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Mine Field Preparation and Coal Mining in Western Donbas: Energy Security of Ukraine—A Case Study

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Abstract: Ukrainian electricity production sector is in a critical situation. It is necessary to increase the coal production to ensure the continuity of electricity production. In this paper, an analysis of coal mining in western Donbas, Ukraine, was presented. The crucial thing is to increase coal production in this region. The new calculation schemes were proposed to increase coal extraction in Donbas mines. The coal pillar parameters, which are necessary for the effective control of the rock pressure caused by the stooping, were substantiated. The obtained parameters for the coal pillars will allow extracting more coal, safely and quickly dismantling the mechanized complex and effectively protecting the ongoing mine work. The case study helps determine the coal losses because of pillar leaving and to improve the stability of the main haulage roads located in the zone of the stooping effect as well as to achieve additional coal production in the mine. Such a technological solution allows to extract the coal more fully at the final parts of the extractive columns and to obtain an additional economic effect. The increase in coal production in coal mines of western Donbas will increase the energy security of all Ukraine.

Keywords: energy sector; mining; coal pillars; zone of bearing pressure

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1. Introduction

Recent world trends have shown that a country's political security depends on its fuel and energy supply. In Ukraine, these issues are managed by the United Energy System of Ukraine (USE). The USE consists of a set of power plants as well as electric and thermal networks operating in the general mode of production, transmission and distribution of electric and thermal energy. Nuclear power plants (NPPs), thermal power plants (TPPs), hydroelectric power plants (HPPs), thermal power plants (CHPs), as well as power plants run on alternative (renewable) sources of electricity (solar, wind, bio- and others). They are operating in one system. All of them are connected by the main electric networks. Thermal power plants (TPPs) produce nearly 27% of all electrical energy in Ukraine [1].

Recently, the amount of commercial coal required by Ukraine's energy sector has increased from 19 to 21 million tons. In 2021, coal production had decreased by approximately 7.7% compared to 2020. Accordingly, this requires the import of coal [1]. Therefore, increasing the efficiency of coal mining is an urgent scientific and practical task.

Ukraine is one of the largest producers of hydrocarbons in western Europe. Ukraine's energy production and consumption significantly has changed during the last decade [2–4]. Energy-sector reforms in Ukraine began after the 2013–2014 Euromaidan protests. Russia's invasion of Crimea led to supply disruptions and energy shortages, particularly in the coal sector. The changes in Ukraine's energy production between 2013 and 2017 are presented in Table 1 [5]. In 1990, 63.9% of the total production of energy in Ukraine was based on coal. Ukraine's coal production and consumption has significantly decreased in last decade. Russian occupation of Crimea as well as the conflict in Donbas destabilized the Ukrainian coal production market and led to the decrease in coal production from 65 million Mg in 2014 to 33.3 million Mg in 2018. Additionally, a feature that characterizes coal mining in western Donbas is that it is conducted under extremely complex conditions. Coal deposits are represented by the three following Carboniferous periods: Lower, Middle and Upper. Total Carboniferous thickness varies from 3000 to 3500 m in the east and to 150 m in the west. The commercial coal-bearing capacity within the area under development is confined to the coal deposits of "Samara" formation (C_{13}) of the Lower Carboniferous period with 6–24 layers of economic importance. Such seams as $C^{v}{}_{10}$, $C^{n}{}_{8}$, $C^{v}{}_{8}$, $C^{n}{}_{7}$, C'_{6}, C_6, C_5, C'_{4}, $C^{v}{}_{4}$, C_2 and C_1 are the most continuous ones. Their prevailing thickness is from 0.7 to 1.2 m. Coal seam angles are from 0 to 7°, while the occurrence depth is from 60 to 900 m. The series mainly consists of 3–6 adjacent seams with an inter-bed thickness of up to 12 m. Almost 40% of the reserves are concentrated within such seams. Generally, the maximum distance between the adjacent seams is no more than 50 m. The rock mass is covered by different geological disturbances [6,7].

Table 1. Ukraine's energy production in 2013 and in 2017.

Energy Source	Year	
	2013	2017
coal and peat, %	47	23
crude oil and oil products, %	4	4
natural gas, %	19	26
nuclear, %	26	38
hydro, %	1	2
geothermal/solar, %	0	<1
biofuels and waste, %	2	6
heat, %	1	1
total, ktoe	85,914	58,851

Horizon layout schemes are currently being used in the mines of western Donbas, Ukraine. A pillar system (usually long pillars up the dip, or less often along the strike) is applied in the mines of this region. Mine workings are supported in virgin coal or in the zone of steady-state rock pressure; as a rule, the workings are reclaimed in the course of the stope advance. Much attention is paid to the main haulage roads since the uninterrupted and efficient operation of the level as well as of the whole mine depends on their condition. The length of operation of the main drifts implies the need to maintain them in good working condition. For these purposes, the method of protecting coal mine workings is mainly used. This helps protect approximately 90% of the length of both permanent mine workings and main haulage roads in the coal mines in Ukraine [6]. Coal pillars are large both along the strike and down-dip or up-dip. Along the strike, they are limited to the extraction pillars and down-dip (up-dip) and to the boundaries of the worked-out area. Customarily, the transportation, conveyor and ventilation mine workings adjacent to the main drifts are located at the angle of 90°. In this case, the coal pillars are of the shape which is close to a rectangle.

