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Article

Liquidation of Shallow-Lying Post-Mining Excavations

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Abstract: This article presents an example of the treatment of rock mass disturbed by shallow mining of hard coal in the Małopolska voivodeship, Poland. Considering various methods of rock mass recognition and ways of eliminating shallow voids, recipes for sealing slurries containing mainly liquefiers were developed and used in drilling and injection works in a 10 m-long hole. The course and intensity of rock layer deformation phenomena depend on both natural conditions and the mining method used. At a small depth of hard coal mining (up to 100 m below ground level), the fracture zone may reach the ground surface. In such conditions, sinkholes of various sizes may form on the ground surface. The proposed recipes for sealing slurries, as well as the presented technology for carrying out backfilling works, can be very useful at the stage of selecting the method for liquidation of shallow-lying voids in the carboniferous rock mass.

Keywords: post-mining areas; post-mining area treatment; discontinuous deformations; sinkholes; shallow mining excavations

1. Introduction

The rock layers in which underground mining excavations have been made are in a certain state of stress caused by the weight of the layers lying above. The execution of mining excavations disturbs the original state of equilibrium, which causes the movement of rock mass particles and changes in stress [1]. The issue of the impact of underground mining on the surface is also of great importance in Poland, mainly due to the huge coal resources trapped in the protective pillars of Upper and Lower Silesia [2]. After a certain defined space in a coal seam has been exploited, the resulting excavation collapses: as the space is increasingly wider, the height of the caving also increases, but only up to a certain limit. The rocks, by crumbling and loosening, increase their volume so that at a certain height of caving, this increase completely fills the empty space after the coal seam has been extracted. The height of the caving is several times the thickness of the extracted seam [3]. At this height, the higher layers no longer collapse but only crack. This is the zone of cracks; its height is equal to the height of the caving zone. Above the crack zone, there is a deflection zone, which reaches the ground surface. At a sufficient depth, three zones are created above the seam being mined with caving: caving; cracks; and deflection. At a smaller depth of exploitation, the crack zone can reach the surface, whereas, at shallow exploitation, sinkholes are formed on the surface. This leads to a very important conclusion that for buildings and other objects on the surface, mining at small depths is the most dangerous because sinkholes or cracks are formed here; when mining at great depths, the ground only lowers, and sinkholes and cracks do not occur. The occurrence of sinkholes on the surface

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depends on the quality and type of rocks lying in the roof of the exploited deposit. Cracks, fissures, and slides occur most strongly in the part of the terrain that is located above the lower limit of exploitation. As a result of the extraction of the deposit in a certain area and filling the resulting void by the rocks of the overlying layers, there are displacements of the rock mass in the area above the extraction performed, reaching, if the deposit is extracted in a sufficiently large area, to the surface. As a result of these displacements, subsidence troughs are created above the selected part of the deposit at individual levels. Of particular interest is the subsidence basin that forms on the surface, where various types of objects are located. Depending on the size of the surface of the exploited part of the seam (deposit), the depth of the seam or the distance of the considered level from the seam, and the properties of the rock mass, one can distinguish between incomplete, complete, and overcomplete basins [4]. The results of many years of field observations and model experiments [5] allow for the distinction of direct influences, indirect influences, and secondary influences. Direct impacts occur as a result of filling the post-mining void (squeezing and filling with collapsing roof rocks). Indirect impacts occur as phenomena accompanying the displacements and deformations of the rock mass caused by direct impacts. These impacts include displacements and deformations caused by dewatering of the rock mass and changes in water conditions, changes in the structural properties of the subsoil of objects, and disturbance of slope stability. Secondary influences occur as a result of the activation of incompletely revealed influences of past exploitation caused by the impact of currently conducted exploitation. The share of indirect and secondary influences may be very significant in some cases, so they can significantly affect the displacement process, deforming the basin created as a result of direct influences of exploitation. When considering the effects of underground exploitation on the surface, the most important are the maximum surface deformations that may occur either during the exploitation or after its completion and the calming down of the ground movements [6]. In the area of the finally formed basin, the maximum deformations occur in its marginal part in the belt located above the exploitation boundary. In the central part of the basin, if a sufficiently large seam has been selected, the final deformations of the terrain are very small, and the final depressions are uniform. The terrain in the central part of the basin is, of course, subject to deformations during the exploitation. The deformations that occur in this part of the basin before the end of the terrain movements, and especially during the period when the exploitation front moves under this part of the finally formed basin, are much greater than after the extraction front has moved away and the terrain movements have ended. Determining the maximum ground deformations that can occur at individual points on the surface during exploitation and the dependence of these deformations on the progress of mining operations and the manner of their execution is of great importance for mining practice. Field observations show that vertical displacements of the rock mass as a result of mining operations begin to occur with a certain delay, increase over time, and, after some time, reach their maximum value [7]. The highest subsidence velocity usually occurs a few or a dozen or so months after the exploitation. This time depends primarily on the depth of exploitation, the velocity of the exploitation front, and, to a lesser extent, the properties of the rock mass. In the case of shallow seam deposition and relatively high velocity of the front, the maximum subsidence velocity can occur after a dozen or so days or a few weeks [8].

What deserves to be emphasized in this work and called innovative is not the application of already known geophysical methods to locate the void in the rock mass but the different process of identifying the obtained results. The complications related to the appropriate interpretation are influenced by the terrain already disturbed by mining activity, often rebuilt anthropogenically, and the position of the water table. The rocks that make up the subsoil give a different picture during geophysical research if they are completely saturated with water or dry. Additionally, the proposed filling method itself assumes direct access to the void and optimization of both the consumption of cement grout and the efficiency of repairing the rock mass in terms of the total length of the drilled holes.

