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Estimation of Excavator-Automobile Complex Productivity at Changing of Engineering and Geological Conditions

Sergey MARKOV[1]*, Maxim TYULENEV[2], Dmitry DUBINKIN[3] *and* ***Elena MURKO[4]***

Authors' affiliations and addresses:
[1]T.F. Gorbachev Kuzbass State Technical University, 28 Vesennaya St., 650000 Kemerovo, Russian Federation
e-mail: markovso@kuzstu.ru

[2]T.F. Gorbachev Kuzbass State Technical University, 28 Vesennaya St., 650000 Kemerovo, Russian Federation
e-mail: ddm.tm@kuzstu.ru

[3]T.F. Gorbachev Kuzbass State Technical University, 28 Vesennaya St., 650000 Kemerovo, Russian Federation
e-mail: ddm.tm@kuzstu.ru

[4]V.V. Zhirinovsky University of World Civilizations, 1/2 Leninsky Prospekt, bld. 1, 119049 Moscow, Russian Federation
e-mail: elena6455@mail.ru

***Correspondence:**
Sergey Markov, T.F. Gorbachev Kuzbass State Technical University, 28 Vesennaya St., 650000 Kemerovo, Russian Federation
e-mail: markovso@kuzstu.ru

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Abstract
In open pit mining of solid minerals, loading of rock mass from the face is usually carried out without moving the excavator until the dump truck is fully loaded. To ensure that the dump truck body is filled at maximum excavator productivity, the volume of rock mass in a single removed face block should correspond to the capacity of the body, taking into account the loosening of rock during excavation. The article considers the influence of such factors as the minimum radius of excavator digging at the level of its placement, the step of excavator movement, the coefficient of rock loosening during its removal from the massif when working in the mining face, on the volume of downhole block and the angles of excavator rotation for unloading, taking into account the safe operation of excavation-loading and transportation equipment. As an example, the excavator Komatsu PC1250 backhoe is considered when paired with a dump truck BELAZ 7531 (240 tons) when loading coal by top and bottom digging, with the dump truck below the level of the excavator from the side of the slope across the strike of the seam.

Keywords
excavator productivity, hydraulic backhoe, heavy autonomous platform, excavator-automobile complex, dump truck productivity, face block, open pit mining, geotechnical system

Introduction

The program of development of the Russian coal industry for the period up to 2035 provides for the development of existing and exploration of new promising areas of coal mining (Shaklein et al., 2024). The share of the Kuzbass region in coal production in the Russian Federation remains in first place both at the moment (about 55%) and in the plans envisaged by the program (from 45% to 48%). This fact points to maintaining high rates of coal mining in Kuzbass by the open pit method.

The excavation and loading equipment used at the existing open-pit mines in Kuzbass is mostly represented by hydraulic shovels, mainly backhoes. This circumstance is due to the fact that coal excavation by backhoes is carried out with minimum losses both by upper and lower digging (Litvin et al., 2021; Martyanov et al., 2021), and their parameters allow loading the excavated rock mass into dump trucks of a wide range of load-carrying capacity and dimensions (Tyulenev et al., 2021; Zou et al., 2019).

The operation of excavation, loading and transportation equipment during surface mining operations is limited not only by the mining and geological conditions of the mined area but also by safety rules for surface mining operations (Mikhailov et al., 2025). According to current safety standards, when using interconnected mechanisms in operation, the horizontal and vertical distance between them is determined by the documentation for the production of works approved by the coal pit's technical manager (chief engineer). In practice, the safe distance between the working equipment of the excavator and the vehicle during rock mass excavation is taken not less than 1 m. The distance between the slope of the bench, dump or vehicle and the counterweight of the excavator is established by the general project of the mining enterprise depending on the mining and geological conditions and the type of equipment and should be at least 1 m.

Technological schemes of complex operation are selected based on the parameters of excavation-loading and transportation equipment, mining and geological conditions and safety rules. In this case, the rational use of parameters for excavators' working equipment is questioned. Working at maximum use of the geometry of movement of the boom, arm, and bucket is not always reasonable. It is connected both with the increase in energy consumption and loads arising in the nodes of the working equipment and with the decrease in productivity of the excavator-vehicle complex (Azure et al., 2021; Behun et al., 2022; Coetzee & Els, 2009).