The studies presented in this paper were conducted for very difficult mining and geological conditions. The coal of western Donbas is hard and tough. According to the Protodyakonov scale of hardness, its f = 3 − 4, and the cutting strength is more than

250 kgf/cm. As for their grade, the coal seams are low-ash and mid-ash; low-sulphur and mid-sulphur. They belong to such technological grades as G6, G16 and D (Ukrainian standards). The coal of the region is considered to be agglomerated, free-processing and mid-processing. Additionally, it is valuable raw material for producing coke [7].

Coal reserves in western Donbass, estimated to be down to a depth of 1800 m, are almost 24.0 billion tons; of which 12 billion tons (i.e., 26.4%) are of high resource definition in the context of total Ukrainian coal reserves. Coking coal is almost 18 billion tons or 31.6% [8]. The distribution of the balance reserves by their thickness among the mines of "DTEK "Pavlohradvuhillia" PJSC is presented in Figure 1.

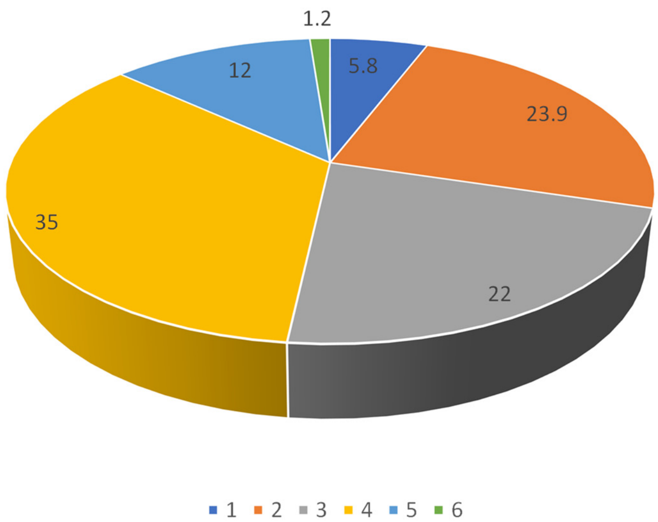

Figure 1. Schematic distribution of coal reserves according to their thickness in the context of "DTEK "Pavlohradvuhillia" PJSC mines: 1—<0.6 m; 2—0.61–0.7 m; 3—0.71–0.8 m; 4—0.81–1.0 m; 5—1.01–1.2 m; 6—>1.2 m [7,9].

The complex conditions result from the low thickness of the coal seams (the average thickness is approximately 1.05 m) and the weak rocks of the deposit roof and footwall. As such, in this paper, both traditional and new technologies for mine field preparation and the mining of the coal reserves are taken into consideration. Underground coal gasification constitutes one of the considered non-traditional technologies [9–12]. In addition to the analytical substantiation of the material-heat balance, test studies of the technology were conducted [13–16]. The economic evaluation of the obtained products confirms the commercial feasibility of the project [14]. Unfortunately, the use of such technologies is limited by a number of factors, the major ones being the low productivity of the gas generator compared to the traditional mechanized complex mining and the complexity of the gasification process control. In addition, the lack of available infrastructure for the application of end products is also a significant deterrent to introducing this technology in western Donbass.

The main aim of this paper was to analyze the mining of coal seams under the conditions of mines in western Donbas in Ukraine in terms of the increase in coal production to ensure energy security. This issue is crucial to ensure safety and economically protect coal production. For this purpose, new calculation schemes were proposed to increase coal extraction in Donbas mines. The analysis presented in this paper allows to improve the stability of the main haulage roads located in the zone of the stooping effect as well as to achieve the additional coal production in mines.

2. Materials and Methods

The part of Zakhidno–Donbaska mine field where the research was conducted is planned to be worked out from 2021 to 2034 (Figure 2). The names of wall faces were changed at the request of the DTEK company. The structural and geological configuration of this section of the mine field is sufficiently described in the paper [17,18]. Clay shales with the thickness of up to 1.3 m represent the immediate roof. Argillites of a general thickness ranging from 3.5 up to 9 m occur in the main roof. The caving step of the immediate roof is 0.4–0.8 m, while in terms of the main roof, it is 5–15 m. The floor of the longwalls is represented by unstable rocks which are prone to swelling and heaving. The mining works are conducted by the powered complex 1KD—80 with the powered support D80 (reaction of hydraulic stands is no less than 320 Atm) and the coal shearer KA—200. The transportation of the loosened coal in the longwall is provided by the scraper conveyor SP 251.14.