2. Methods of Rock Mass Investigation in Shallow Exploitation Areas

In order to identify the causes of sinkholes and to investigate voids and caverns in areas of shallow hard coal mining, a wide range of geophysical and geotechnical studies are carried out. The geophysical method and research methodology should be selected each time to suit the specific geological structure and geomechanical condition of the rock mass and the need to solve a specific problem. However, it should be noted that in industrial practice, there is no single universal method that allows for solving every technical task. Therefore, for some more complex tasks, it is necessary to use several research methods. Geophysical studies are non-invasive, quick to perform, and allow for covering the studied area with a larger number of measurement points. Based on previous experience, it can be stated that the most preferred methods for studying the rock mass in areas of shallow mining and the accompanying discontinuous deformations are the following:

- Microgravimetric;
- Electrical resistivity tomography;
- Seismic tomography;
- Georadar.

To verify the obtained results, drilling of test holes and geotechnical tests are carried out. Then, based on the obtained test results, a technical project is made, and mining works related to shoring up shallow mining excavations from the ground surface are carried out.

2.1. Microgravimetric Method

The microgravimetric method, due to its high sensitivity to density contrast in the rock mass, is one of the most effective geophysical methods for detecting discontinuous post-mining deformations. Practical applications of the microgravimetric method for locating shallow-occurring post-mining voids were the subject of many research works carried out in the years 2001–2024 [9,10]. The microgravimetric method uses the variability of the Earth's gravitational field, which depends on its structure. The change in the gravitational field is influenced by any inhomogeneity in the density distribution of the rock medium, which generates its own gravitational field [9]. Therefore, the distribution of the gravity value depends primarily on the difference in the volumetric densities of the rocks that build this inhomogeneity and the occurrence of deformations of the rock medium caused by natural and anthropogenic processes. This distribution is also a function of the size, shape, and depth of deformation [11]. In the microgravimetric method, depending on the research objective, measurements are taken along the given profiles or on the surface in a precisely defined grid of measurement points. They consist of measuring the acceleration of gravity Δg at each measurement point, which is the basis for further analytical calculations. As part of the processing of results, interpolation grids and gravity anomaly maps in Bouguer reduction for the studied area are developed, which are the starting point for gravimetric interpretation (qualitative and quantitative). The surface image of these anomalies is a reflection of spatial structural changes, i.e., the distribution of rock mass density within the soil medium.

2.2. Electrical Resistivity Tomography Method

The electrical resistivity tomography method, like other electrical resistivity methods, uses the differentiation of the electrical properties of the rock medium. It is a combination of electrical resistivity profiling, due to measurements carried out along the profile, and geoelectric probing due to the increasing depth range during the tests [12]. The number of measurements using the electrical resistivity tomography method corresponds to the performance of a dozen, or so, classic profilings using systems with different depth ranges and several dozen probings with different maximum lengths of the supply line [11]. A series of continuous measurements is performed based on the automatic selection of a combination of 4 electrodes, from among all those connected at equal intervals to the cable along the profile, in accordance with the specified type of system, e.g., Schlumberger or other. The measurements are performed using systems with increasingly larger spacing with the desired step along the designated profile [8]. The maximum spacing of the measuring system depends on the length of the profile and translates into the depth range of the tests. The average depth of measurement penetration is, depending on the specified measuring system, from 1/3 to 1/6 of the distance between the extreme electrodes [13]. The depth range is also influenced by the resistivity characteristics of the rock medium, which depend on humidity, porosity, salinity, and others [6]. The results of measurements using the electrical resistivity tomography method are presented in the form of apparent resistivity cross-sections. The tests can also be performed in 3D—by taking measurements along many profiles in different directions. The electrical resistivity tomography method is characterized by a wide range of applicability. It is used to recognize the geological structure, determine the depth and thickness of overburden layers and embankments, determine slip planes in landslides, and locate sinkholes and voids of anthropogenic origin [14,15].

2.3. Seismic Tomography Method

The seismic tomography method (also known as seismic screening) consists of measuring the velocity of seismic waves propagating in a rock medium. Changes in the structure, density, and elastic properties of the tested medium directly affect the distribution of wave velocity values, the so-called "velocity field". Such studies are most often performed in the vertical plane in the surface hole, between holes, or in the horizontal plane [16]. The Multichannel Analysis of Surface Waves (MASW) technique is often used to study the state of the rock mass in the areas of shallow mining excavations in Poland. This is a non-invasive method of studying a geological medium, providing information on its structure and geomechanical state. The MASW technique uses the registration of generated transverse S-waves, which are a component of Rayleigh surface waves propagating in the tested medium and recorded during measurements. In the MASW technique, the direct relationship between the S-wave velocity and the density of the tested rock medium and the elastic properties expressed by the shear modulus (stiffness) G [13] is important. The applied refraction tomography technique (SRT) is based on classical refraction tests. However, unlike refraction, it gives good results in media with a relatively low-variability geological structure and layers that differ significantly in wave velocities [17]. Tomography allows for locating more complex structures where there are changes in the seismic wave velocity in the vertical and horizontal directions, e.g., fault zones and voids. The effect of tomographic tests is the determination of the longitudinal velocity field of the P-type wave in the tested medium.