At the same time, the loading of blasted rock mass or coal is optimal in conditions when the excavator performs the loading of one dump truck without moving on the working site during loading of one dump truck (Dubinkin et al., 2022; Tyulenev et al., 2017). Thus, the question arises of selecting such parameters of the one-time excavated face block that can ensure:

a) loading of one dump truck without moving the excavator;
b) maximum productivity of the excavator.

At the same time, it is necessary to solve the question of optimal selection of excavation-loading equipment for specific mining and geological conditions, in which this equipment will work in conjunction with specific transportation equipment.

Material and Methods

The excavation and loading equipment considered in this article is represented by an excavator - backhoe Komatsu PC1250, universally used at coal mining enterprises of Kuzbass. As transportation equipment, the dump truck BELAZ 7531, with a carrying capacity of 240 tons, is considered. This type of dump truck is widely used at the Kuzbass coal mines (Markov et al., 2019); at the same time, a heavy autonomous platform has been developed on its platform in KuzSTU together with Bauman Moscow State Technical University and with the support of the Government of Kuzbass within the framework of the complex scientific and technical program "Clean Coal – Green Kuzbass" and in accordance with the development goals of the Russian Federation.

At present, digital twins of surface coal mining enterprises are being actively created, including mathematical models of surface mining processes and the widespread use of various CAD systems (Conigliaro et al., 2009; Hai-zuo et al., 2020; Kim & Chi, 2019; Mishra & Mohanty, 2020; Yoshida et al., 2013; Zavadsky et al., 2022). To determine the parameters of face blocks, 3D modelling of the geometry of the subsoil area and a technological scheme were used, along with the specified excavation-loading and transportation equipment in the nanoCAD software.

Mining and geological conditions of mining of seam coal deposits in Kuzbass are represented by the widest range of dip angles of seams (from 5° to 87°), their thicknesses (from low thicknesses of a few centimetres, which are of no industrial importance, to several tens of meters) and thicknesses of interlayers. Discontinuous tectonics is represented by strike-slip faults and scale thrusts in the boundary parts of the Kuznetsk Basin (Markov et al., 2021; Murko et al., 2021). Discordant magmatic bodies are also present, complicating the mining of sedimentary coal-bearing rock strata (mainly south and centre of Kuzbass).

Results and Discussion

Let's consider a variant of sloping coal seam excavation when the excavator rotation axis lies in the plane of the longitudinal axis of the dump truck. It is assumed that the dump truck stands perpendicular to the bottom edge of the ledge, as shown in Figure 1.

At such positioning of the excavator, excavation of the coal seam can be carried out simultaneously by lower and upper scooping. The stripping block located below the level of excavator installation is shown in Figure 1 in red and above the level in green.

At the same time, the depth of digging H_{dig} below the level of excavator installation will be limited by:

- technical factors: the maximum unloading radius at which the excavated rock mass can be evenly distributed in the dump truck body, the dimensions of the dump truck, the trajectory of the excavator bucket teeth;
- technological factors: safe distance from the dump truck to the lower edge of the mining slope and its position relative to the excavator; safe distance from the body of the excavator to the slope of the upper excavated layer;
- geomechanical factors: stable and temporary slope angles of faces and ledges;
- geological factors: the angle of dip of the layer, its thickness.