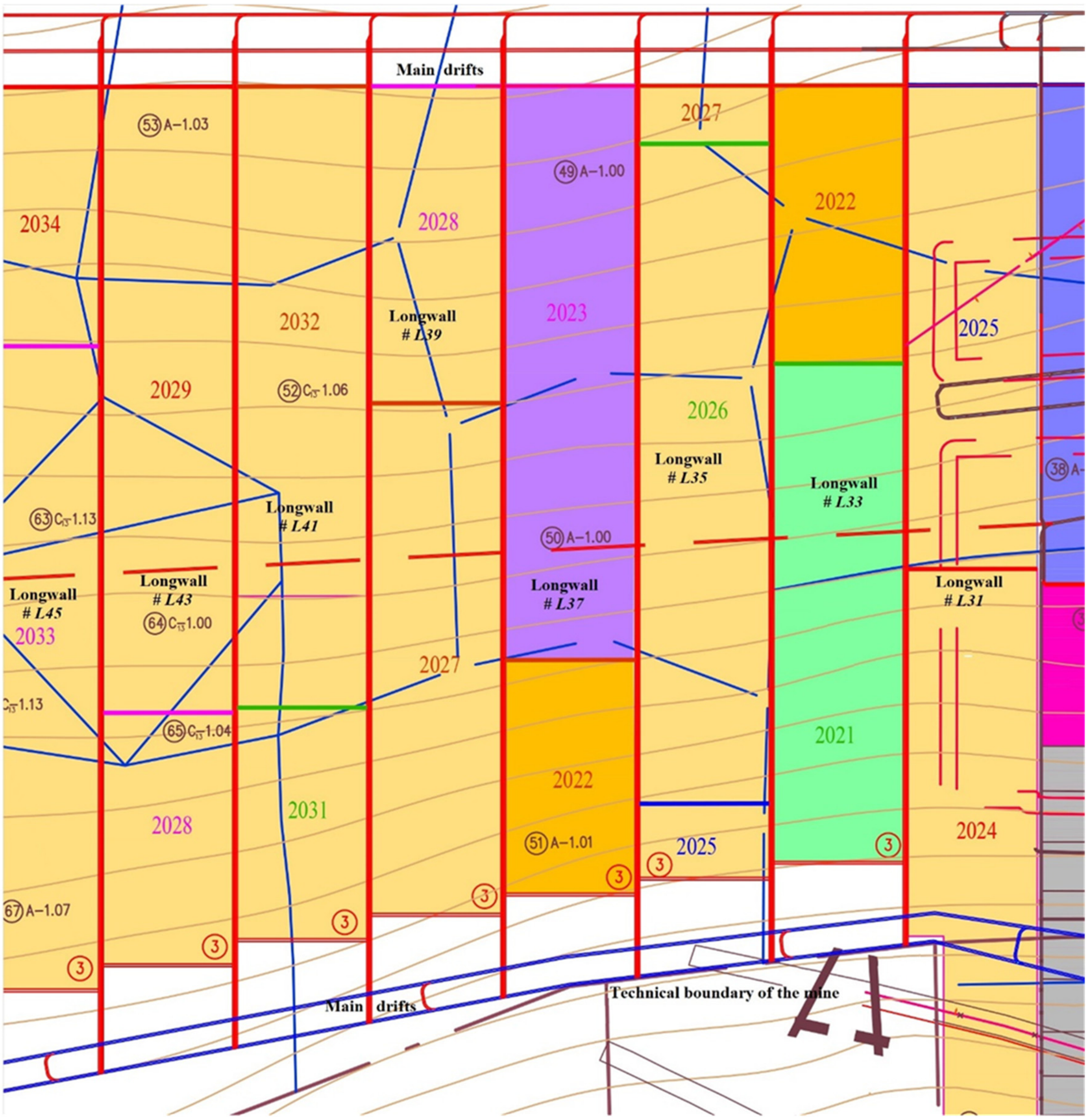

Figure 2. Plan of the mine field: 64 C_{13}1.00—exploration well number with the indicated coal seam thickness; 2025—planned year of pillar exploration.

Thus, due to objective reasons for the protection of the in-seam working with the coal pillar, it is important to correctly select their shape. The general principle of the protection of main drifts from the effect of stooping operations with the help of coal pillars is their location outside the abutment zone. However, due to the lack of a reliable method to determine the stresses in the rock mass, the size of the reference pressure zone is usually established under mining conditions by the indirect characteristics of rock pressure. Therefore, while measuring the different characteristics of abutment zone manifestations (i.e., displacement, deformation, etc.), the resulting parameters of the zone will differ. An analysis of the scientific literature in the field concerned shows that a large variation in the size of the reference pressure zone is mostly due to the difference in the assessment methods [19,20].

