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The Choice of Technology and Equipment for Coal Seams of Different Bedding Excavation at Kuzbass Surface Mines Based on Digging Capacity and Unit Costs

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Abstract
The paper deals with an approach to the choice of equipment and technological schemes for the extraction of coal seams of different bedding by excavators of high specific productivity. A wide variety of mining and geological conditions for the coal seams bedding in the quarry fields of Kuzbass (Western Siberia, Russia) determines the use of a variety of high-performance excavation (rope and hydraulic shovels, hydraulic backhoes, draglines) and transport (dump trucks, railway trains, draglines) equipment used in various technological schemes. The problem lies in the choice of the excavator type and the technological scheme of its use for extracting coal from seams with different dip angles and thickness within the boundaries of one quarry field in order to achieve maximum productivity and economic efficiency of the entire site development. This article substantiates the analysis of the present and promising coal mining technologies using mechanical shovels, draglines and hydraulic backhoes in order to determine the optimal technological schemes for specific conditions. The basic principle of the proposed idea is to ensure the maximum ratio of the excavator's actual performance and unit costs, taking into account geological conditions and coal loss during extraction. In this regard, based on the analysis, the article presents recommendations for choosing a technological scheme when replacing equipment based on mining and geological conditions. Under certain circumstances, the analysis may result in a recommendation for a complete replacement of the excavator fleet. The advantage of the presented method, along with computational efficiency and visualization, is the applicability for the analysis of technological schemes of any complexity, which makes it possible to use it for the design of sections that develop complex-structured coal deposits

Keywords
quarry excavators, hydraulic backhoe, rope shovel, dragline, productivity, unit costs

Introduction

Kuzbass is the largest coal basin in Russia in terms of reserves and capacity, and the only supplier of some unique coal grades in the country. In Kuzbass, explored coal reserves are estimated at 730 billion tons; annual coal production is 210-230 million tons, of which more than 160 million tons are mined in an open way. Export supplies of Kuzbass coal account for 55-60% of the total production (Katsubin and Makridin, 2018).

The need to analyze the prospects for replacing traditional equipment for coal mining in Kuzbass (rope shovels and draglines) with modern hydraulic excavators is due to the prospect of increasing coal production in the cluster to 330 million tons by 2030 (Cehlár et al., 2020). In this regard, the annual capacity of recently designed enterprises increases to 20 million tons, and of reconstructed ones – up to 15 million tons (Miliy, 2020). The development of sites with more complex mining and geological conditions requires taking into account the reduction of coal losses when designing new technological schemes for the use of excavation and transport equipment sets (Korkachev and Koryakov, 2019).

A characteristic feature of the Kuzbass deposits is the wide spread of coal seams strata with different bedding conditions – from shallow to steep with sufficient depth (more than 200 m). The analysis of mining and geological conditions of Kuzbass shows that all coal deposits in the basin, according to the conditions of bedding, can be conditionally divided into three parts: Northern, Central and Southern. The first coal mining cluster – the Northern Kuzbass and the Kemerovo industrial area (the Kedrovsko-Krokhalevskaya and Glushinskaya brachysynclinal folds) are favourable for open-pit mining. The total reserves of this area are estimated at more than 5 billion tons, including 0.4 billion tons suitable for open pit development. The length of the Kedrovsko-Krokhalevskaya brachysynclinal folds is 12 km along the long axis and 8 km along the short axis. The North area is being developed by the open-pit mines "Kedrovsky", "Chernigovsky" and "Barzasskoye tovarischestvo" with an average annual capacity of 3-7 million tons.

In general, the deposits of the Northern Kuzbass are characterized by the formation of coal seams with a thickness of 1.5-11 m, a wide range of dip angles (0.5-40°), varied surface topography (from flat to high-relief), plicative and disjunctive disturbances, a significant number of synclinal and anticlinal folds. Coal-bearing deposits are everywhere overlain by Quaternary loess-like loams from 0.5 to 60 m thick (Martyanov, 2018). All this creates significant difficulties in the design of surface mines and the selection of optimal technological schemes for using excavators for coal extraction (Tosun, 2014).

Various mining and geological conditions predetermined the use of various technologies of open-pit mining in Kuzbass. For example, enterprises in the Eastern part of the central Kuzbass are mining with a predominance of direct dumping technology due to the shallow bedding. In some cases, part of the volume of bedrock is removed by loading into dump trucks. The considerable thickness of loose deposits predetermines the use of hydromechanization means. Enterprises in the Western part of Kuzbass are developing steep seams, which predetermines the use of transport technology (mainly, with the removal of rock mass by dump trucks with a carrying capacity of 180-320 tons). The sections of the Southern part of Kuzbass develop deposits of low dipping coal seams strata. The development of the overburden and coal seams is carried out by rope shovels with loading into dump trucks. Rocks between coal seams are mined either by rope shovels using transport technology or by draglines with direct dumping.

Analysis of the main indicators of coal mining enterprises in Kuzbass shows that the cost of producing one ton of coal annually grows by 5% with a deterioration in the quality of coal due to an increase in the growth of losses and clogging by overburden (Kolesnikov et al., 2018). Despite the supply of new models of excavators transport and drilling equipment, the efficiency of open-pit coal mining is continuously decreasing. The reason for this is the use of technological schemes developed for rope shovels at the sites with hydraulic excavators – more manoeuvrable equipment with a complex bucket trajectory (Prakash et al., 2013).

At the coal deposits of Kuzbass, 80% of overburden require preliminary loosening for excavation (Strelnikov, 2019). This leads to significant losses of coal, its dilution and a decrease in the efficiency of open-pit mining. The use of equipment and technology that excludes the drilling-and-blasting method of loosening makes it possible to eliminate the negative consequences of the traditional method of rock preparation (Hrehová et al., 2012).

To address this issue, to date, milling-type excavation and loading machines (manufactured by Wirtgen, Vermeer, Huron Manufacturing) have been developed. The excavation process of these machines is carried out due to the rotation of a wide-grip working body of a rotary or auger type and continuous horizontal movement of the entire machine. An example of such machines used in Kuzbass is the Wirtgen 2200 SM, designed for milling rocks with a strength of up to 50 MPa, a cutting width of 2200 mm and a cutting depth of up to 300 mm, and a working capacity of up to 390 tons per hour (Gerike et al., 2020) (Fig. 1).

Fig. 1. Wirtgen 2200 SM milling-type excavation and loading machine in Kuzbass

Despite the insignificant losses of coal during its extraction by a milling-type mining machine (less than 0.5%), their significant drawback is the limited scope of their application due to the use of the principle of cutting rocks in the working body, which significantly increases the energy intensity of destruction and makes it impossible to use them in the complex deposits development (Elevli and Elevli, 2010). In addition, modern milling machines are equipped with a constant dust suppression system, which makes their use in the climate of Western Siberia (with negative Celsius temperatures from November to March) very difficult. In this regard, milling machines are used in isolated cases at the open-pit mines of Kuzbass.

