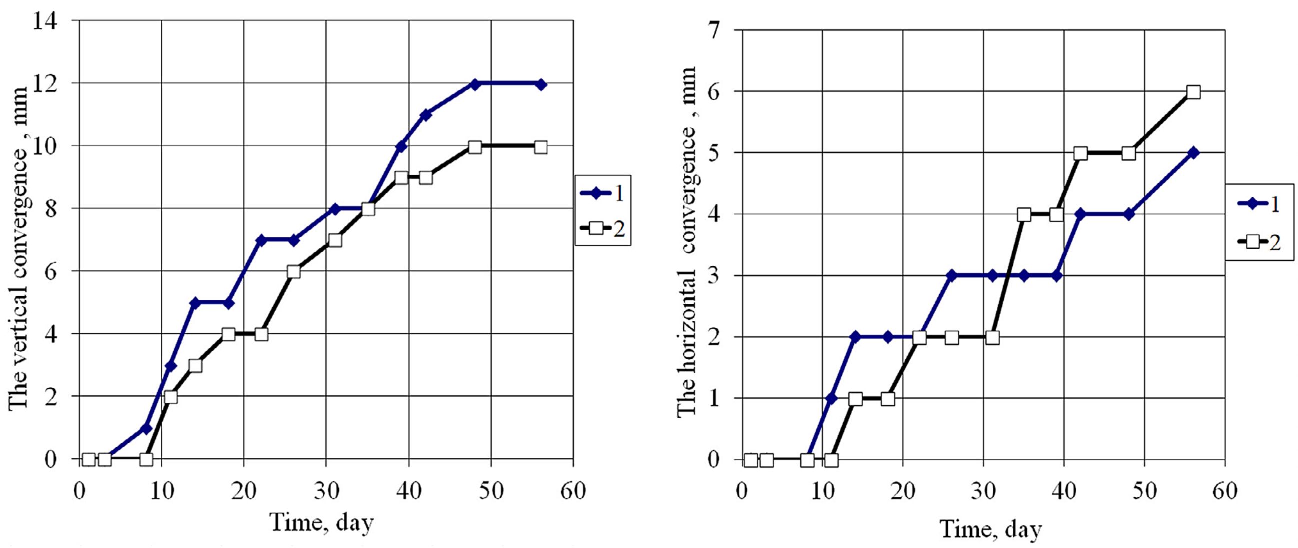
Each contour monitoring station contained 4 benchmarks installed in the roof (benchmark 1), the roadway floor (benchmark 2) and in the sides (benchmarks 3, 4) of the roadway (see **Figure 6**). The side benchmarks were installed at a height of 1.5 m from the roadway floor. The benchmarks had a shape of a steel screw with a ring screwed into a wooden chop, which was clogged into a bore-hole with a depth of 0.5 m.

The measurements were made using a tape measure. First, the distance between benchmarks 1 and 2 was measured. After that, a thread was stretched between benchmarks 3 and 4, and a plummet was hung to benchmark 1. Line 3-4 was taken as a neutral axis. The distance from the roof benchmark 1 to the thread was measured according to the position of the plummet. Then, the distance between benchmarks 3 and 4, as well as the distance between benchmark 3 and the plummet was measured. The rising of the roadway floor was measured by the difference in the distance from the benchmark to the neutral horizontal axis. After the construction of the stations and before the end of each stage of the measurements, the leveling of the support benchmarks was carried out.

The observations at the stations were carried out during all the stages of existence of the roadway: its mining, coal extraction and its maintenance within 3 months after the extraction.

## 3. Results

At the first stage of the observations in the conveyor roadway of the northern main longwall of seam $k_8^i$ at a




a) b)