When conducting underground mining operations, it is necessary to consider all potential tectonic disturbances both within a gap and without the rock discontinuity. Massive deviations from the normal structure of rock as well as a decrease in its mechanical durability and water inflow may occur within the zone of the developing fault or folded deformations. The angle at which the stope line and the direction of the main fracturing come into contact affects the depth of rock inrushes within the unsupported areas. The method of roof control has an influence on sudden rock inrushes within the unsupported areas and on the formation of rock layering.

The tectonic fractures cross the natural ones, but unlike the natural fractures, they are inclined to the bedding planes forming additional attenuation planes in the rock, which causes an emergency roof collapse in the face area if they are significantly developed. Because tectonic fracturing sometimes forms a whole network of intersecting fractures, the shape of the pieces into which the rock disintegrates can be very diverse. Tectonically broken clay shales (mudstones) in the immediate roof of coal seams collapse (crumble) particularly easily, and the strata control in such cases is very difficult. In contrast, tectonic fracturing in limestones and sandstones is less developed than in other rocks [19]. The cracks caused by the rock pressure are formed in the mine workings near the stopes and development faces; these fractures are always located in parallel to the face plane, bending around its horsebacks [21]. End fractures are located approximately perpendicularly to the main ones; these fractures are less developed. Their main difference with regard to the main cracks is that the distance between them is greater; the fracture surface is less even, hilly and resembles broken rock. In many cases, end fractures are interrupted when approaching the main fractures, and then appear again a little further away from them. They are at an angle of 60–90° relative to the layered fractures [22].

In previous papers, authors have paid much attention to the analysis and substantiation of techniques aimed at the determination of the stress–strain state of rock mass in the context of different mining technologies and the different geology, structure and lithology of the rock mass [23]. The area under modeling is an anisotropic medium affected by mining. There are no unambiguous interpretations as there are for the stress value deviation from the gradient balance state in the context of highly loaded coal extraction.

A step-by-step algorithm of our work was formed using the recommendation for case study research from [24,25]:

- Analysis of coal contribution to thermal energy generation in Ukraine;
- Analysis of mining and geological conditions at the enterprise and the identified shortcomings in the mining process (the state of the main mine workings);
- Developed technological solutions for the location of mine workings;
- Recommendations for improving the technological schemes;
- Economical substantiation of the proposed solutions (amount of additional mined coal);
- Conclusions and relevant recommendations.

In this paper, we try to justify the shape of the final part of the pillar when working out the extraction column to establish the possibility of coal saving. Moreover, these measures must be taken to ensure the stability of the main workings. This approach is extremely important for stabilizing the heat generation of energy from coal extracted under complicated mining and geological conditions. This may serve as a good example for the improvement of mining technologies for other countries as well, as the structure of energy production in Europe is changing.

In the present paper, for the assessment of rock mass stresses and the establishment of the basic technological parameters of mining, the method described in [17,26] was applied. This method employs analytical and experimental research to manage mining pressure. Based on the available practical measurements of rock movement, one can establish the stresses in the roof and the footwall of the seam. The results obtained were verified by the statistical processing of measurements carried out directly in the mine. The load on the support of the extracting and preparatory workings accounts for the reflection of the discharge of the main vertical stresses over time.

3. Results and Discussion

The stable exploitation of the bituminous coal in the Donbas region is of key importance for ensuring the continuity of the supply of coal. However, this requires a detailed analysis of the operating conditions in western Donbas. To protect mine workings with coal pillars and ensure stability, one is guided by mining and geological parameters such as the depth of the working layout or the coefficient of the structural weakening of rocks [18]. The coefficient of the structural attenuation for western Donbas rocks ranges from 0.6 to 0.75 (mudstones and siltstones). Taking this fact into account, the design resistance of the rocks to simple compression does not exceed 20 MPa. As a rule, mine workings intersect with numerous zones of plicative and disjunctive disturbances; thus, the calculated depth of their location should be increased by approximately 1.2 times compared to the actual depth. This means that the width of the coal pillar protecting the main haulage road, located at a depth of 450–500 m, should be 96 m. The maximum width of the protective pillars reaches 150 m, which leads to unjustifiably large coal losses. If the abandoned pillar is 120 m in width, a stope is 250 m long and the average layer thickness is 1.2 (with a volumetric weight γ_{coal} = 1.35), then the losses equal 48,600 Mg; if the pillar is 150 m wide, the losses are 60,750 Mg of coal. With the current trend of increasing the face length up to 300 m and more, the coal loss in the pillars is increased by a factor of 1.5–2.

After working out approximately 50–60 extraction pillars with the use of coal pillars to protect the main drifts, the amount of remaining coal exceeds its 2–3-year design capacity. Despite the unjustifiably large loss of coal, the stability of the main drifts over a long distance is more than unsatisfactory for the normal functioning of these workings.