In fact, the existing schemes for mining coal reserves at the Kuzbass open pit mines are based on the use of dragline and rope shovel excavators, which are gradually being replaced by hydraulic backhoes (Molotilov et al., 2009; Mattis et al., 2012; Tyulenev and Zhironkin et al., 2017). As a starting point for the analysis of technological schemes for coal extraction by excavators of various types, this article states that the work of hydraulic backhoes is more efficient than rope shovel excavators.

Modern economic realities oblige mining companies to continuously increase production levels and reduce costs (Cehlár et al., 2018). In coal mines, this is usually achieved by increasing the bucket capacity of excavators, while the main position in designing their technological schemes is occupied by choice of the excavator type (Fig. 2). In this regard, the fleet of excavators at coal mines in the North of Kuzbass is represented by the following rope shovels: EKG-10, EKG-6.3US, EKG-8U, EKG-12.5, EKG-12, EKG-15 (made in Russia, with a bucket capacity 6.3-15 m^3), P&H- 2300, 2800 (made by Komatsu, with a bucket capacity of 18-33 m^3), etc., draglines of Russian production ESH 13.50, ESH 10.70, ESH 13.50, ESH 20.90, ESH 25.90 with a bucket capacity of 10-25 m^3, etc. The fleet of hydraulic excavators of the backhoe type replacing mechanical shovels and draglines in coal mining is represented by models from Liebherr, Volvo, Terex, Komatsu (with a bucket capacity of 6.7-20.6 m^3).

Fig. 2. The main types of excavators used in coal surface mines of Kuzbass (from left to right: rope shovel, dragline, hydraulic shovel)

Since the mid-2000s, most of the coal mines of Kuzbass systematically began to carry out the massive put into operation of hydraulic excavators. During this period, a number of significant advantages of hydraulic excavators in comparison with rope shovels were revealed. The development of coal-saturated zones with conventional rope shovels is accompanied by large losses due to the need to leave a rather thick coal layer at the contacts with host rocks and in zones of geological disturbances (Belyakov et al., 1985; Shishaev and Mochalov, 1988; Bi et al., 2020). By using modern hydraulic excavators of the backhoe type, which, due to the diverse kinematics of the bucket movement, can dig along any path and face height, it is possible to achieve a reduction in losses and clogging of coal (Bhaveshkumar and Prajapati, 2019). At the moment, it is possible to summarize the advantages of hydraulic backhoes described by the authors over rope shovels and draglines in coal surface mining (Nam and Drebenstedt, 2004; Zhang et al., 2011; Janosevic, 2012):

• reduction of the working cycle time;
• the ability to work in various conditions due to design features;
• better filling of the bucket and increased cutting force on the teeth;
• increased manoeuvrability and mobile characteristics, higher travel speed;
• reduction of losses and improvement of the quality of marketable coal.

As criteria for comparing excavators in this article, the productivity and unit costs for coal extraction are taken, which depend both on the type and specific model of equipment and on the technological scheme of its use.

Materials and Methods

Technological schemes for excavating coal seams, used at the open-pit mines of Kuzbass, are quite diverse and allow covering a wide range of mining and geological conditions and various models of equipment.

In particular, when using draglines for coal extraction with loading into dump trucks, the excavator is installed on the overburden of the seam roof (Demirel and Frimpong, 2009; Mohammadi et al., 2016). For these purposes, draglines with a bucket volume of 10-15 m^3 (it can be ESH 13.50 by Uralmash, P&H 2355 by Komatsu Mining, 680W by Busyrus International, W2000 by BEML) and dump trucks with a carrying capacity of 55-120 tons (BelAZ-7514 or 7555D by BelAZ, CAT 773E or 777R by Caterpillar, HD465-7R or HD785-7 by Komatsu, T 236 by Liebherr, TR60 by NHL-Terex) can be used. Excavation is carried out with bottom digging and loading of coal into a dump truck at a level of dragline's standing. This technological scheme in relation to the development of the hinge part of the fold is shown in Fig. 3.

The advantage of this technological scheme is the utmost simplification of the organization of the equipment operation. Dragline works out the entire hinge part of the fold in one working stroke; moreover, excavation is carried out in one layer of 20 m high, which is typical only for layers of a high thickness (over 15 m). The disadvantage of this scheme is its effective use in a relatively narrow range of mining and geological conditions – flat seams of high thickness or in the hinge parts of folds.

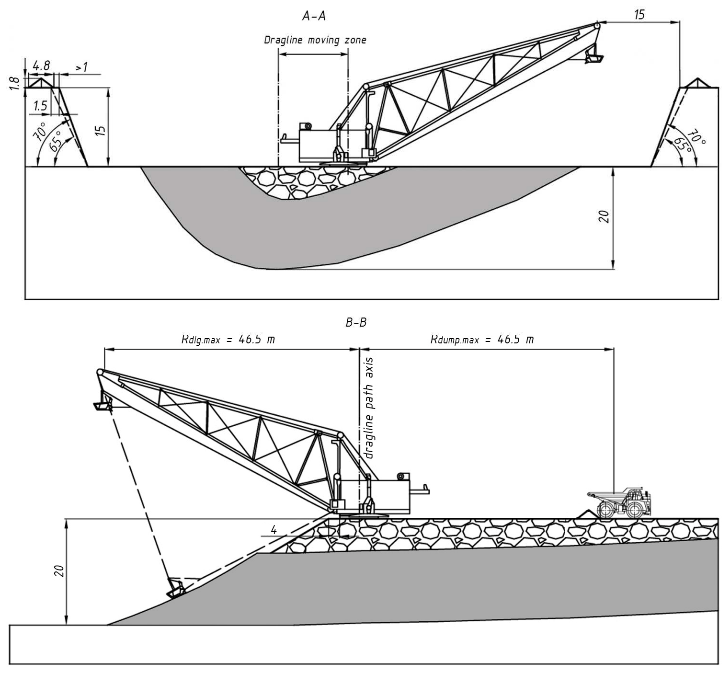

Fig. 3. Technological scheme for extracting the hinge part of a fold of a coal seam by dragline ESH 13.50 (with a bucket capacity of 13 m^3 and a boom length of 50 m) and loading into a BelAZ-7555D dump truck (carrying capacity 55 tones). Sections A-A, B-B (the beginning)