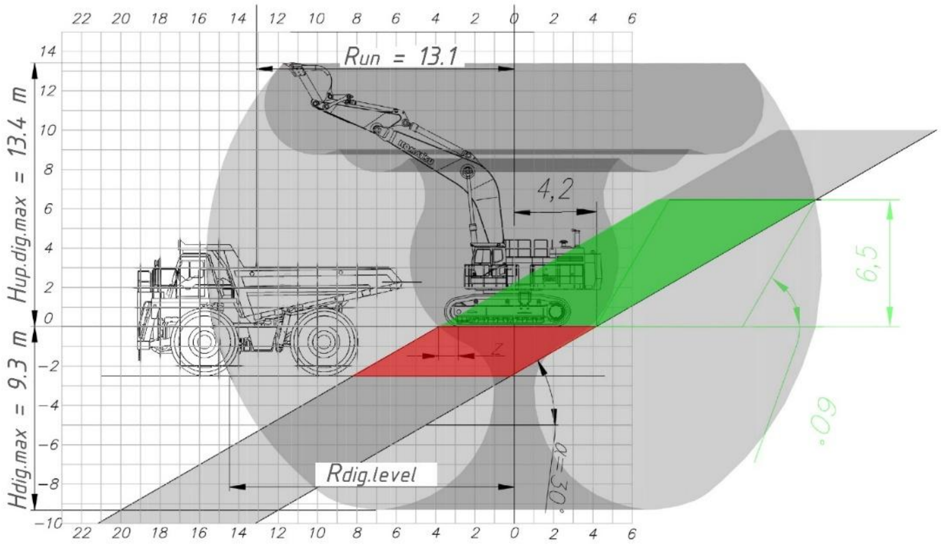


Fig. 1. Technological scheme profile of coal seam mining using a backhoe

Under these conditions, the depth of digging H_{dig}, in this case, takes the value of 2.5 m, the minimum radius of digging at the level of placement of the excavator is limited by the distance from the axis of rotation of the excavator and the bottom of the seam and is $R_{dig.level.min}$ = 4.2 m, the radius of unloading R_{un} = 13.1 m.

After mining the next block, the face is formed starting from the working site along the minimum radius of the digging and the plane limiting the face block from the side of the dump truck (limiting plane) at a stable slope angle of 60° (Figure 2).

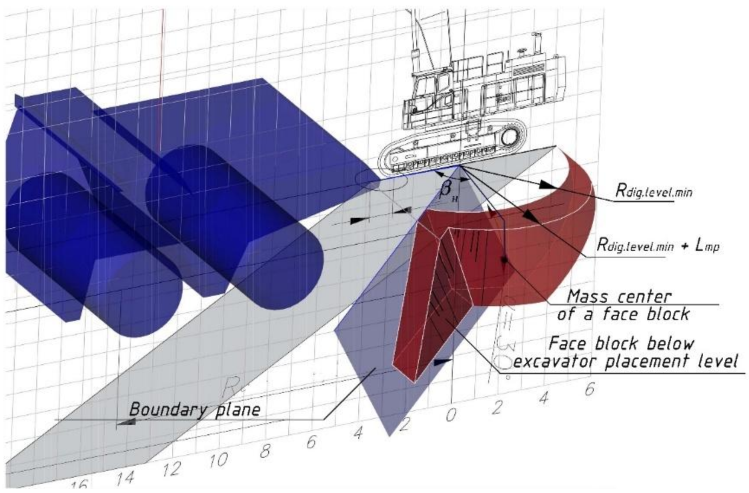


Fig. 2. Schematic to determine face block geometry below excavator placement level

The excavator moving pitch L_{mp} is regulated by the parameters of the face block located below the excavator placement level, namely the limiting plane. Its trace on the working site is the trace of the intersection of the vertical plane, in which the excavator arm can move at the bottom, digging at a safe distance from the dump truck body. The limiting plane is inclined away from the dump truck at the angle of stable slope of the coal bench (60°). The position of the limiting plane can be changed by shifting the longitudinal axis of the dump truck relative to the axis of rotation of the excavator "forward" in the direction of face movement.

As simulation results showed, the excavator's moving pitch cannot be more than 1.81 m. This is due to the condition of working out the lowest and farthest part of the face block from the place of positioning the excavator, which is located at the intersection point of the limiting plane, the dump truck placement site and the external trajectory of the bucket teeth. If the moving step is more than 1.81 m, the part of the seam in the surrounding area of this point will not be mined. The specified distance determines the maximum *engineering (technological) radius of digging* at the excavator placement level $R_{dig.level.max}$ and the volume of face block V_{fb} = 36.2 m³.

The maximum height of digging is limited by the trajectory of the bucket teeth, the temporary angle of slope on the coal seam and the position of the bottom of the excavated seam relative to the axis of rotation of the excavator and is $H_{dig.up}$ = 6.5 m (Figure 1).

The minimal possible technological minimum radius of the digging at the excavator placement level $R_{dig.level.min}$ when excavating the upper block is determined by:

- trajectory of the bucket teeth position;
- the position of the roof and ground of the seam.