A review of the obtained data allows noting a number of distinctive signs in the behavior of the mass around the mine workings. Accordingly, the following principles must be followed for further research:

- Additional measures in the form of rock lifting do not provide the operational capacity of mine workings;
- The unloading of the mass by means of the damaged rock removal and the cleaning of new surfaces contributes to the development of a new cycle of rock destruction and an increase in the displacements of the mine working contour;
- Maintaining the mine workings in the required operational condition can be ensured by the natural yielding property of the mass by means of reducing the development of the destruction zone around the mine working and the use of the bearing capacity of the border zone of the destroyed rocks by limiting the displacements.

It should be noted that, in terms of soft rocks, a short-term sharp increase in the limit zone of the broken rock around the mine working with its subsequent retimbering with the closed unyielding support provides a sharp decrease in shifts and increases the mine working stability. The issues of unjustified losses of coal and the stability of the main haulage road in terms of the concrete example have been considered specifically for the conditions of western Donbas mines [20]. The experience of mining in western Donbas show that leaving the protective pillar does not ensure the operational state of the mine workings during the planned long-term period. The studies conducted in the Zakhidno-Donbaska mine (Figure 2) demonstrated that the reason for this is the movement of the zone of high rock pressure (HRP) into the depth of the pillar after the face stopped [18]. Therefore, there is a need to revise the way to protect the main drifts with coal pillars, i.e., the pillar shape, since the rectangular one does not provide the long-term stability of mine workings.

While solving the problems concerning the state of mine workings and extraction areas, apart from the rock pressure caused by the stooping operations, it is also necessary to consider the factors that characterize the rock mass fracturing, regardless of its type. Layer thicknesses ranging from 0.1 to 0.3–0.7 m make these rocks of medium stability and form a perch behind the waste-edge chock. If the thickness of the layers exceeds 0.7 m, they turn into very stable rocks hanging outside the working area.

The externally uniform clay rocks can be stratified if they are made up of the flakes located in one direction. The planes of their stratification are usually smooth or shell. The weakness planes (having a flat surface), coinciding with the stratification, separate a flat body from the above- and underlying rocks, breaking it into "boards" (sheet joints). Thus, even very thick uniform rocks can be divided into separate layers; at the same time, rock displacement directly depends on their stratification. Rock fracturing breaks the integrity of rocks and weakens their stability. There is inherent natural fracturing (cleavage), tectonic fracturing and fractures caused by rock pressure. The main fractures, being of a rupture character, are clear and often contain mineral substances. Relative to layered fractures, they are approximately perpendicular (at an angle of 85–90°) and they usually progress independently in each layer. Their direction is distinguished by considerable continuity (dozens of kilometers). The greater the size of these fractures, the farther away they are from one another. The distance between the fractures ranges from a few millimeters to several meters. Rocks easily fall apart along these fractures. The surfaces of the tectonic fractures are usually covered with furrows of sliding; they often constitute the planes of rock displacement. Rock friction results not only in furrows, but also in the so-called "mirrors of sliding" (polished shiny surfaces) which are mostly visible in clay slates [6]. Local areas or stripes, so-called "fairings" or "slides", are formed in the roof rock; these areas have shiny smooth surfaces sometimes covered with "soapy rock" but are not associated with the overlying rocks, and they also collapse easily.

These are usually curvilinear with wrong rough planes, but a fresh break on their surface enables them to be easily differentiated from the other types of fractures. Most often, they are formed within the face area of a longwall but remain hardly noticeable with their further opening. Fracture formation due to rock pressure often leads to sudden inrushes from the roof. In terms of the inclination of the main inherent fractures towards the face, the developing rock pressure crosses the main fractures. If the fracture crossing happens at a low level, then the rock blocks (called "chests") rush in the face area. From the side of the worked-out area, the "chests" usually have a smooth surface which is the plane of the main fracture; from the side of the longwall face, they show an uneven fracture surface. That is why the face line must be located at an acute angle to the main fractures to prevent possible inrushes from the roof [19]. The aforementioned demonstrates that the fractured rock mass is the key factor while protecting the main haulage roads.

The way of laying out the main drifts in parallel to the action of the maximum stresses along the horizontal axis σ^1 is known. In this case, the systems of fractures are located at an angle of 50–54° to the longitudinal axis of the main drift and at the same angle to the stope line in the extracted mining area. In this context, mine workings are perpendicular to the main haulage roads; therefore, the left protective pillars take on the rectangular form. When stooping operations approach the main drift from the side of the extraction column, the rock pressure wave "rolls" towards the maximum tensile stresses along horizontal axis σ^3. Consequently, this leads to the weakening of the carrying capacity of the pillar and the deformation of the main drift contour. An increase in a square coal pillar (as well as the consequent coal losses) does not favor the increase in its bearing capacity. In terms of deep depths, this factor plays a negative role as it causes the heaving of the floor rock and its breaking.