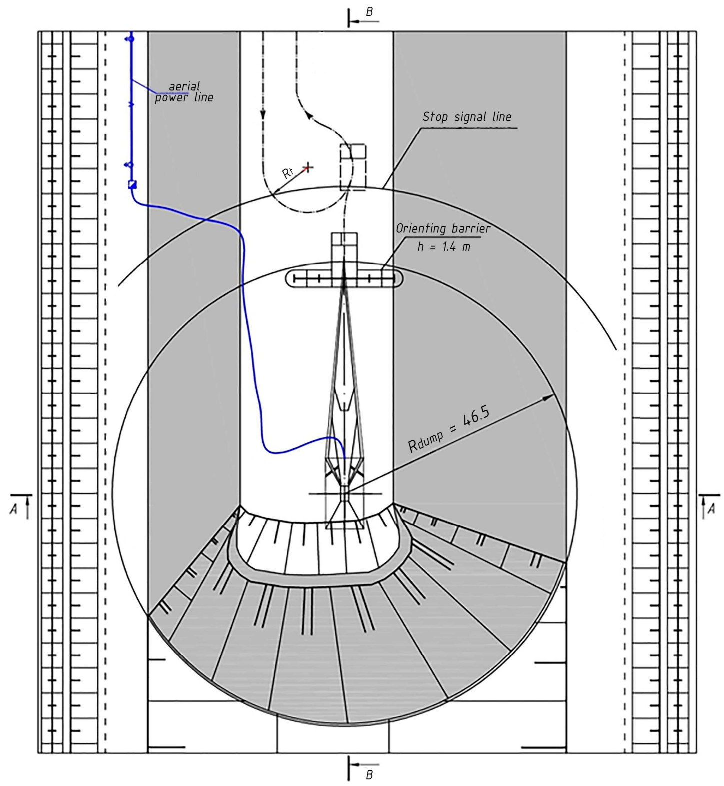

Fig. 3. Technological scheme for extracting the hinge part of a fold of a coal seam by dragline ESH 13.50 (with a bucket capacity of 13 m³ and a boom length of 50 m) and loading into a BelAZ-7555D dump truck (carrying capacity 55 tones). Sections A-A, B-B (the end)

The technological scheme of coal excavation with a rope shovel provides for upper digging and loading into dump trucks at the level of the excavator standing (for the rope shovel EKG-10 with a bucket capacity of 10 m³, which is widespread in the Kuzbass surface mines), is shown in Fig. 4.

The analysis shows that in difficult geological conditions when excavating inclined coal seams, the operation of rope shovels is ineffective (Che and Yang, 2010; Vukotic and Kecojevic, 2014). Despite a number of advantages of using shovels for coal extraction (high reliability and maintainability (Karpuz et al., 2001)), their main disadvantage is the increase in losses compared to hydraulic shovels and backhoes due to the peculiarities of the bucket trajectory and the impossibility of manoeuvring directly with the bucket.

The positive experience in the practical use of hydraulic backhoes suggests the feasibility of completely replacing the fleet of rope shovels with them. For example, rope shovels with a bucket volume of 10 m³ (EKG-10 by Izhora Plants PH 1900 AL by P&H, R 9350 by Liebherr, WK 10B by WK, CAT 7495 by Caterpillar, Marion-182M by Marion, 182M by Busyrus International) can be replaced by hydraulic backhoe such as Komatsu PC-1250 and Liebherr R 994 with a bucket capacity of 6-13 m³.

The variety of use of hydraulic excavators in coal mines is due to the different mining and geological conditions of coal seams bedding. The most effective method is bottom digging and bottom loading of the bench (Janosevic, 2012). To design technological schemes for the use of hydraulic backhoes for coal extraction in the open pit mines of Kuzbass, the following general input is used:

- digging depth (face height) is approximately equal to the dump truck body height;
- the minimum value of the excavation cycle is achieved when the dump truck is located at an angle of 45-60° to the excavator axis;
- the angle of rotation of the excavator during loading varies from 60 to 135°;
- to reduce the time of dump trucks exchange, they can be fed in reverse to the left and right sides;
- with well-crushed rocks, the excavator can load in layers from top to bottom, which reduces the time by speeding the bucket lifting. The bucket can be penetrated at any height parallel to the bottom of the bench, which is important for the selective mining of coal seams.

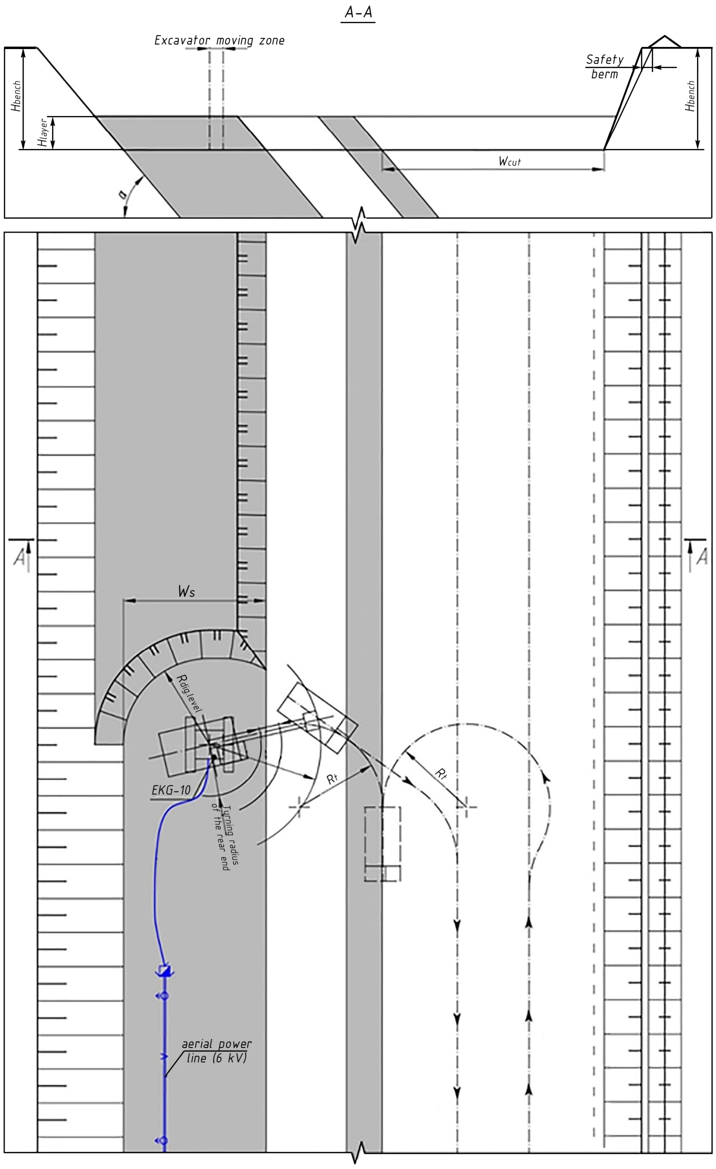

Fig. 4. Technological scheme of excavation of coal seams with a shovel EKG-10

To design technological schemes for extracting coal seams with hydraulic backhoes, it is necessary to determine the parameters of the mining method: the height of the bench (the extracted layer), the width of the excavator's stope, the width of the excavator's working platform and its elements that ensure the safety of mining operations. This is especially important for using backhoes in disjunctive dislocations conditions, where, on the one hand, the high manoeuvrability of the hydraulic excavator perfectly fits these conditions. On the other hand, the platforms in disjunctive areas are quite narrow, so the safety berms must be strictly observed.