2.4. Ground-Penetrating Radar Method

The Ground-Penetrating Radar (GRP) method belongs to the group of radio wave methods and is extremely effective for recognizing the state of the rock mass in the area of shallow hard coal mining. Its effectiveness in recognizing geomechanical disturbances of the rock mass is significantly related to the phenomenon of wave attenuation caused mainly by waterlogging of the rock mass and other factors widely described in the literature [10,14]. The ability to process and interpret the content of the GPR recording is also extremely important, especially in the context of the inventoried old mining excavations in the subsoil. Measurements are carried out using research equipment called a GPR, which consists of a central unit and two antennas: a transmitting and a receiving one. The electromagnetic wave emitted into the rock mass by the transmitting antenna is reflected, refracted, and attenuated. The reflected wave at the boundary of media with different dielectric constants is recorded by the receiving antenna. The image obtained in the form of a wave is a reflection of the geological structure of the studied medium and the discontinuous deformations of anthropogenic origin occurring in it [18]. For the correct identification of the rock mass in the area of shallow mining excavations, GPR studies should be conducted in the form of many suitably designed GPR profiles. A spectral GPR operating in the FMCW (Frequency Modulated Continuous Wave) technology is extremely useful for conducting such studies, i.e., a continuous signal modulated in the frequency domain is generated. The use of this type of GPR for the study of the rock mass condition in the area of shallow hard coal mining allows for obtaining high imaging resolution as a function of distance [17].

3. Liquidation of Shallow Voids in the Rock Mass

Mining operations conducted in the past at shallow depths left behind unfilled voids and remnants of unselected coal. This coal is left in pillars, protective shelves, and collapsed rubble, to which fresh air has access, weathers, and self-heats, and can become a source of troublesome underground endogenous fires. The issue of filling shallowly deposited old mining goaf is gradually becoming increasingly important due to the progressive increase in demand for new construction areas. Modern construction requires high stability of the subsoil, while at the same time, old buildings are increasingly threatened as a result of the progressive weathering of the disturbed rock mass. Unintentional, spontaneously occurring collapses in old workings pose a significant threat and are often the cause of local disasters or the reason for preventive evacuations of people from endangered facilities and closing road or rail transport routes. One of the most important parameters of backfill material is its compressibility. Depending on the technical equipment and technological possibilities in a given region, backfilling of excavations can be carried out using dry backfill [19], hydraulic [20], paste [21], and cemented foam with fly ash [22]. Due to waste management in underground mining, backfilling of excavations is carried out using fine and coarse particle size grading tailings [23]. Fly ash has found a wide application in underground mining and backfilling technologies. Currently, waste-water suspensions are used in underground hard coal mines primarily for sealing goaves, liquidation unnecessary corridor excavations, reducing fire hazards, filling voids behind the lining of corridor excavations, filling shallow post-mining voids, binding highly mineralized waters, creating artificial ceilings for layered mining, and also for transporting inert gases such as nitrogen and carbon dioxide [24].

One example of an installation built in the 1990s is the Borynia coal mine in Poland (Figure 1). The installation consists of a pneumatic unloading system for fly ash delivered by cement wagons (the ash is unloaded into silos), tanks for mine waste, a silo for materials modifying the suspension (cement), a mixer, a pipeline supplying water to the mixer, a feeder system: scales and counters allowing for precise dosing of the suspension components supplied to the mixer, a computer system for controlling the operation of the installation, an installation for expanding and adding CO_2 to the suspension, a pump feeding the suspension to the backfill pipeline, and a compressed air installation for cleaning the pipelines.

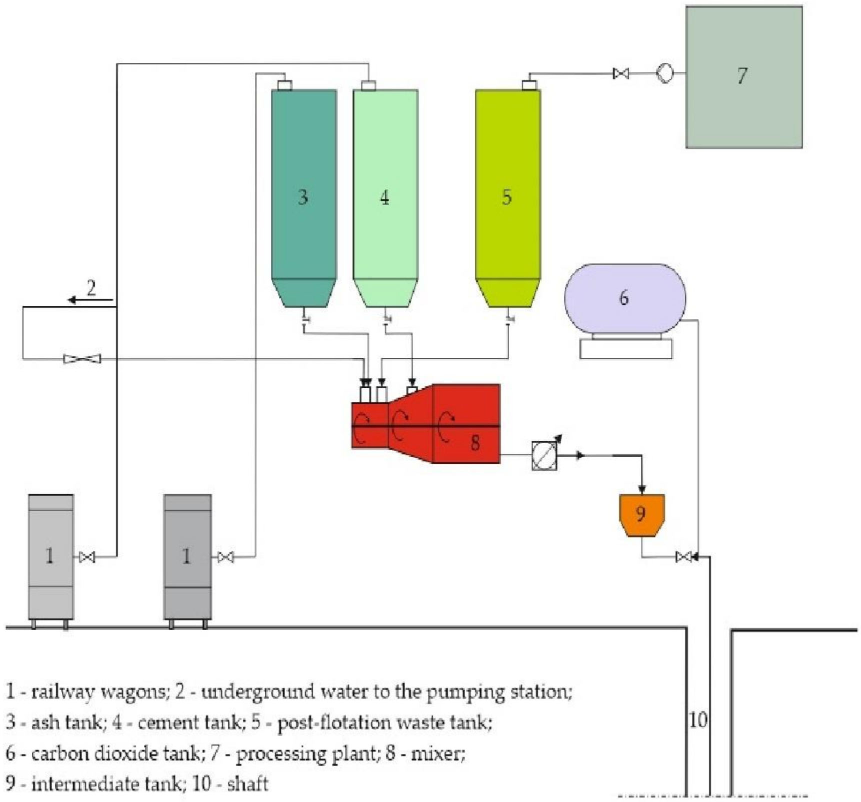


Figure 1. Installation for preparing ash–water suspension in the Borynia hard coal mine in Poland.