1, 2 – contour monitoring station KS # 1 and KS # 2, respectively

**Figure 7:** The vertical (a) and horizontal (b) convergence of the conveyor roadway during the stage of its mining

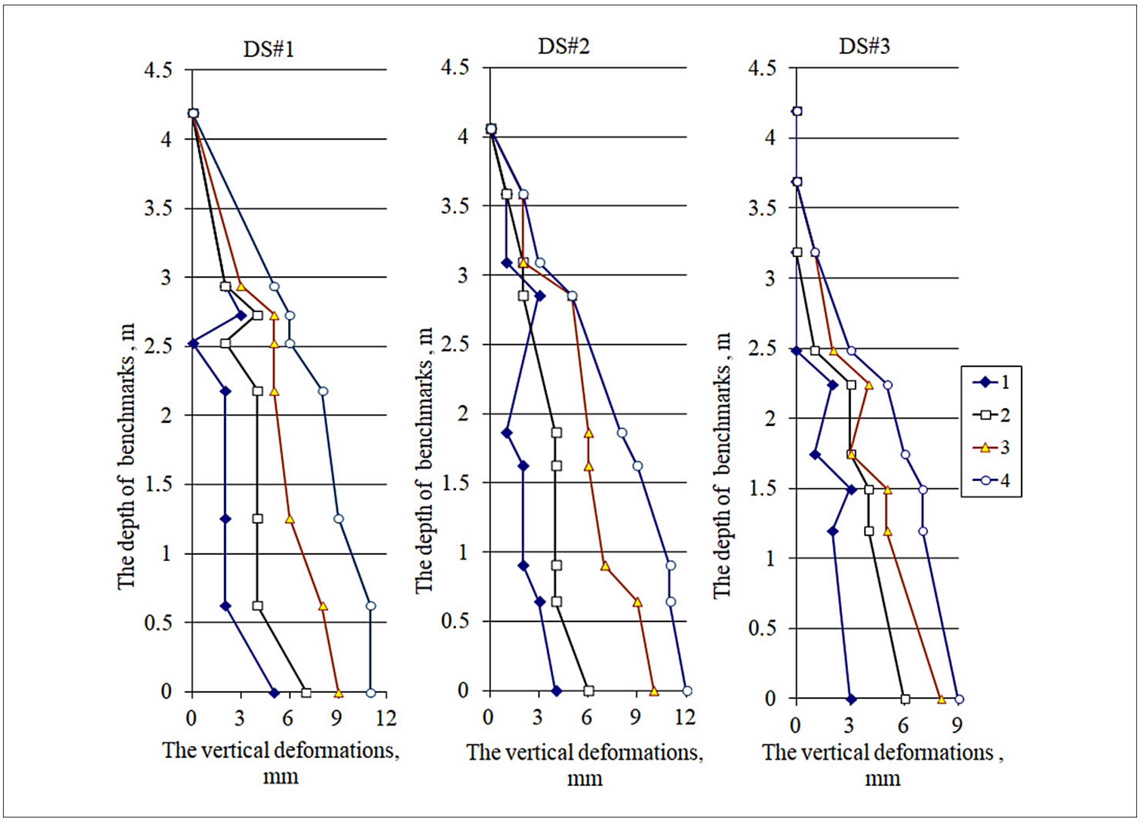



**Figure 8:** Graphs of the vertical deformations of the depth benchmarks in the experimental areas at the stages: 1 – 0-14 days, 2 – 0-26 days, 3 – 0-42 days, 4 – 0-56 days

depth of 450 m at the Dobropolskaya Mine, the deformations of the roadway contour were insignificant (see **Figure 7**). This period lasted 56 days from the start of mining the roadway. The mining rate was 107 meters per month.

While processing the results of the field observations of the vertical deformations of the telltales, it was assumed that the deepest benchmark did not move. This assumption is based on the logic of the mechanism of the roadway in the zone of inelastic deformations over time. For the first 56 days of the observations, at the stage of mining the roadway, such an assumption was appropriate. The analysis of the dynamics of the crack formation and stratification of the rocks in the first stage after mining the roadway can be carried out according to the graphs of the deformations of the depth benchmarks (see **Figure 8**).

In order to conclude on the nature of deformations in a mine array, one needs to study the mutual displacement of two adjacent benchmarks. If the displacement of adjacent benchmarks occurs at the same distance over the observed time, then it can be assumed that the rocks between the benchmarks are displaced by a single block. In such a case, the deformation line in **Figure 8** will be vertical. For example, at station DS # 1 the rocks at a depth of 2.2-0.6 m fall to the same distance within 0-14 days, which is 2 mm. It can be assumed that during this period, the block of rocks at a depth of 2.2-0.6 m is displaced without stratification and compression.

If the lower benchmark is lowered further than the higher benchmark, then the rocks between these benchmarks expand. If the relative extension is greater than the limit for this type of rock, then cracks tend to appear between the benchmarks in the rock. In such a case, the deformation line in **Figure 8** deviates from the vertical counter-clockwise. An example is the 0-0.6 m range at DS # 1 station within 0-14 days. The benchmark at a depth of 0.6 m is lowered by 2 mm, and the benchmark at a depth of 0 (contour) is lowered by 5 mm, so the rock within 0-0.6 m expanded by 3 mm. The relative extension between the discussed benchmarks is 3/600 = 0.005. Knowing that the limiting relative deformation strains for sandy mudstone are 0.002, one can conclude that rocks within 0-0.6 m get stratified, since relative deformations 0.005 are bigger than limit ones 0.002. Thus, it is suggested to accept the relative deformation of the rock extension between the benchmarks for the criteria adopted to judge the rock stratifications.