The excavated block above the excavator placement level, as noted above, along the strike of the seam is rigidly limited by the excavator moving pitch L_{mp} = 1.81 m, which determines its volume.

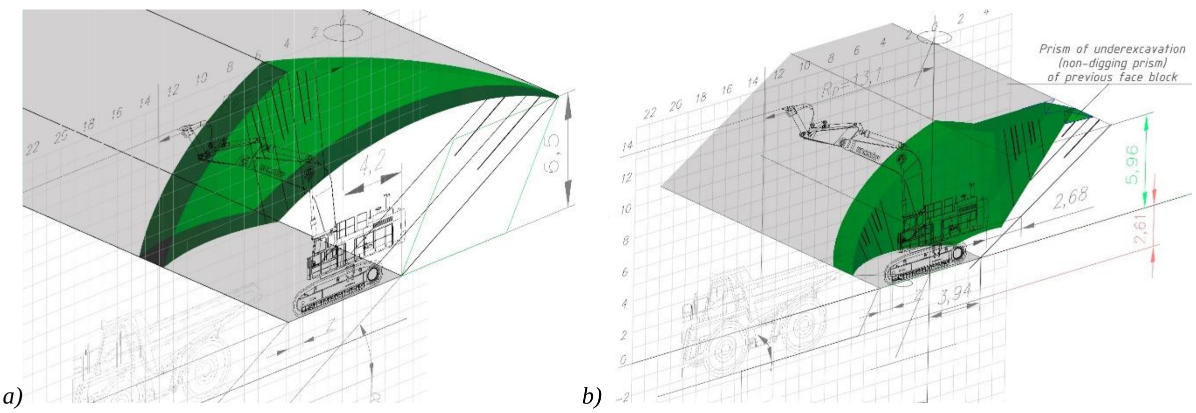
Considering these limitations, the configuration of the face block above the excavator placement level is shown in Figure 3.

The results of modelling showed that when changing (increasing) the minimum radius of the digging at the excavator placement level, the position of the centre of mass of the bottom digging block changes and the angle of rotation of the excavator on unloading increases, i.e. the parameters that determine the productivity of the excavator. Thus, at an increase of the minimum radius of the digging at the excavator placement level from the minimum value of 4.2 m to the maximum value of 6.7 m, the excavator's rotation angle for unloading β_n at the excavation of the bottom face block increases by 4.4° (Figure 4). This change is well approximated by the expression:

$$\beta_n = -0.081R^2_{dig.level.min} + 2.64R_{dig.level.min} + 61.664 \qquad (1)$$

or a simpler expression:

$$\beta_n = 1.7575R_{dig.level.min} + 64.01 \qquad (2)$$



a) b)

Fig. 3. Geometry of face block above excavator placement level: a) at the maximum radius of the digging $R_{dig.level.max}$; b) at the minimum radius of the digging $R_{dig.level.min}$

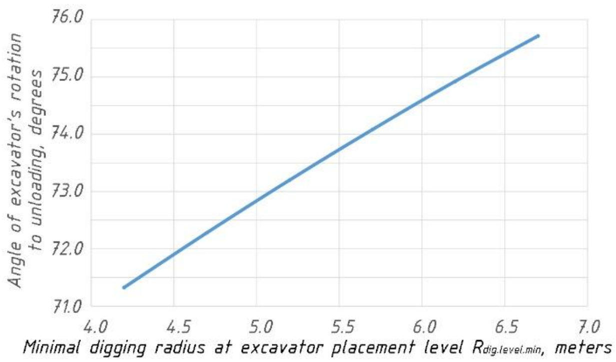
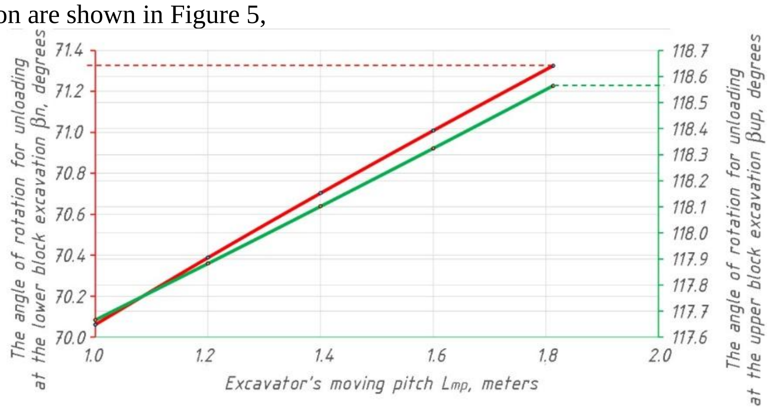


Fig. 4. Change of horizontal angle of excavator rotation βn between the direction from the axis of rotation of the excavator to the centre of mass of the lower face block and the direction to the point of unloading depending on $R_{dig.level.min}$.