The possibility of placing ash suspensions with CO_2 was determined based on a technical test in fire prevention in an underground hard coal mine [25]. Carbon dioxide added to the suspensions was gasified from the liquid state using an installation consisting of an atmospheric evaporator and a tank with liquid CO_2 with a capacity of 30 tons. The tank was equipped with an electric heater, allowing the device to operate with a capacity of up to 0.5 tons of liquid CO_2/h. Carbon dioxide was added to the suspension after the mixer. From this point, all components were transported together along the entire length of the pipeline (Figure 2). The joint disposal of CO_2 and fly ash in underground hard coal mines does not require the construction of special installations in those mines where backfilling of excavations is used. It is necessary to expand the existing technical facilities for preparing ash–water suspensions with devices for introducing CO_2. Moreover, the joint disposal of carbon dioxide and water ash does not negatively impact the conduct of technological operations.

A significant difficulty in the technology of filling voids with ash is designing the necessary quantities and locations of backfill holes for proper tight filling of the voids. The problem results from the inaccessibility of the voids and, therefore, limited possibilities of their location and, thus, inaccurate knowledge of their dimensions and shapes. The voids are located on the basis of old mining maps with an estimated consideration of their development due to occurring collapses and on the basis of modern methods of examining the rock mass described in Section 2. It should be noted that the geophysical location of voids with currently available equipment does not give fully satisfactory results due to large disruptions of the geophysical underground reading and surface reinforcement of the area. Reconnaissance by drilling is the most expensive, but it gives good results, and, in addition, most of the holes made are used as backfill holes. The backfill injection technique requires the installation of a head pumped by pipelines on the casing pipe of the borehole. Ash is transported by cement trucks (Figure 3). The ash tank is connected to the compressor and the backfilling pipeline. The working pressure of the fly ash pumping ranges from 30 to 45 kN/m^2. The pumping capacity is approximately 0.6 to 1.0 m^3/min. Air consumption for transporting 1 m3 of ash is 0.9 to 1.5 m^3. The backfilling pipeline outlet is placed directly under the ceiling of the void or, in the case of large voids, it is moved during the backfilling process, starting from a certain distance above the floor upwards at specific intervals (e.g., every 1.5 m).

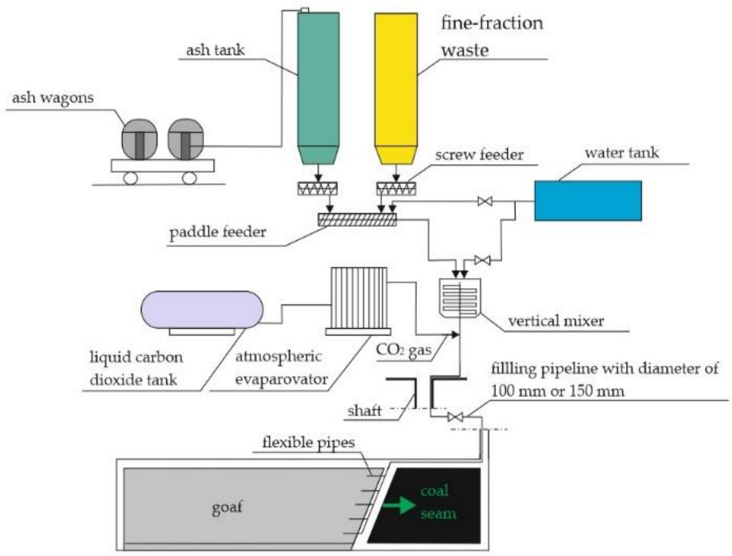


Figure 2. Diagram of the installation for placing ash–water suspensions with carbon dioxide in the post-mining space in an underground hard coal mine.

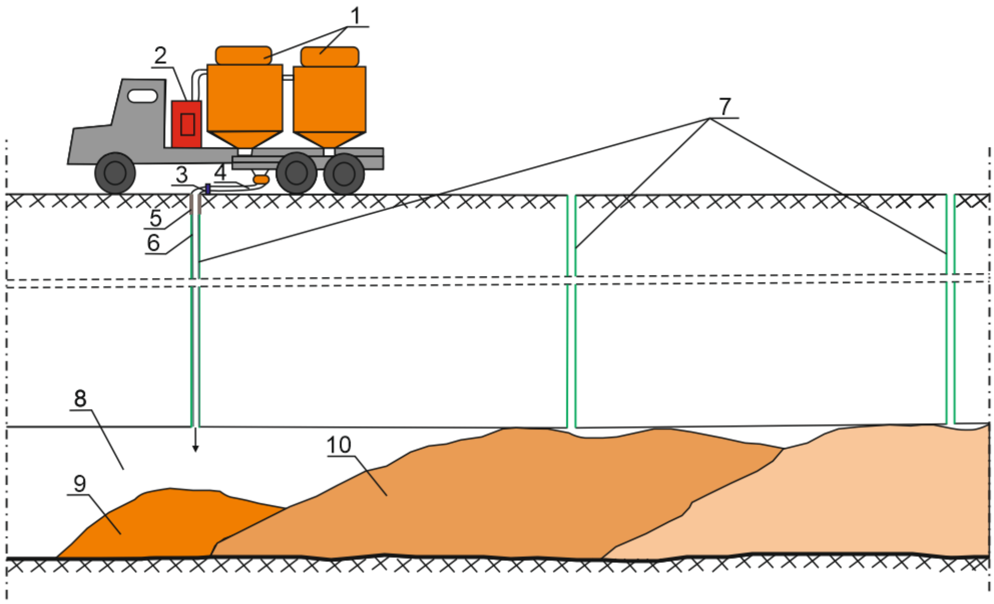


Figure 3. Fly ash backfilling of shallow voids: 1—tanks with fly ash; 2—compressor; 3—valve; 4—hose; 5—head; 6—pipeline; 7—filling drillholes; 8—filling void; 9–10—filling cones.