If the lower benchmark is lowered less than the higher benchmark, then the rocks between these benchmarks get compressed. In such a case, the deformation line in **Figure 8** deviates vertically clockwise. An example is the 2.5-2.7 m range at DS # 1 station within 0-14 days. The benchmark at a depth of 2.7 m is lowered by 3 mm, and the benchmark at a depth of 2.5 is lowered by 0 mm, so the rock within 2.5-2.7 m is compressed by 3 mm. The relative compression deformations are 3/200 =

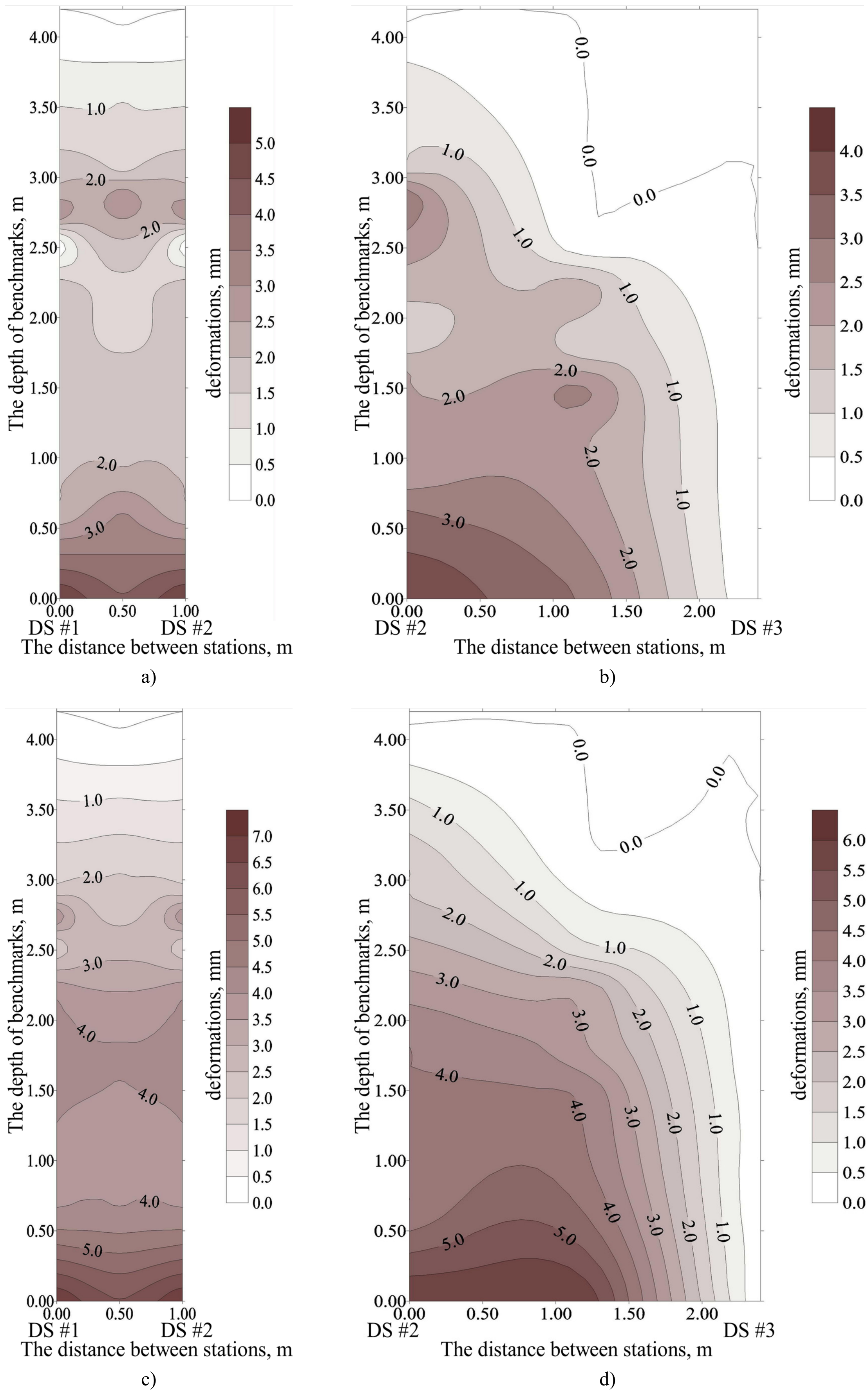



**Figure 9.** Isolines of the spread of vertical deformations over the telltales DS # 1-DS # 2 (a, c, e, g) and telltales DS # 2-DS # 3 (b, d, f, h) at the stage of 0-14 days (a, b), 0-26 days (c, d), 0-42 days (e, f) and 0-56 days (g, h)