The height of the working bench depends on the physical and mechanical properties of rocks, the mining and geological conditions of their occurrence (mainly, the dip angle of the seam and its thickness) and the operating parameters of the excavator. The minimum bench height is determined from the condition of filling the bucket in one cycle (Jin et al., 2014).

According to the Russian Federal norms and rules in the field of industrial safety, "Safety Rules for the Development of Coal Deposits by the Open Way" (approved by the Order of the Federal Service for Environmental, Technological and Nuclear Supervision No. 488 dated November 20, 2017), when using hydraulic backhoes, the safe bench height is determined by calculations taking into account the trajectory of the excavator bucket (for a hydraulic backhoe see Fig. 5).

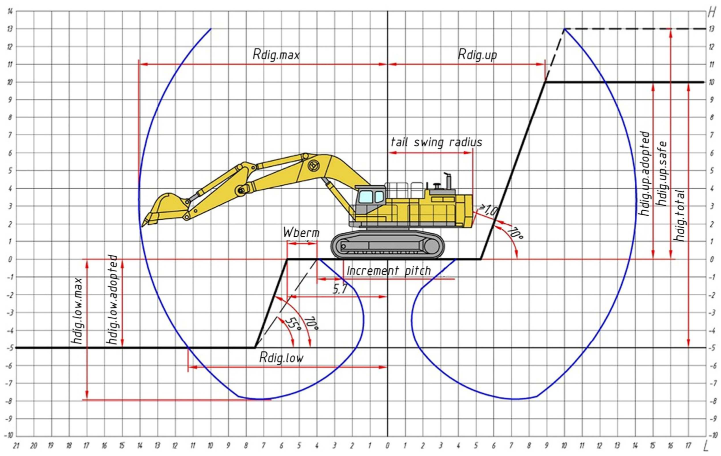

Fig. 5. Kinematic diagram of the Komatsu PC1250 hydraulic backhoes

The maximum bench height for hydraulic backhoes with bottom digging depends on the angle of the stable slope, taking into account the additional load on the rock caused by the excavator, as well as the digging depth (Conigliaro et al., 2009). The maximum bench height with a stable slope angle of 55-60° and a rock loosening ratio of 1.35-1.45 will be 78-82% of the maximum digging depth.

Taking into account the data in Fig. 5, it is advisable to excavate coal with a hydraulic backhoe with a bench height of 10.0 m with the installation of an excavator on a sub-bench with a height of 3.2-5.0 m.

The width of the excavator stope (A_e) for hydraulic backhoes is determined by the formula (1) (Strelnikov, 2019):

$$A_e = R_{d.r.} + 0.5 \cdot C + l_s + b_f \tag{1}$$

where $R_{d.r.}$ – the accepted digging radius of the excavator at the standing level, m
C – the width of the caterpillar track of the excavator, m
b_f – the width of the prism of possible rockfall, m
l_s – the safe gap between the prism of possible collapse and the excavator's caterpillars (taken at least 1.0 m);

The calculated value of the width of the excavator stope for the hydraulic backhoe is presented in Tab. 1.

Tab. 1. Values of the elements of the width of the excavator stope for the hydraulic backhoe

Excavator brand	Lower layer's height $H_{n.s.p}$ [m]	Width of the possible rockfall prism b_f [m]	Width of the caterpillar track W [m]	Accepted digging radius at the standing level $R_{d.r.}$ [m]	Excavator stope width A_e [m]
Komatsu PC1250SP-7	5.0	1.7	4.6	8.7	18.1
Liebherr R994	5.0	1.7	5.7	11.1	17.5

The width of the working platform for excavators is calculated according to standard methods and is 54.5 m (Matushenko, 1975).

When developing technological schemes for excavating coal seams with hydraulic backhoes, the main criterion was the layer-by-layer excavation with a layer's height determined by the condition of maximum digging of the coal seam. For this, three main variants of technological schemes have been identified: for coal seams with the dip angle of less than 5˚, from 5˚ to 25˚, from 25˚ to 50˚.

Technological scheme of coal bench excavating with seams dipping angle of 5˚

The technological scheme of working out a coal bench for seams with the dip angle of 5˚ is carried out by the hydraulic backhoe standing at a sub-bench platform. The layer height is 5.0 m. Excavation is carried out with bottom digging. From the side of the seam's roof, the excavator extracts the seam to the maximum value of the digging radius, ensuring complete excavation of soil rocks. However, the technological parameters of the excavator (the maximum digging radius and at the standing level) in this case are not enough for working out the rocks at the top of the seam. In this connection, the cutting of rocks in the top of the seam and moving to the zone of the excavator's digging radius is carried out using the Komatsu D9R bulldozer. Coal loading in BelAZ 7555D dump truck is carried out with bottom scooping. As the rocks in the top of the seam are prepared for excavation, the underlying layer is being mined in a similar manner. This scheme is recommended for use in confined spaces. A draft of the technological scheme for mining a coal bench with the dip angle of seams of 5˚ is shown in Fig. 6.