After filling the void and dismantling the pressure pipelines, the quality of the backfill is checked. The boreholes are drilled to the original depth, and water is pumped into the hole, maintaining a pressure of 100 N/cm^2 for 15 min. If the pressure does not drop during this time, the backfill quality is considered good; otherwise, fly ash is pumped in until positive results of the backfill control are obtained. A separate issue is determining the necessary number of backfill holes for proper filling of the void and support of its ceiling. The ash backfill flowing out of the nozzle of the backfill pipeline suspended under the ceiling of the void takes the form of a truncated cone, the bases of which are located on the floor and roof of the excavation (Figure 3). From the point of view of designing the density of backfill holes, it is important to know the angle of the cone slope and the radius of its upper base. As a result of industrial tests [26], the slope angle (α) is assumed to be 9°, and the radius (r) of the upper sub-base is 7 m. Therefore, assuming that the backfilled void has the shape of a chamber or a gallery with the width s $\leq$ 2 r and height h (for larger widths, backfill holes should be located in two or more lines), the following cases are considered (Figure 4):

Case I: When complete support of the roof is required. The distance between the backfill holes located in the axis of the excavation should be

$$L = \sqrt{4r^2 - s^2} \tag{1}$$

Case II: When the holes are located on the axis of the excavation at a distance of L = 2r. The relationship between the percentage of roof support (X) and the width of the excavation is

$$X = \frac{0.873\, s^2(180 - 2\gamma) + 25\, s^2 tg\gamma}{rs}, (\mathrm{m}) \tag{2}$$

where

γ can be determined from the dependence as follows:

$$cos\gamma = \frac{s}{2r}, \tag{3}$$

Case III: When the holes are located in the axis of the excavation at a distance of $L > 2r$. The volume of the unbacked part of the void will be limited by the planes of the roof and the sides and the surfaces of two interpenetrating cones. Starting from the equation of the cone in the cylindrical coordinate system using integral calculus, the volume of the unbacked part of the void (V_p) can be determined as follows:

$$V_p = tg\alpha \left[\begin{array}{c} s\left(\frac{1}{6}L\sqrt{L^2+s^2} - Lr + \frac{1}{3}r\sqrt{4r^2-s^2}\right) \\ +\frac{1}{12}\left(L^3 ln\frac{L}{\sqrt{L^2+s^2}-s} + s^3 ln\frac{L+\sqrt{L^2+s^2}}{\sqrt{L^2+s^2}-s} + 8r^3 arc\ tg\frac{s}{\sqrt{4r^2-s^2}}\right) \end{array} \right] \tag{4}$$

The percentage of voids not filled with backfill (Y) is

$$Y = \frac{25tg\alpha}{3sLh}\left[2Ls\sqrt{L^2+s^2} - 12Lrs + 4rs\sqrt{4r^2-s^2} + L^3 ln\frac{L}{\sqrt{L^2+s^2}-s} + s^3 ln\frac{L+\sqrt{L^2+s^2}}{2r+\sqrt{4r^2-s^2}} + 8r^3 arc\ tg\ \frac{s}{\sqrt{4r^2-s^2}}\right] \tag{5}$$

The percentage support of the ceiling, in this case, is

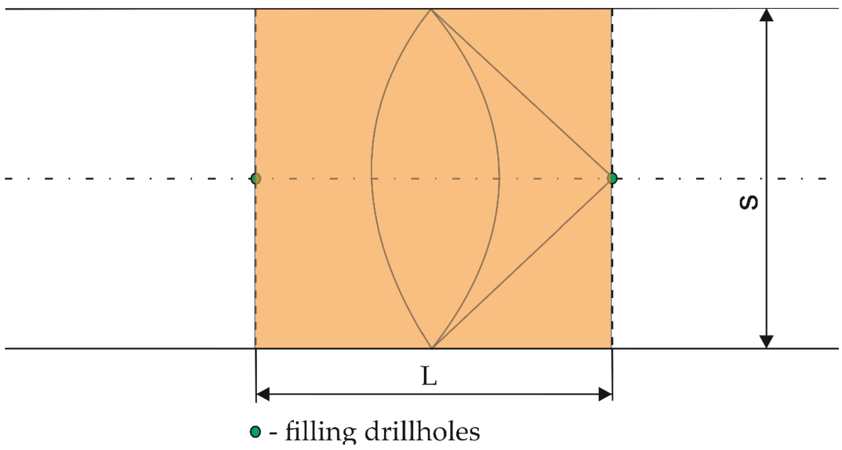
$$X = \frac{1.74r^2(180 - 2\gamma) + \left(50s^2 tg\gamma\right)}{L\ s} \tag{6}$$

In practice, the void deviates from the shape of a regular cuboid, and the surface of the support is not a conical surface. For practical purposes, it is sufficient to assume that the unsupported part of the void has the shape of a prism with height c and base s.