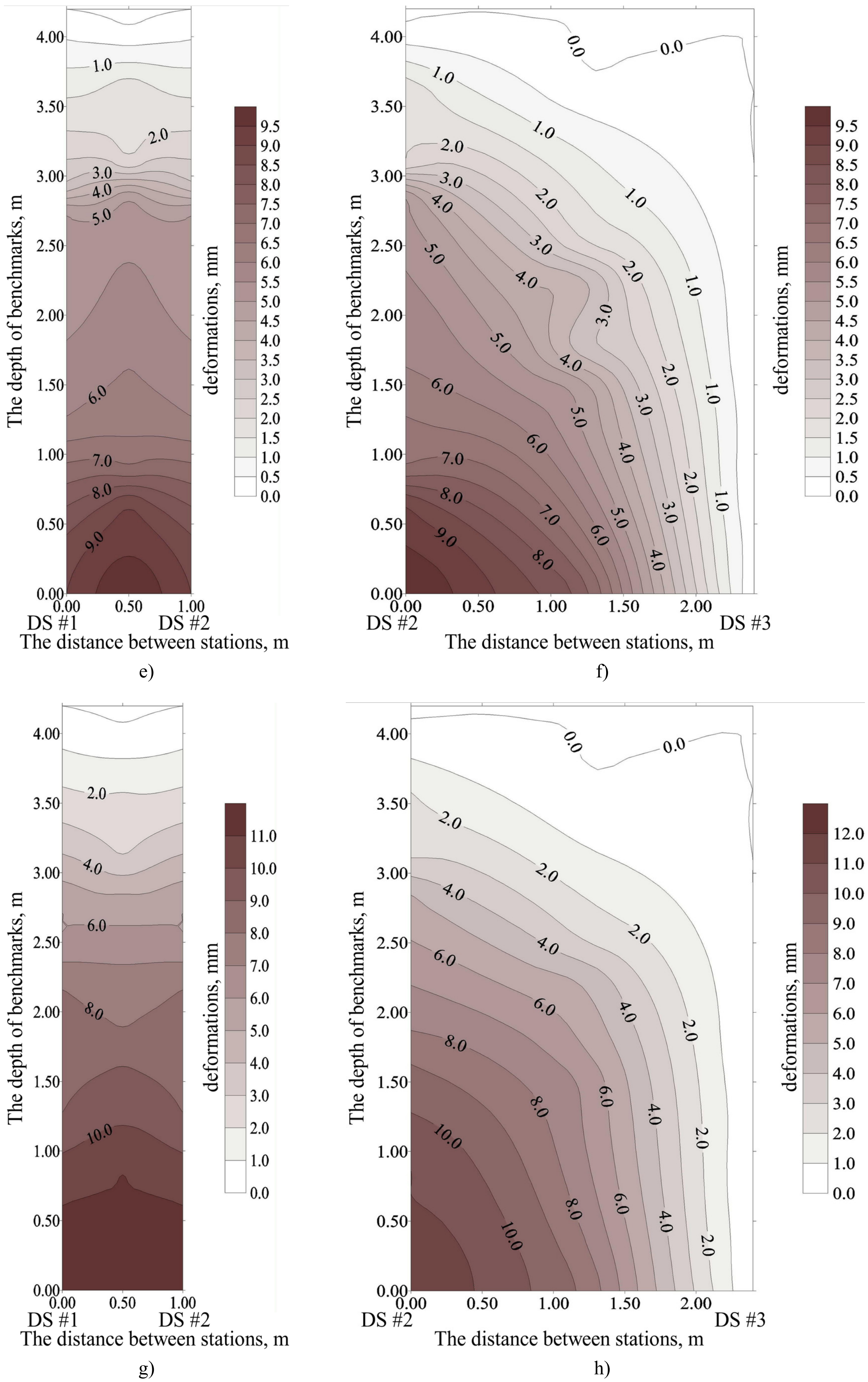
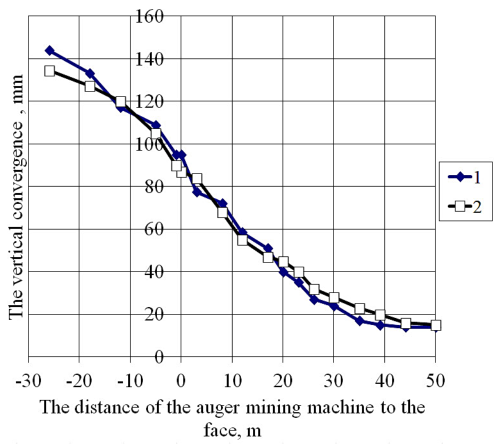
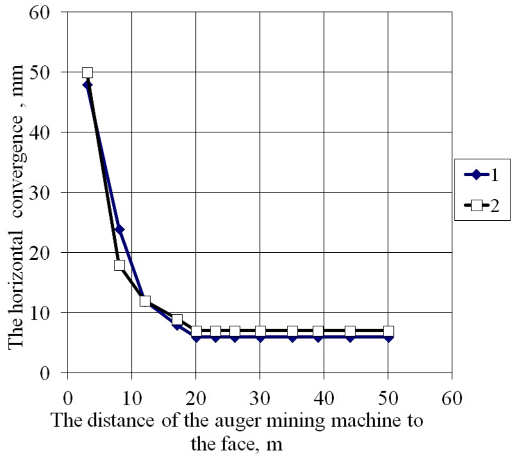