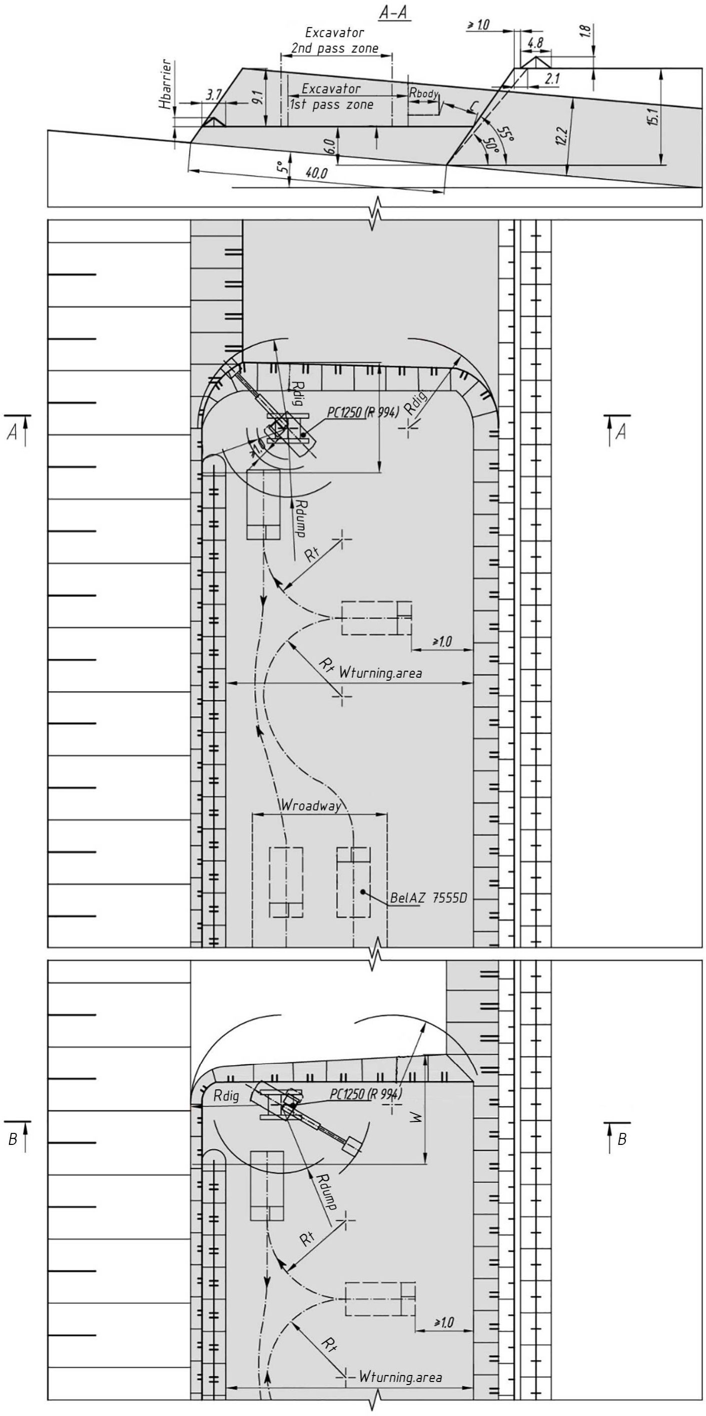

Fig. 6. Technological scheme of coal bench mining with the dip angle of seams of 5˚

Technological scheme of coal bench mining with a dip angle of seams of 5-25˚

The technological scheme of working out a coal bench with the dip angle of seams of 5-25˚ is also carried out by the hydraulic backhoe installed at the platform of a sub-bench. Working with cross stopes, the excavator extracts the upper layer of coal ready for excavation with the upper digging. Loading into dump trucks is carried out at a standing level. In order to ensure safety, protective shafts are formed from the side of the coal bench.

In the second path, when the excavator moves in the opposite direction, the underlying layer is worked out. Extraction is carried out by bottom excavation, with loading into dump trucks at the level of standing. The previously formed protective shaft is removed by the upper scooping. The scheme is effective when developing coal seams of small thickness. The technological scheme of working out a coal bench when coal seams dip with an angle of 5˚-25˚ by a hydraulic backhoe is shown in Fig. 7.

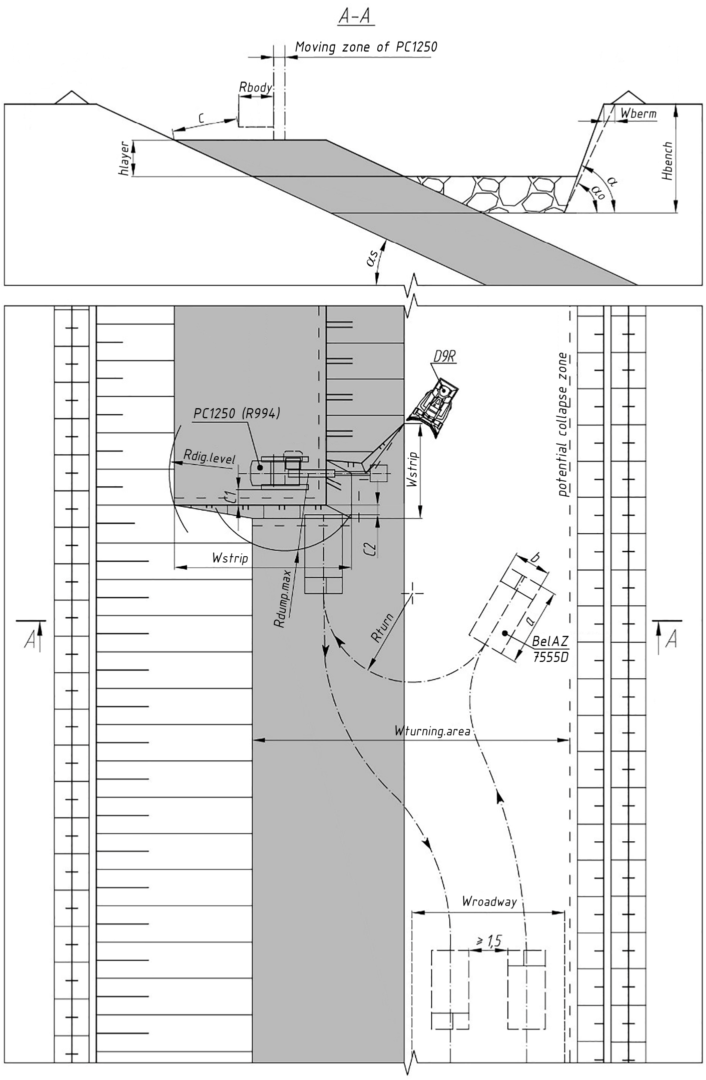

Fig. 7. Technological scheme for working out a coal bench with a seam dip angle of 5˚-25˚ by a hydraulic backhoe.

Technological scheme for working out a coal bench with a seam dip angle of 25˚-50˚ by a hydraulic backhoe

The technological scheme of working out a coal bench with a dip angle of seams of 25˚-50˚ is also carried out by hydraulic backhoe with the installation of an excavator at the platform of the sub-bench. This geological condition is also associated with the presence of adjacent seams, which makes it difficult to mine coal with a rope shovel.

As the first seam is developed, the preparation and development of the second, more powerful seam of the strata is underway. The mining is carried out by a complex face with alternating extraction of overburden and coal. The top layer of a shotpile of overburden and coal is mined with top digging and loading into dump trucks at the standing level. A protective shaft is formed on the shotpile side.

As the upper layer is worked out, the excavator extracts the underlying layer by the backward path. Extraction is carried out at first ahead of overburden, with the cleaning of the coal seam roof, and then it is worked out. The excavator is installed at the sub-bench. The work is carried out by bottom digging and loading below the level of the excavator standing. The low layer is being worked out using similar technology.

The technological scheme of working out a coal bench with a seam dip angle of 25˚-50˚ with a hydraulic backhoe is shown in Fig. 8-9.