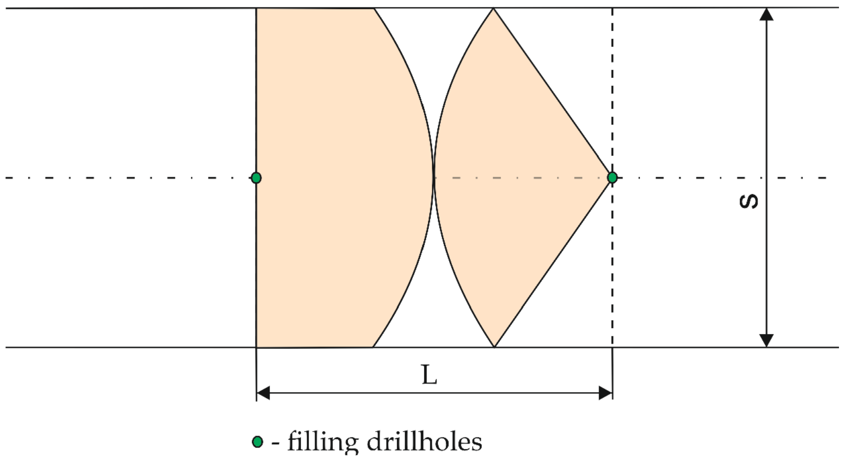
$$c = tg\alpha(0.5L - r),\ (m), \tag{7}$$

Adopting such a simplification allows us to determine the quantity Y.

$$Y = 25\frac{(L-2r)^2 tg\alpha}{L\ h},\ (\%), \tag{8}$$



(**a**)



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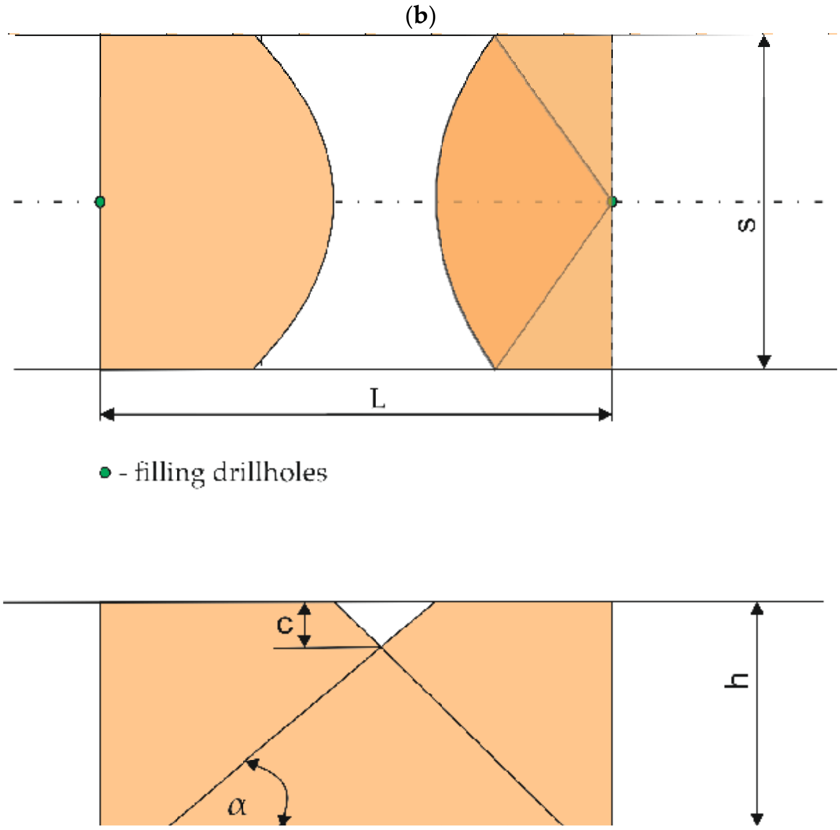

(**c**)

Figure 4. Schemes of the arrangement of filling cones in the void: (**a**) Case I; (**b**) Case II; (**c**) Case III.

The cement slurry cones that form cause the slurry to spread inside the cavity and rubble and support the roof. Due to the limited number of drilled holes, it is beneficial to use a liquefier, which will make the slurry much more fluid, which increases its range. The volumes of slurries that can be injected through one hole into the void in the rock mass, for slurries that do not contain a liquefier in their composition, will tend to cause a faster increase in the injection pressure and stop the introduction of slurry through a given hole. Thanks to the liquefier, the slurry spreads in the void, causing it to be filled better and reducing the number of holes that need to be drilled.

4. Case Study

An example of the treatment of rock mass disturbed by shallow hard coal mining can be the work carried out in one of the towns in the Małopolska province, Poland, where we are dealing with the effects of shallow historical mining. As a result of the increasingly frequent occurrence of discontinuous sinkhole phenomena on the surface of the area in the form of sinkholes, a decision was made to conduct a site reconnaissance using geophysical methods. As a result of the conducted microgravimetric, georadar, and resistivity electrometry studies, the occurrence of anomalies indicating a change in the continuity or density of the soil–rock medium was found. Next, based on the obtained research results, drilling works were planned to be carried out, the aim of which was to treat the subsoil and protect against further formation of sinkholes. In the lithology of this area, Quaternary layers can be distinguished, lying horizontally above the Carboniferous formations. Drilling and backfilling works consisted of drilling holes to the depth of the mine floor. In order to properly secure the ground surface, it was planned to drill a series of holes in a regular grid with a side of 15 m and in places where, based on the results of geophysical surveys, it can be concluded that the bearing capacity of the terrain has significantly weakened. An example profile of the hole at the place of drilling is shown in Figure 5. The strength parameters of individual rock mass layers have been presented in Table 1.