**Figure 9.** Continued. Isolines of the spread of vertical deformations over the telltales DS # 1-DS # 2 (a, c, e, g) and telltales DS # 2-DS # 3 (b, d, f, h) at the stage of 0-14 days (a, b), 0-26 days (c, d), 0-42 days (e, f) and 0-56 days (g, h)




a)




b)

1, 2 - contour monitoring station KS # 1 and KS # 2, respectively

**Figure 10.** Vertical (a) and horizontal (b) convergence of the conveyor roadway mine depending on the distance of the auger mining machine to the face

0.015. It can be assumed that the rocks within 0-14 days at a depth of 2.5-2.7 get destroyed by compression. That is, it is suggested to take rock deformations between benchmarks as the criteria adopted to judge the rocks compression.

Thus, it is seen from the graphs that larger deformations are observed in the center of the roadway (stations DS # 1 and DS # 2). It was on the 14th day after mining the roadway that the rocks stratified at a distance from the contour of 2.7 m (DS # 1 and DS # 2), which is seen from the displacements referred to the fixed benchmark of 3 mm. At the first station, the zone of compression of the rocks between the benchmarks was observed at 2.7 and 2.5 m. In the immediate proximity of the bolt (DS # 1), the rocks are displaced by a single block, which is observed from the benchmarks at a depth of 2.2-0.6 m between the rows of the bolts (DS # 2), the displacement gradually increases in the direction of the contour. In 14 days, the displacement of the contour in the center of the roadway (DS # 1 and №2) is 4-5 mm, and at station № 3 it is 3 mm. At all the stations, the contour part, which is 0.6-0.8m, has the largest stratification. At the stage of 0-26 days, some more stratification slowly occurs in the contour part in the zone of 0-0.6 m, (at stages 0-56 days) cracking increases in the zone 0.6-1.2 m from the contour, and the contour seam lowers more synchronously. This may be due to the involvement of the support washer and beam. The bolted mine array moves as a single block in its middle part. In the area of bolting, there is a gradual stratification of the rocks. In this case, the rock in the roof in the bolting zone and behind it is in fact a seam of mudstone, which means that the interseam contacts are not crossed by the experimental wells.

The isolines of the spread of the deformations in 2D, which were built using the Surfer package, are shown in **Figure 9**. While building them, we made some assumptions that the vertical displacements on the adjacent bolted rows are the same, and in the corner of the roadways there are no displacements at all.

The characteristics of the deformations in the longitudinal section of the roadway along the central axis of the roadway are shown in **Figure 9 a, c, e, g**, and its cross-section is shown in **Figure 9 b, d, f, h**. It can be concluded from **Figure 9a** that above the upper point of the bolt, there is a compression zone due to the displacement of the rocks towards the contour at the zone of 3.0-2.6 m. In this area, some defects can occur, which, with the development of deformations, can lead to the stratification of the bolted part located above rocks. The area of the rocks at a depth of 2.3-1.0 m is vertically deformed without stratification, as the bolted support provides their monolithic character. The contour zone of 0.45-0.5 m displaces in 14 days by 3 mm and at a depth of 1.0 m it is 2 mm, which indicates the presence of stratification in this area. These stratifications develop gradually, and in 56 days they are 11 and 10 mm at a depth of 0.5 and 1.0 m, respectively.