Owing to the layered structure of the rock, because of stooping operations within the zone of bearing pressure, the blocks limited to technological fractures are formed over the seam along the layers and in parallel to the face. The stability of the main haulage road will depend on the relative positioning of the mine working and the technological blocks. If the direction of the long axis of the mine working and the technological fracturing coincides, then the mine working stability will be minimal. Along with the increasing angle of incidence between the direction of the mine working development and the technological fracturing, the mine working stability will increase and reach its maximum value at an angle of incidence equal to 45°. Specifically, as the technological blocks will lean on pillars on the different sides of the mine working, they will block it. Therefore, permanent mine workings are planned so that their long axis will not coincide with the azimuth of the tectonic fracturing of the rock mass. This situation is like the one in a stope, as mentioned above; stooping operations are the result of the subsequent state of the main haulage roads' mother entries in terms of their completion. The practice of seam development has shown that to prevent blockages of faces with clearly seen main fractures in the roof, sometimes coinciding with the fractures in the formation, the face line of the longwall should be located at an angle of 15–20° to the main fractures. In terms of such an arrangement of the face line and the main natural fractures, each section of the roof between the two adjacent main fractures will always have three supports—the coal mass, face support and rubble or collapsed rock of the roof which will prevent the longwall collapse.

If the angle of incidence is less than 15° (especially if it is below 10°), the roof becomes less stable. At the angle ranging from 0 to 5°, i.e., when the face line coincides with the direction of the main fracturing, the roof loses its stability and collapses. The less developed frontal fracturing is also of great importance. When the longwall is worked out up-dip or down-dip, the stope line should also not coincide with the direction of the end fracturing [22].

Natural fracturing creates a number of systems of differently oriented cleavage fractures, which result in a complex geological situation during stooping operations. Natural fracturing, being a positive factor facilitating coal extraction, also plays a negative role creating roof instability and promoting the penetration of water and gas into the stopes. Moreover, natural fracturing breaks the roof into separate blocks which can fall independently and move under the effect of horizontal effort. In terms of stopes, it is important to consider not only the direction but also the inclination of the main fractures. If fractures incline on a face, the roof in the longwall is more stable because blocks acting as the main support have a coal mass; in terms of the face area, the blocks have face support and waste-edge chock. Additionally, during displacement, the blocks, imposed on each other, have to overcome the friction force among them. As for the inclination towards the worked-out area, the main fractures open, and the rocks are divided into separate blocks leaning only on organ timbering (or waste-edge chock) and face support. Blocks are easily displaced under the effect of their own weight. In the case of an insufficient loading capacity, the timbering can be deformed and then there will be longwall blockage. The separated blocks can be also displaced towards the developed worked-out area and down-dip, overturning the face support and waste-edge chock. This is the explanation for the different behaviors of the one and the same rock in longwalls. The aforementioned show that the fractured structure of the rock mass is the determining factor while protecting main haulage roads.

There is a known method to locate the main drifts in parallel to the action of maximum stresses along the horizontal axis σ^1. In this case, the fracture systems are located at an angle of 50–54° to the longitudinal axis of the main drift and at the same angle to the stope line in the extracted mining area [18]. Here, the extraction mine workings are located perpendicularly to the main drifts, because of which the remaining protective pillars acquire a rectangular shape.

Nowadays, the $C^{v}{}_{10}$ layer is being prepared in the Zakhidno-Donbaska mine of "DTEK "Pavlohradvuhillia" PJSC. The considered problems of the influence of rock pressure and fracturing are the most relevant to be solved prior to the commencement of stooping operations. Taking into consideration the fact that the coal mass near the main drift is in the unloading zone, whose dimensions are substantiated in [19], the stooping operations are stopped at its boundary; thus, the coal pillar assumes a trapezoidal shape. Therefore, considering the effect of rock pressure and various manifestations of fracturing on the stope conditions as well as the results of studies given in [20–22], different options for protecting the main haulage roads in the form of trapezoid-shaped pillars were examined.

Three applications based on these options are presented in Figure 3, which shows the stope location at the angle α to the permanent mine working, and stooped at a close distance d from it:

(a) The location of the stooped worktop at the angle of 20° and at a short distance of 15 m—$\alpha = 20°$, $d = 15$ m;
(b) The location of the stooped worktop at the angle of 15° and at a short distance of 20 m—$\alpha = 15°$, $d = 20$ m;
(c) The location of the stooping cut at the angle of 11° and at a short distance of 25 m—$\alpha = 11°$, $d = 25$ m.