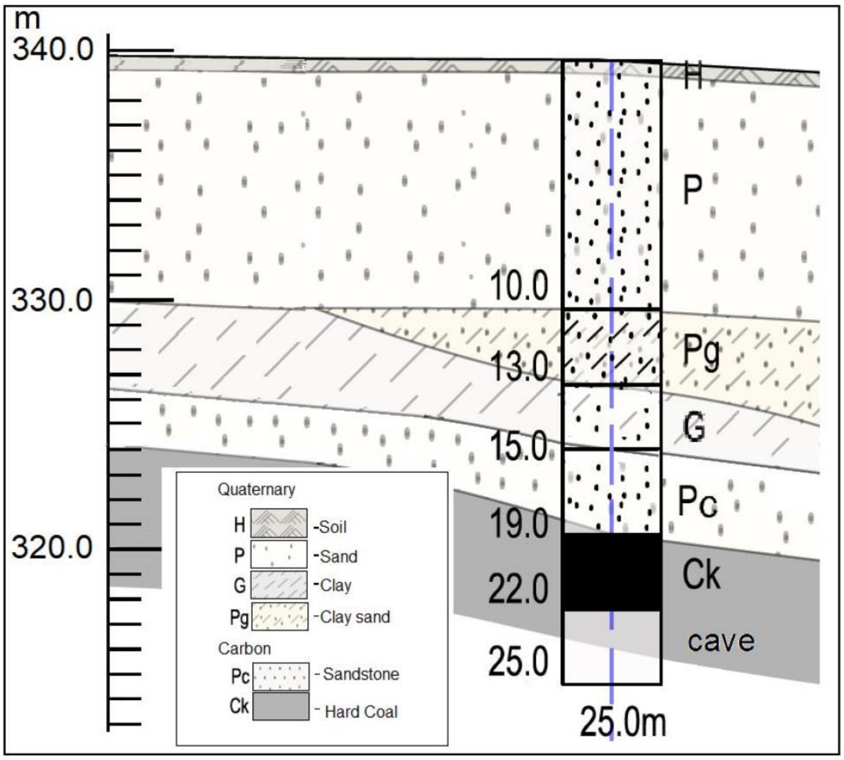

Figure 5. Lithological profile occurring at the site of the reclamation works.

Table 1. Strength parameters of individual rock mass layers.

Rock Layer	Uniaxial Compressive Strength, MPa	Tensile Strength, MPa
Clay sand	0.98	0.07
Clay	0.79	0.06
Sandstone	7.44	0.63
Hard coal	12.39	0.97

The drilling and injection works were carried out in several successive stages [27]:

- Dry-drilling of a hole using a 160 mm diameter auger drill, reaching the layer of clay or clayey sands of the Carboniferous (8 ÷ 10 m);
- insertion of a PVC casing pipe with an external diameter of 120 mm;
- cementing the annular space between the wall of the hole and the casing pipe;
- waiting for at least 48 h for the cement slurry to set;
- drilling a hole using the rotary method with the right circulation of drilling fluid to the depth of the bottom of the post-mining void in the coal excavation;
- measuring the occurrence of the static water table in the holes within a given location;
- running the drill string to a depth of approx. 0.3 m above the bottom of the void and starting to inject the cement–ash mixture;
- pulling the drill string up several times if the hole is found to be lacking in absorption (as a result of the local formation of a cement slurry flow cone that clogs the outlet of the drill string);
- ending the injection of the slurry when the rock mass loses its absorption capacity;
- waiting at least 7 days for the slurry to set;
- checking by placing the drill bit on the injection cone of the drill bit together with the drill string;
- liquidating the borehole by injecting it into the top cement slurry.

Backfilling works were carried out using cement–ash mixtures developed by the AGH University of Krakow, Faculty of Oil and Gas Drilling, Department of Drilling and Geoengineering, Laboratory of Geoengineering and Sealing Slurries, which were to be characterized by [28–31] as follows:

- density similar to the medium of application;
- the highest possible flowability;
- low sedimentation (below 10%);
- beginning and end of setting time adjusted to the works carried out;
- mechanical strength greater than the surrounding medium;
- low unit price;
- inert impact on the soil and water environment.

The flow parameter is particularly important in the aspect of obtaining a large radius of grout spreading in the drilled voids. It should have a value greater than 160 mm [32]. Flow can be increased by the amount of mixing water used, but this worsens the operating parameters of the fresh and hardened grout. A beneficial solution is to use a liquefier, which, in this case, was an appropriately selected compound from the polycarboxylate group. The use of a minimum amount of liquefier admixture significantly increased flow without causing deterioration of other parameters. The recipes of the proposed mixtures are presented in Table 2.

Table 2. Parameters of the proposed sealing slurries.

Contents			Recipe 1	Recipe 2	Recipe 3	Recipe 4
Mixing (M)	Cement	%	10	10	10	10
	Ash	%	90	90	90	90
Liquefier		BWOM	0	0.1	0.3	0.5
Water (W)		W/M	0.75	0.75	0.75	0.75
BWOM—by weight of dry binding ingredients.						