From **Figure 9 b, d, f**, it can be concluded that the vertical deformations both in the depth of the array and in the contour, are maximal in the central part of the roadway. The middle part, which is located at a distance of 1.2 m from the axis, is a dangerous one from the point of view of stratifications. The stratification of the contour rocks led to the rare cases of destruction of the roof and its stratification. The local rock falls were prevented using mesh.

Before the excavation, a control measurement was carried out at the telltales, but more than half of the benchmarks at this stage were not informative any more. The benchmarks either lost contact with the measuring ring (corroded wire), or they slid in the well while tightening the rod (bolt defect). Therefore, at the stage of excavation, the dynamics of the rock deformations was monitored at the contour stations. The extraction was


**Figure 11.** Condition of the rocks of the roof (a, c) and sides (b, d) of the conveyor roadway of the northern main longwall of seam $k_8^{\prime\prime}$ at a distance of 25-30 m before the face (a, b) and 25 m after the face (c, d)

carried out using an auger mining machine at one side, according to which the asymmetry of the vertical deformations in the roadway was observed. The influence zone of the face on the vertical convergence was about 30m, and the horizontal one was about 15 m (see **Figure 10**). During the face extraction, the side benchmarks were lost, therefore, the measurements of the horizontal deformations were observed only at the area before the face (see **Figure 10b**). The auger mining rate was 32 metres per month along the roadway.

Foot deformation was not observed with reference to the neutral axis. The rocks of the roof actively stratified with cakes which were 5-8 cm thick in the influence zone of the face. The destroyed rocks were supported with mesh (see **Figure 11a**). Before auger-mining the face, the extrusion of coal and its destruction at the part of uprising of the seam was observed. Therefore, some additional horizontal bolts were installed in the sides of the roadway (see **Figure 11b**). When removing the side bolts before coal extracting, some rock falls from the sides were observed.

After extracting the coal, the stratification of the roof was activated, which led to some certain cases of deformation of the mesh and rock falls. In these places, a number of bolts were installed next to the beams under the metal strip (see **Figure 11**), and some timber poles were put under each beam. After the coal extraction, the wells were filled with short-cut timber poles and clayed. Over time, the side of the roadway over the well fell out at a depth of 10-15 cm up to the roof line.

A general view of the condition of the rocks in the roadway at a distance of 25-30 m before the face is shown in **Figure 11 a, b**, and at a distance of 25 m behind the face it is shown in **Figure 11 c, d**.

The conducted research is innovative for auger mining roadways with bolts. It is obvious that the dynamics of rock stratification around roadways depends on their maintenance, which determines the dynamics of the stress changes in the mine array while mining. For a single roadway, a roadway before a longwall and a roadway with auger mining, the dynamics of deformation will be different. Therefore, it is impossible to use the measurement results done in certain conditions in different ones. The magnitude and dynamics of rock stratification determines the design of the roadway support and the load on it. Thus, knowledge of the details of the dynamics of rock separation is important.

The presented work describes the dynamics of rock stratification around the mine roadway with auger mining for the first time. The temporal and geometric nonlinearity of deformation of rocks and their stratification in roadways with bolts was determined. The uniqueness of the work is explained by a detailed study of the near contour zone, frequent measurements and a small distance between the mechanical benchmarks.