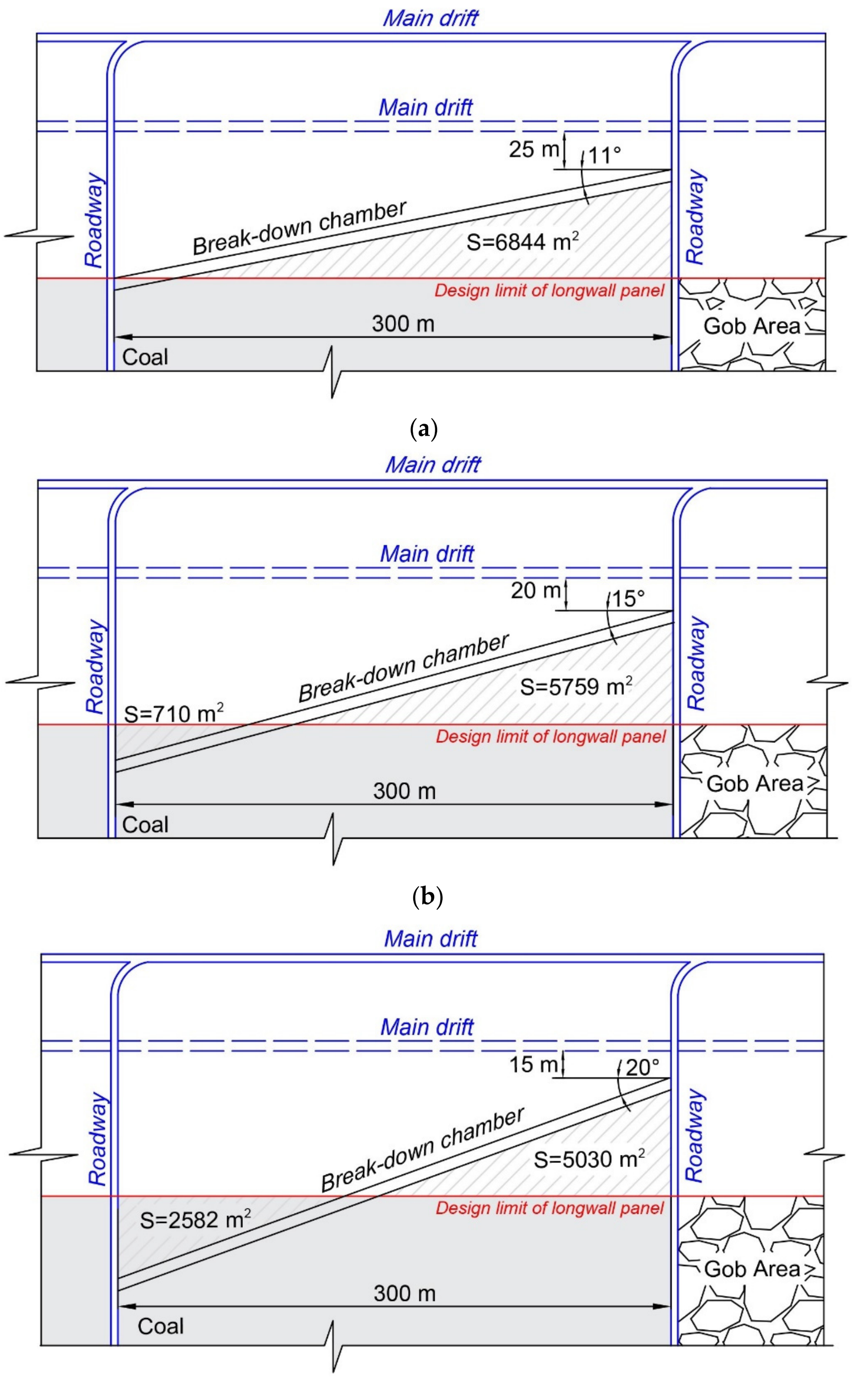

Figure 3. (**a**–**c**) Locations of the mine workings and parameters of the protection way of the main workings in the form of left pillars (swung by 180°).

As a result of the studies of more than 100 coal mine working maps in Ukraine, it has been determined that the main haulage roads are in satisfactory condition, in cases where coal pillars are left at angles of 11, 15 and 20° on either side along the length of the stopped longwall face (when extraction column operations are completed). Such parameters of the coal pillars help distribute the rock pressure so that it leads to a gradual loading on the support and to its decreased deformation. In terms of the proposed solution, the variable pillar width facilitates the diffusion of the load on the support during stooping operations near the main drift and improves the perception of the internal stresses of the rock mass.

In addition, changes in the shape of the coal pillar left for the main drift protection make it possible to reduce coal losses by 35–45% compared to the rectangular shape (1) and obtain additional coal mining (2):

$$P = S_p \cdot m_s \cdot \gamma_c, \ [\text{Mg}], \quad (1)$$

where S_p is the area of arbitrarily left pillars to protect the main drift, m^2; m_s is the extracting seam thickness, m; and γ_c is the coal density, Mg/m^3, respectively.