Laboratory tests of sealing slurries were performed based on standards [33–37]. The obtained parameter results for fresh sealing slurry recipes are presented in Table 3. The obtained parameter measurement results for hardened sealing slurry recipes are presented in Table 4.

Table 3. Parameters for fresh sealing slurry recipes.

Parameter		Recipe 1	Recipe 2	Recipe 3	Recipe 4
Density	g/cm^3	1.54	1.54	1.54	1.58
Flowability	mm	190	195	210	230
Resting	%	4	4	4	4
Start of setting time	h:min	17:40	31:00	33:00	35:00
End of setting time	h:min	22:50	33:30	36:30	38:50
Binding time	h:min	6:00	2:30	3:30	3:50

Table 4. Parameters for hardened sealing slurry recipes.

Parameter		Recipe 1	Recipe 2	Recipe 3	Recipe 4
Bending strength after 7 days	MPa	1.134	1.054	0.865	0.810
Compressive strength after 7 days	MPa	4.511	2.876	2.412	2.004
Bending strength after 14 days	MPa	1.288	1.134	1.014	1.087
Compressive strength after 14 days	MPa	8.036	4.252	4.158	4.098
Bending strength after 28 days	MPa	2.271	3.078	2.658	2.474
Compressive strength after 28 days	MPa	9.157	9.045	9.267	6.978

The proposed sealing slurry recipes, especially those containing liquefiers, are useful for backfilling operations in areas where shallow mining activity is the cause of sinkholes. All tested recipes are characterized by parameters corresponding to the specificity of the application, resulting from the depth of the voids in the rock mass and due to the technological parameters of the flow hydraulics and filling of underground voids. The limits of the method's applicability are very wide. Since the binder used after setting remains in the place of application, does not move like sand backfill, and has similar strength to the surrounding rocks, it allows for filling in missing fragments of the substrate, extracted as useful minerals.

5. Discussion

The proposed technology for filling shallow excavations using a mixture of cement, fly ash, water, and various contents of liquefiers is characterized by a setting time ranging from 2.5 h to 6 h. The filling time of the excavations does not play a very important role in the case of inactive excavations because there are no additional stresses from the moving exploitation front. However, it is significant in the event of a dynamic outflow of groundwater, which can directly contribute to a decrease in the efficiency of the backfilling process. Liu et al. [38] conducted laboratory tests in which they determined the relationship between paste backfill material with the addition of fly ash and water, indicating that water plays a significant role in the hydration process. The natural inflow of water to the cement backfill material can contribute to a significant weakening of its strength parameters [39]. The basic parameter of the cement-based backfill mixture is its flowability. In the proposed recipe, a relationship was found in which the flowability also increases with the increase in the fluidity content. In the studies conducted by Qiu et al. [40], it was found that the plasticity limit of the backfill mixture could be increased for an increased content of solids while reducing flowability. Particularly dangerous for shallow-lying excavations are rock mass tremors, which contribute to changing the structure of rock layers by weakening them and whose effects are very often visible on the ground surface [41]. In the case of cracked rock mass, the possibility of penetrating the cracks on one side is a beneficial phenomenon because it additionally seals the rock layers, preventing the migration of gases. However, taking into account the amount of material that would have to be supplied to fill the void with additional cracks, it may turn out that the costs increase significantly considering the 10% cement content. The obtained values of the compressive strength of the cement-based backfill after 7 days from the date of execution are in the range of 0.81 to 1.13 MPa, which means that they meet the requirements of the standard [42]. When filling old shallow excavations, the compressibility of the backfill material and the possibility of its transport to the backfilling site should also be taken into account while meeting the technical and economic balance criteria.

The proposed cement slurries consist of a small amount of cement, fluidized ash, and liquefiers. The main cost of the slurries prepared is fluidized ash obtained as a by-product during the combustion of hard coal. The cost of this component depends on the distance from the heat and power plant. There are several heat and power plants in Upper Silesia, which means that the transport distance never exceeds 50 km. The proposed R1 recipe, which includes cement, ash, and water, has a preparation cost of 30 USD/m^3. This cost mainly results from the transport of ash, purchase of cement, preparation, and injection. The use of a liquefying admixture increases the cost of 1 m^3 by 1 USD for each 0.1% of the liquefier admixture used.

Due to the fact that sinkholes occur over a long period of time, often several dozen years after the end of exploitation, monitoring of the rock mass is recommended, including both the lowering of the terrain surface, water level, and the concentration of mine gases.

6. Conclusions

In order to identify the geomechanical condition of the rock mass above shallow mining excavations after hard coal mining, a wide range of geophysical studies should be carried out. The geophysical method and research methodology should be selected each time for the specific geological structure of the rock mass and the need to solve a specific problem. Based on previous industrial experience, it can be stated that the most preferred methods for examining the rock mass in areas of shallow mining and accompanying discontinuous deformations are microgravimetric, electrical resistivity tomography, seismic tomography, and georadar. To verify the obtained research results, research holes should be drilled, and geotechnical studies of the rocks occurring in the overburden should be carried out. Then, based on the research results obtained in this way, a technical project for land treatment should be prepared. Due to the increasing number of buildings in mining areas from year to year, there is a great need for scientific research on the impact of underground mining on the surface of the land. Even after the end of exploitation, continuous and discontinuous deformation impacts may become apparent, contributing to the formation of sinkholes; therefore, further research will be aimed at determining the extent of sealing of voids in the rock mass using drilling and geophysical methods.

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