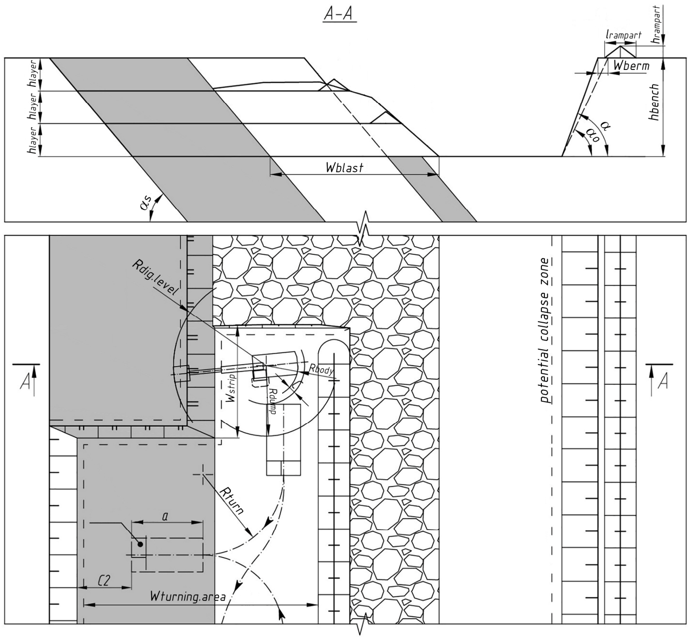

Fig. 8. Technological scheme of coal bench mining with seams dip angle from 25° to 50° (the beginning of development)

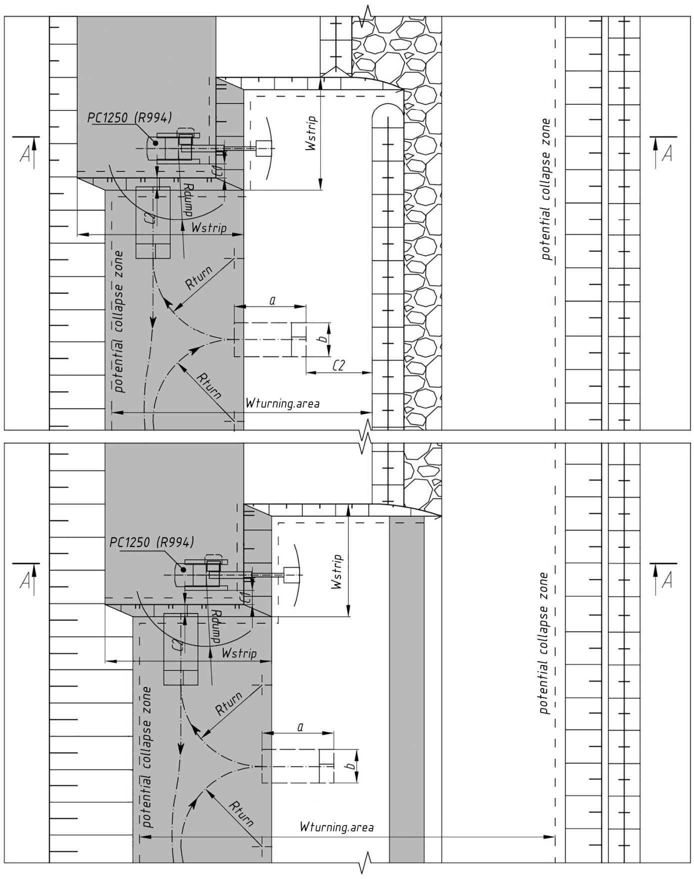

Fig. 9. Technological scheme of coal bench mining with seams dip angle from 25° to 50° (the end of development)

Comparison of the efficiency of coal seams excavation by various types of equipment – draglines, rope shovels and hydraulic backhoes – was carried out according to the criterion of the ratio of productivity and operating costs during the year. At the same time, it was assumed that losses during coal mining are 12-15% for draglines with a bucket capacity of 10-13 m^3, 8-10% for rope shovels with a bucket capacity of 10-15 m^3, 4-7% for hydraulic backhoes, depending on the height of the excavated layer (Tyulenev and Litvin et al., 2017).

When designing re-equipment of coal mines, the annual productivity of excavators, taking into account all influencing parameters, is determined by the formula (GIPRORUDA, 1983):

$$Q_{an} = Q_d \times N \tag{2}$$

where Q_{an} – annual digging capacity of the excavator, m^3 / year;
N – number of days of excavator utilization in a year.

$$Q_d = Q_{sh} \times n_{sh} \tag{3}$$

where Q_d – daily digging capacity of the excavator, m^3 / day;
n_{sh} – number of shifts in a day.

$$Q_{sh} = 3600\frac{V_b \times K_e \times K_f}{t_c} \times t_{sh} \times K_{sh} \times K_{fsr} \times K_{dbw} \times K_{sp} \times K_{fsr} \times K_{orp} \tag{4}$$

where Q_{sh} – shift digging capacity of the excavator, m^3 / shift;
V_b – bucket volume, m^3;
K_e – excavation coefficient:

$$K_e = \frac{K_{bf}}{K_{rd}} \tag{5}$$

where K_{bf} – bucket filling rate;
K_{rd} – rock fragmentation index;
K_f – coefficient of influence of the face on digging capacity (0.8-0.9);
t_c – operative excavation cycle time, sec:

$$t_c = (1.1 \div 1.2)t_c^b \tag{6}$$

where t_c^b – base excavation cycle time, sec;
t_{sh} – shift duration, hours;
K_{sh} – use factor of the excavator in a shift;
K_{dbw} – coefficient considering drilling and blasting during a shift in average;
K_{sp} – coefficient considering sprinkling of a face during a shift;
K_{fsr} – coefficient considering excavation of frozen and sticking rock;
K_{orp} – coefficient considering oversize rock pieces.

The experience of designing open-pit mines in complex-structural areas of Kuzbass deposits has shown that the formula (4) takes into account all factors affecting the performance of excavators and, therefore, can be used to compare the types of excavators used for coal mining.

When comparing the economic efficiency of coal extraction by different types of excavators, it is advisable to determine the unit costs of coal mining excluding overburden by the formula (7) (Martyanov, 2018):

$$C_u = \frac{C_t}{(S_r \times \gamma_c + 1) \times Q_{an}} \tag{7}$$

where C_u – unit costs of coal excavation, USD/ton;
C_t – total costs of coal excavation except for overburden, thousand USD;
S_r – stripping ratio, m³/ton;
γ_c – coal density, ton/m³;
Q_{an} – annual digging capacity of the excavator, thousand m^3.

Actual total costs of coal excavation C_t are determined as the sum of the cost of equipment depreciation, the cost of diesel fuel for hydraulic backhoes or electricity for rope shovels and draglines, labour costs and the cost of enriching coal to a high-grade quality level (in the case of using EKG-10 rope shovel).

Results

In order to assess the efficiency of coal seams extraction by presented excavators, taking into account mining and theological conditions and technological schemes (Fig. 3-9), the values of shift, daily and annual productivity were calculated (Tab. 2-5).