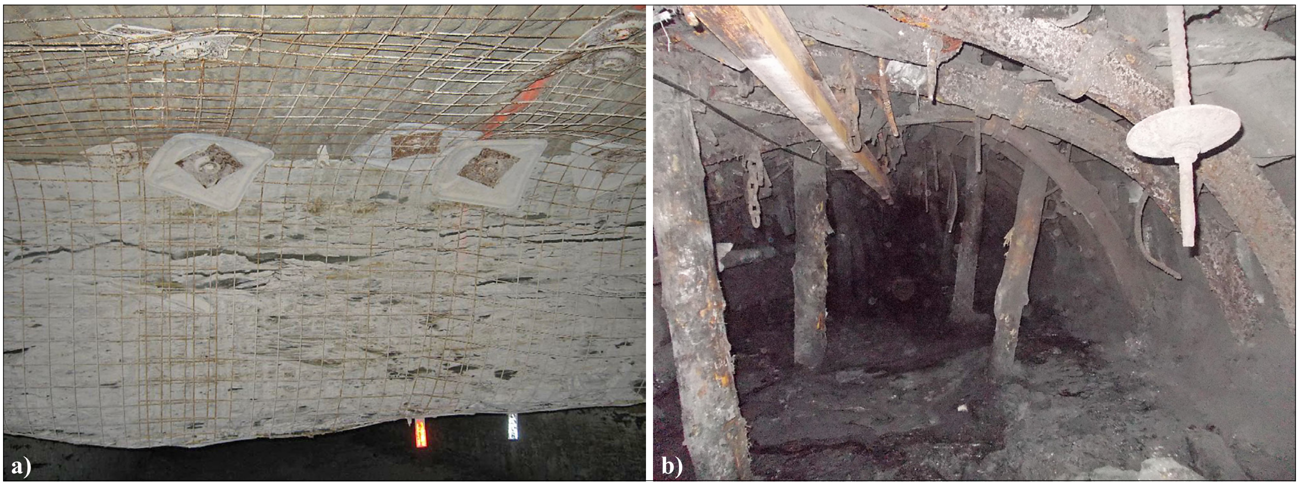



**Figure 12.** Bed separation in weak shale fixed by rock bolts
a) Collections Illinois, USA (**Molinda and Mark, 2010**)
(b) Management Board of the «Pokrowskoje» Mine, Ukraine (authors' photo)

While the results of the observations at the contour stations do not essentially differ from the studies of other authors (**Heritage, 2019**, **Niedbalski et al., 2013**, **Xie et al., 2018, Małkowski et al., 2016, Jena et al., 2016, Singh et al., 2004**), the telltales have shown some new results. In particular, it was found that the stratification of contour rocks differs in time from the generally accepted one. If most authors (**Heritage, 2019**, **Niedbalski et al., 2013**) note that stratification begins on the roadway contour and gradually develops into the depths of the rocks, then the conducted studies determined that for the roadways with bolts, the destruction of rocks can occur outside the zone supported with anchors before the rocks inside the bolt zone get cracked. The resin bolts retain stratification within the length of the bolt. However, some more defects occur at depth and they cause more stratification. The occurrence of these defects contributes to the displacement of rocks within the confined zone as a single block. This can lead to a rock fall with anchors from the mine array. Such cases are known in mining (see **Figure 12**).

In order to explain the mechanism of occurrence of such phenomena, the following hypothesis is proposed. It is known that destruction occurs when the stresses in the rock mass exceed the ultimate strength of the rocks, i.e. the condition is met:

$$\sigma_{eqv} > (\sigma) \tag{1}$$

Where:

$\sigma_{eqv}$ – equivalent stress, MPa;
$(\sigma)$ – rock strength, MPa.

An inelastic deformation zone is developing. The rocks around the roadway are in a state of triaxial stress with unequal components ($\sigma_1>\sigma_2>\sigma_3$), which is caused by mining the roadway. It is known that an increase in the intermediate or minimum stress leads to an increase in the ultimate strength of the rocks (**Norel, 1983, Alexeev, 2010, Mogi, 1974, Zhang et al., 2019**). Anchor bolts perform the function of mechanical devices that change the natural ratio of the stress components in the rock mass, which develops around a roadway, namely, they increase the intermediate or minimum stress. Thus, within the zone of the rock anchorage, despite the higher equivalent stresses in the mine array, with the help of anchorage, certain conditions are created under which rock destruction does not occur. Whereas behind the zone with anchors, if the specified condition is met, there will be destruction which causes stratification. The scheme of the occurrence and development of stratification in the described case is shown in **Figure 13**.

Thus, rock bolts can change the usual evolutionary order of the excavation disturbed zone. Changing the stress ratios in the rock mass due to anchoring can cause an unusual order of rock stratification. In this case, the rocks beyond the rock bolt boundary will initially delaminate, and the anchored rocks will delaminate less. This causes a change in the deformation pattern and loading of support systems. The excavation disturbed zone in the above study is proposed to be determined using strain analysis.

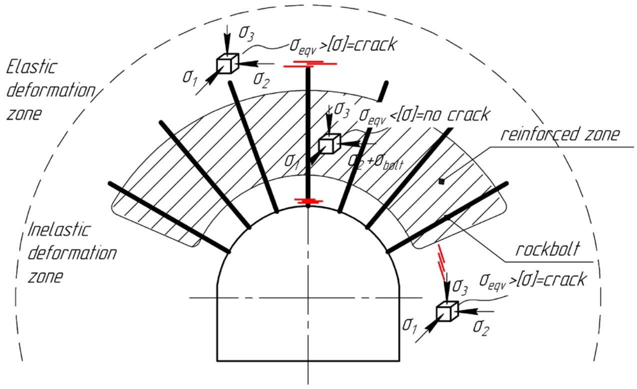



**Figure 13.** Scheme of the occurrence and development of stratification around a roadway with roof bolts

In such situations, it is necessary to provide additional measures to increase resilience. For example, some additional long cable bolts put in the rocks beyond the stratification zone will stop the development of cracks behind the anchored zone.