Moreover:

$$P_{add} = S_{add} \cdot m_s \cdot \gamma_c, \ [\text{Mg}], \quad (2)$$

where S_{add} is the area of the extraction columns which is subject to robbing and which provides additional production, m^2.

At the same time, the strength properties of the pillar do not decrease, and the timbering deformation in the drift decreases. Taking into account the fact that the coal mass near the main drift is weakened by the unloading zone, the coal-face operations are stopped at its border, which gives the coal pillar a trapezoid shape. In terms of the proposed options for the protection schemes of the main workings with trapezoidal pillars, the values of additional coal production (*Padd, kt*) and the width of the pillar (*d, m*) were obtained depending on the angle α of the face swinging (Figure 4).

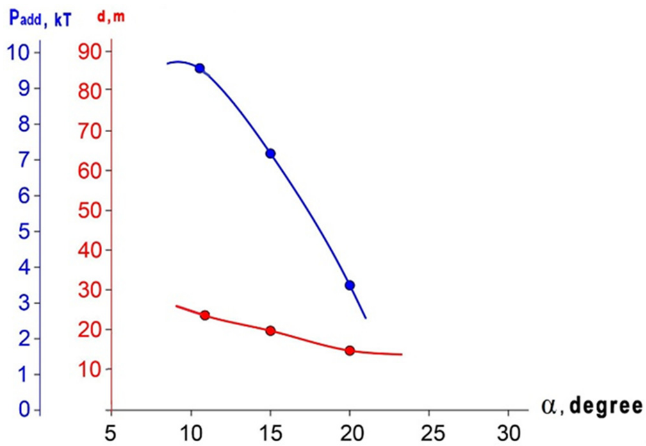

Figure 4. Dependence of the inclination angle of the break-down chamber on the distance to the permanent mine working and additional extraction from the extraction column area which is subject to robbing.

The creation of the pillar of the non-rectangular shape will increase the stability of workings. It is the new technological solution for protecting the main roadways. Introducing the special shape pillars, locating the stope at an angle of 10°, 15° and 20° to the main roadway as well as decreasing the width of the guard pillar, respectively, to 87, 64 and 31 m, creates the possibility of reducing coal losses from 3.5 to 9.5 thousand tons. In addition, the main goal will be achieved—the protection of the main roadway. Points on the curves correspond to the parameters indicated in Figure 3a–c: α = 11°, d = 25 m; α = 15°, d = 20 m;

α = 20°, d = 15 m. At the same time, the indicator characterizing the reduction in coal losses is presented as follows:

$$k = \frac{S_1}{S_2}, \quad (3)$$

where S_1 and S_2 are the areas of rectangular and trapezoid pillars equal to 1.39, 1.26 and 1.11, respectively.

According to the mining plan, the presented part of the mine field will be in operation for the next 10 years. The obtained dependencies can be used in establishing the technological parameters of mining operations at the end of the extraction columns. Moreover, the non-rectangular shape of protective barriers allows the more complete extraction of coal. This is associated with obtaining an additional economic effect and it allows one to provide the necessary stability of the preparatory workings of the main value.

4. Conclusions

In Ukraine, coal is an raw material and energy source that enables the production of approximately half of the electricity that can be generated from all possible energy sources. The main reasons hindering the development of the coal industry are delays in payments for shipped coal and insufficient funding for the renewal of fixed assets, making it impossible to purchase new and repair equipment, as well as maintaining mining in accordance with operational requirements, which leads to reduced productivity in mines.

Technological measures to increase the stability of main roads and reduce coal losses in the pillars are proposed and substantiated. This leads to increased production in the mine. The following conclusions may be drawn based on the results of the study performed on the improvement of working out technologies at the end of the extraction columns for an average coal seam thickness of 1.0–1.3 m and seams surrounded by weak rocks:

- The exploitation of western Donbas coal mines is crucial for the security of Ukrainian energy security, although it takes place under extremely difficult conditions.
- The exploitation of Zakhidno-Donbaska mine in western Donbas, Ukraine, was analyzed. To ensure the stability of the main drifts in this coal mine, coal pillars of 100–150 m width are usually abandoned, which leads to unreasonably large losses of coal. Pillar leaving at the main haulage roads provides only temporary support for their initial stability.
- Inadequate attention paid to the assessment of mining and geological conditions results in the formation of coal pillars of insufficient dimensions. It is necessary to reconsider the question regarding the shape of the abandoned coal pillar with the corresponding correction of the general principles concerning the main drift protection.
- A method to protect the main drifts by leaving the trapezoid-shaped pillars resulting from the face swinging was proposed. This allows reducing the coal loss in the pillars. It is shown that in terms of permissible parameters, when the angle of the face swinging is 11° and the distance from the end of the stopped face to the permanent mine working is 25 m, additional coal reserves of up to 9239.6 Mg could be extracted.

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