Tab. 2. Data for calculating the annual productivity of excavators with loading coal into a dump truck

Indicators	Rope shovel EKG-10	Dragline ESH 13.50	Hydraulic backhoe Liebherr R994	Hydraulic backhoe Komatsu PC1250
Bucket volume V_b [m³]	10	13	13	6.7
Rock fragmentation index K_{rd}	1.25	1.25	1.25	1.25
Bucket filling rate K_{bf}	1	0.94	1	1
Rock fragmentation index K_{rd}	0.80	0.75	0.80	0.80
Base excavation cycle time t_c^b [sec.]	31.9	57.2	34.4	25.0
Operative excavation cycle time t_c [sec.]	33.6	60.2	36.2	26.3
Density of coal [ton/m³]	1.4	1.4	1.4	1.4
Oversize rock pieces share [%]	5	5	5	5
Dump Truck Carrying Capacity [ton]	55	55	55	55
The volume of rock mass in the body of a dump truck with a "header" [m^3]	31.3	31.3	31.3	31.3
Dump truck installation time for loading [min.]	0.7	0.7	0.7	0.7
The number of rock mass buckets loaded into the dump truck	3.1	3.3	2.4	4.7
Number of cycles for loading a dump truck	4	4	3	5
Dump Truck Loading Time [min.]	2.2	4	1.8	2.2
Dump Truck Waiting Time [min.]	0.15	0.15	0.15	0.15
Shift duration t_{sh} [hours]	8	8	8	8
Use factor of the excavator in a shift K_{sh}	0.8	0.7	0.75	0.75
Time for preparatory and final operations [min.]	31	30	35	35
Time for personal needs [min.]	10	10	10	10
Bulldozer work time [min.]	10	10	10	10
Diesel refuelling time [min.]	0	0	20	20
Number of shifts in a day n_{sh}	3	3	3	3
Holidays per year [days]	14	14	14	14
Average annual excavator repair time per year [days]	45	53	20	20
Downtime due to weather conditions per year [days]	7	7	7	7
Number of days for technological runs per year [days]	10	10	10	10
Number of days of excavator utilization in a year N [days]	289	281	314	314
Coefficient considering excavation of frozen and sticking rock K_{fsr}	1	1	1	1
Coefficient considering oversize rock pieces K_{orp}	0.84	0.84	0.84	0.84
Coefficient considering drilling and blasting during a shift in average K_{dbw}	0.97	0.97	0.97	0.97
Coefficient considering sprinkling of a face during a shift K_{sp}	0.92	0.92	0.92	0.92

Tab. 3. Values of the annual productivity of excavators for loading coal into a dump truck

Indicator	Rope shovel EKG-10	Dragline ESH 13.50	Hydraulic backhoe Liebherr R994	Hydraulic backhoe Komatsu PC1250
Shift performance Q_{sh} [m³/shift]	2640	2225	2870	2490
Daily productivity Q_d [m³/day]	7920	6675	8610	7470
Average annual productivity Q_{an} [thous. m³/year]	2312	1948	2784	2323

The calculated values of excavator productivity show the expected results. Comparing the performance indicators of the ESH 13.50, EKG-10, Liebherr R994 and Komatsu PC1250 excavators, we can conclude that the performance of hydraulic backhoes in coal mining in Kuzbass open pit mines is higher than the performance of rope shovels and draglines with a similar bucket volume. This value is achieved not only by increasing the bucket capacity: different volumes of EKG-10 (10.0 m³) and Komatsu PC 1250 (6.7 m³) buckets provide similar average annual productivity – about 2.3 million m³/year, which is achieved due to the advantages mentioned above of the hydraulic backhoe. Dragline with a bucket volume of 13 m³ has the lowest performance among compared excavators and is used for excavating coal in special cases, such as for the development of the hinge part of a fold in a coal seam (Fig. 3). At the same time, the Liebherr R994 hydraulic backhoe has a maximum capacity (2.7 million m³), which is achieved through an optimal combination of manoeuvrability, cycle time and bucket capacity.

To determine the unit costs of coal excavation except overburden C_{sc} for various types of excavators, the following values of the indicators used in formula (7) were adopted: stripping ratio S_r is 6.2 (average for Kuzbass surface mines), coal density γ_c is 1.4, coal preparation costs up to the high level of quality (when using a mechanical shovel EKG-10) – 0.18 USD/ton, which at the estimated performance of the excavator will be 416.17 thousand USD annually. Data on cost, unit consumption of electricity and diesel fuel are shown in Tab. 4.

Tab. 4. Values of cost, the unit consumption of electricity and diesel fuel for excavators

	EKG-10	ESH 13.50	Liebherr R994	Komatsu PC 1250
Cost [USD thous.]	1950	1830	2210	1990
Unit diesel fuel consumption [l/m³]	–	–	0.069	0.084
Unit power consumption [kWh/m³]	0.8	1.5	–	–

Using the data on the annual productivity of excavators (Table 3), unit diesel fuel and power consumption (Table 4), as well as data on the wages of excavator operators at the open-pit mines of Kuzbass, total costs of coal excavation except for overburden for excavators of the considered types are shown in Tab. 5.

Tab. 5. Calculation of the total annual costs when using excavators for coal extraction (thousand USD annually)

Excavator	Cost type	Value
EKG-10	Depreciation	89.71
	Costs for fuels and lubricants (or electricity)	258.82
	Labour costs	419.11
	The cost of enrichment of coal to a high-grade level of quality	416.17
	Total	*1183.81*
ESH 13.50	Depreciation	85.29
	Costs for fuels and lubricants (or electricity)	416.71
	Labour costs	388.21
	The cost of enrichment of coal to a high-grade level of quality	0
	Total	*890.21*
Liebherr R994	Depreciation	180.88
	Costs for fuels and lubricants (or electricity)	325.12
	Labour costs	123.53

	The cost of enrichment of coal to a high-grade level of quality	0
	Total	*629.53*
Komatsu PC 1250	Depreciation	171.56
	Costs for fuels and lubricants (or electricity)	388.47
	Labour costs	123.53
	The cost of enrichment of coal to a high-grade level of quality	0
	Total	*683.56*

From data in Tab. 5, it follows that the total costs of coal excavation except for overburden for machines with close values of the bucket capacity are the maximum for the dragline ESH 13.50 and the minimum for the Liebherr R994 hydraulic backhoe. At the same time, the Komatsu PC 1250 hydraulic backhoe with a bucket capacity of 6.7 m^3 has similar values of annual productivity with an EKG-10 rope shovel with a bucket capacity of 10 m^3 (about 2300 thousand m^3 – Table 3). However, the total cost of coal excavation for it is 23% less (Table 5).

The results of calculating unit costs of coal excavation except for overburden C_{sc} for various types and models of excavators, together with their annual productivity, are presented in Fig. 10.