The above mentioned problem is typical for great depths and soft rocks. In conditions when rock stratification occurs behind an anchored rock zone, one cannot be guided only by experience and practice, as this can lead to rock collapse and accidents. Thus, the obtained results are new for tunneling and suggest a more accurate approach to the choice of support design for auger mining.

## 4. Conclusion

The observation at the contour monitoring stations for the conditions at the Dobropolskaya Mine prove that outside of the influence zone of the work of the coal auger, the deformations of the contour of the roadway, which is supported using roof bolts, grow linearly within 32-38 days, and then have a fading character. The value of the lowering of the roof, with respect to the thickness of the bolted strata, is within 0.005-0.006, thus, with the assumption of a proportional stratification, the entire seam is within the range of elastic deformations. However, the studies at the telltales indicate that the stratification does not take place proportionally.

For the conditions at the Dobropolskaya Mine on the 14th day after the excavation at a distance from the contour of 2.7 m, the rocks lose solidity due to the stratification with respect to the fixed benchmark by 3 mm. The rocks between the benchmarks at a depth of 2.7 and 2.5 m get compressed. The relative deformations of the rocks indicate that defects occur in this area, which, in the course of the roadway, can lead to the separation of the roof-bolted part from the above-mentioned rocks. Stopping the development of such defects and stratification, as well as rock falls from the roof by using the roof bolts with length of 2.4 m is impossible, which requires the installation of long cable bolts or fiber bolts.

The bolted rocks at a depth of 2.3-1.0 m are vertically deformed as a single block. The contour area of 0.6-0.8 m has the largest stratification.

In the zone of influence of the auger mining machine, the rocks actively stratify with cakes which are 5-8 cm thick. Before auger mining the face, the squeezing of coal and its destruction from the uprising side of the seam was observed. After the coal extraction, the stratification of the roof is activated, which leads to single cases of deformation of the mesh, rock falls and the formation of a dome.

Thus, the studies prove that roof-bolting can be successfully used to support the roadways that are used for auger mining. However, at the stage of roadway maintenance, one should design the reinforcement of the support, or use long flexible cables or fiber bolts behind the face.

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SAŽETAK

## Terenska istraživanja deformacija mekih stijena okna s podgradom krovine sidrenjem kod iskopavanja tankih slojeva ugljena svrdlima

Rudarenje ugljena svrdlima (augerima), tj. strojevima za iskopavanje ugljena bušenjem, tehnologija je primjerena za vađenje tankih ugljenih slojeva, a učinkovitost uvelike ovisi o stabilnosti rudničkih okana na ugljenome čelu, što se rješava podgradama. Prikladan odabir varijabli podgrade moguć je samo kada se razumiju svojstva slojeva u toj krovini te njihova podložnost deformacijama kod bušenja svrdlima. Suvremene metode praćenja svojstava stijena temelje se na mehaničkim provjerama, sondiranju i optičkome ispitivanju. Postoji nekoliko studija takvih uvjeta, a ovdje su dane inovacije kod opažanja deformacija *in situ*, tj. u oknima u kojima se buši. Tako se bolje opisao proces deformiranja te tehnologija izgradnje adekvatnih podgrada. Odabrano je nekoliko terenskih studija kojima su izučena geomehanička svojstva stijena tijekom bušenja uz uporabu injektiranja u dužini od 2,4 m. Praćenjem uslojenosti i pojava mehaničkih nedostataka u oknima kartiranjem, mjerenjem visine i vizualnim opažanjem uočavani su nedostatci. Rezultati su pokazali kako je podgrađivanje sidrenjem poželjno.

**Ključne riječi:**
rudarenje ugljena bušenjem, podgrada sidrima, terensko praćenje, opažačka stanica

## Author's contribution

**Ivan Sakhno** (Doctor of Technical Sciences, Professor of the Department of Mineral Deposits Development) provided the field research in the coal mine, interpretations and presentation of the results. **Svitlana Sakhno** (Candidate of Technical Sciences, Associate Professor of the Department of Geotechnical Engineering) provided the geological description of rocks and the study area, analyses of the results of measurements of telltales. **Alla Skyrda** (Associate Professor of Language Training Department) provided the statistical processing of measurement results, and analyses of the results.