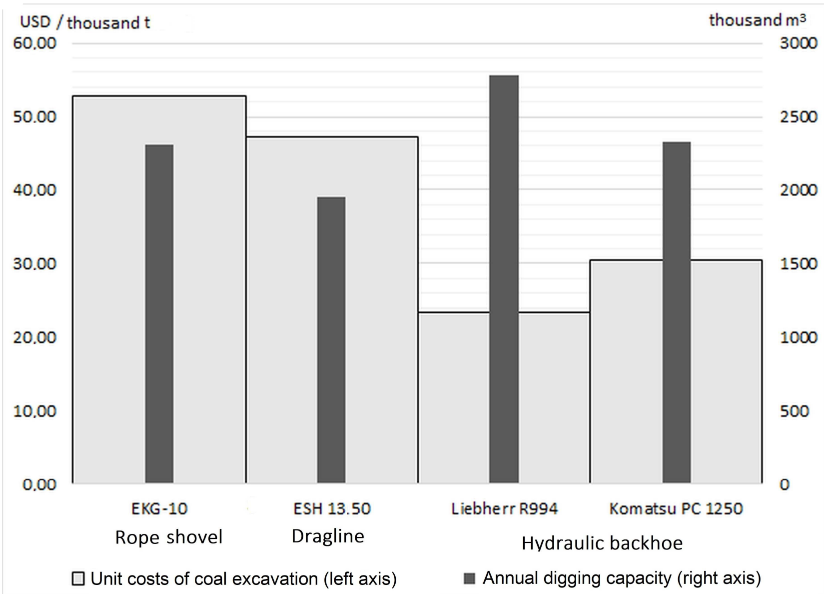

Fig. 10. Comparison of unit costs of coal excavation except for overburden and digging capacity for different models of excavators

Based on the comparison of the obtained data on the annual unit costs, it can be concluded that the use of the Liebherr R994 excavator and, to a lesser extent, the Komatsu PC 1250 excavator is more cost-effective.

Discussion

When analyzing the technology of excavating coal in Kuzbass open pit mines with various types of equipment, its productivity and cost, as well as coal losses during excavation, it is obvious that hydraulic backhoes have many advantages over draglines and rope shovels in the extraction of coal seams with different bedding conditions.

First, due to their smaller dimensions and weight, the presence of a self-contained diesel engine, hydraulic excavators are more manoeuvrable and have a shorter excavation cycle time, as well as develop a greater cutting force in the rock. Hydraulic backhoes have these advantages not only over draglines (which are rarely used when excavating coal with loading into dump trucks due to increased requirements for operators), but also over rope shovels, which are traditionally used in the open-pit mines of Kuzbass to work in coal-saturated zones.

The key difference between the process of excavation of rock mass by hydraulic backhoes and rope shovels and draglines is the various kinematics of the bucket movement along complex trajectories (Fig. 5), which makes it possible to scoop up previously loosened rock along any trajectory and significantly reduce losses from non-digging and clogging of coal in any conditions (up to 5%). On the contrary, for excavating coal with a rope shovel, additional enrichment to the high-quality level is required due to the capture of a part of the blasted rock at the contact with the coal seam in order to avoid coal losses in the non-digging cones (reaching 12%).

Secondly, the productivity gain of hydraulic backhoes is primarily due to shorter cycle times with a similar or even larger bucket capacity and a shorter dump truck loading time (Table 2). As a result, the average annual productivity, determined taking into account mining and geological, production, technical, climatic and organizational factors, for hydraulic excavators used at Kuzbass surface mines exceeds the productivity of shovels with a similar bucket volume by 20%, and draglines by 43%. At the same time, the unit costs for excavating 1 thousand tons of coal, excluding overburden for hydraulic backhoes, are 42-55% lower than for rope shovels and 36-51% lower than for draglines. Thus, the calculation results unequivocally indicate in favour of the use of hydraulic backhoes for excavating coal in similar mining and geological conditions.

Thirdly, hydraulic backhoes demonstrate high technological efficiency associated with the minimum level of coal losses in the development of seams of any category in terms of dip angle – shallow, inclined and steeply dipping. This is ensured by the layer-by-layer extraction of coal with a layer height (sub-bench) equal to 2.2-5 m. An important condition for the safe operation of a hydraulic excavator when developing a coal sub-bench is to observe the width of the safety berms in the area of the prism of possible rockfall when calculating the width of the excavator stope.

Thus, there are technological and economic advantages of replacing the traditional excavation equipment for coal extraction – rope shovels (in some cases draglines) – with hydraulic backhoes. The modernization of the excavator fleet at Kuzbass coal surface mines allows avoiding the main limitation to the growth of economic efficiency as the quarries deepen and the mining and geological conditions become more complicated – the growth of coal losses, especially of valuable grades.

At the same time, it is necessary to highlight a number of restrictions on the modernization of the excavator fleet in the course of replacing rope shovels with hydraulic backhoes.

The first limitation is coal deposits of low grade and market price due to high ash content and low calorific value, especially for thin seams (less than 3 m). The net present value of these coals may not be sufficient to support the lease payments or the required return on investment in expensive equipment such as a hydraulic backhoe.

The second limitation is depleted coal deposits, which are less than 10 years away from the end of their development. To replace traditional rope shovels with hydraulic backhoes, the return on investment is likely to be insufficient, given the trend of increasing operating costs after 5-6 years of operation.

At the same time, these restrictions apply to a small part of coal deposits currently being mined in an open way in Kuzbass and in the world as a whole.

Conclusions

When developing promising coal deposits in Kuzbass by surface mining, a tendency was observed in increasing the share of coal extracted with hydraulic backhoes. Prospects for the growth of coal production in the basin in 2021-2030 raised the question of a large-scale technical re-equipment of the excavator fleet of surface mines, especially those related to the extraction of coke coal. The article compares technological schemes, performance indicators and operating costs for coal extraction by various types of excavators – draglines, rope shovels and hydraulic backhoes with loading into dump trucks.

As a result of comparative analysis, it was found that hydraulic backhoes, having technological advantages over other types of excavators (a higher level of average annual productivity and the ability to maintain it in the development of seams with any complexity of mining and geological conditions), also have a lower level of unit operating costs. This is due to the absence of the need for additional enrichment of excavated coal (in comparison with a shovel, which is characterized by significant contamination of coal by contact overburden), a short excavation cycle and greater manoeuvrability (in comparison with a dragline), as well as with a smaller number of maintenance personnel. Hydraulic backhoes have an indisputable advantage over milling machines when extracting coal from seams – the ability to use not only for coal seams with shallow but also inclined and steep dipping. At the same time, restrictions on the use of hydraulic backhoes for coal extraction affect a small part of coal deposits that are being mined today by open way – mainly depleted and of low grade.

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