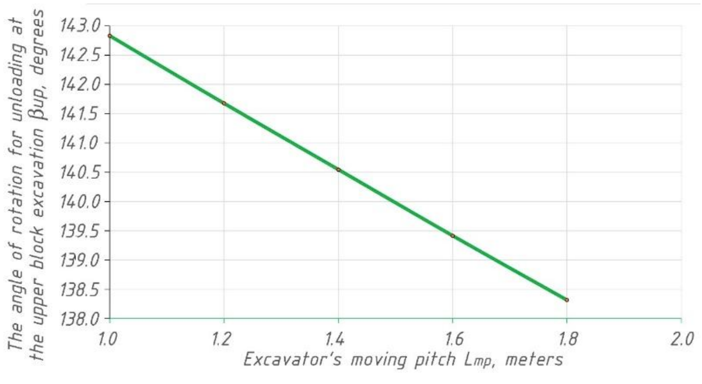
The volume of the face block below the excavator placement level V_{fb} at the step-by-step increase of the minimum digging radius at the excavator placement level $R_{dig.level.min}$ does not change at constant excavator moving pitch L_{mp} for excavation of each subsequent block.

Thus, in order to minimize the loss of time for dump truck loading by bottom digging and to save the productivity of the excavator-automobile complex, it is inexpedient to increase the minimum radius of the digging at the excavator placement level, as it does not affect the excavated volume of rock mass, but increases the angle of excavator rotation for unloading, which leads to increased loading time, loss of excavator productivity and increased idle time of dump truck.

At the change of excavator moving pitch, there is a change of horizontal rotation angles for unloading, namely, their rising at the increase of Lmp, which unfavourably affects the excavator cycle time and productivity. This is due to the change in the horizontal projection of the position of the centre of mass of the removed block in relation to the horizontal projections of the axis of rotation of the excavator and the point of unloading. The resulting plots of variation are shown in Figure 5,



a.)



b.)

Fig. 5. Change of excavator rotation angles for unloading when excavating face blocks from its moving pitch: a – upper digging block at the maximum value of digging radius $R_{dig.level.max}$; b – upper digging block at the minimum digging radius $R_{dig.level.min}$.

Since the excavation of the upper block is rigidly linked with the excavation of the lower block, it is not possible to change any parameters of the former except Rch.y min.

Consider the variant for the maximum value of $R_{dig.level}$ (Figure 3, a), equal to 10 m, and moving pitch of excavator L_{mp} = 1.81 m. The angle of rotation for unloading the upper block in such conditions is fixed in the value β_{up} = 119°. The angle of the slope of the face is unchanged and accepted by the conditions of stability 60°. The total maximum height of the excavated layer for these mining and geological conditions is $H_{dig} + H_{up.dig} = 2.5 + 6.5 = 9$ m.

The results of calculations have shown that the volume of the upper block in the considered case is $V_{fb.up}$ = 93.61 m³ that in sum with the lower block gives the total volume $V = V_{fb.up} + V_{fb.low} = 129.9 \approx 130$ m³ in the pillar. Considering the average coal loosening coefficient C_{loose} = 1.35, the total volume of excavated rock mass will be equal to 175 m³.

Based on the passport data of the considered dump truck BELAZ 75310, the capacity of its body "with a cap" 2:1 is 141 m³.

The performed calculations allow us to conclude that in the considered mining-geological and mining-technical conditions (angle of seam dip 30°, seam thickness 4 m, height of the lower excavated layer 2.5 m, height of the upper excavated layer 6.5 m, work mode at excavation of the upper layer – on the maximum value of the digging radius $R_{dig.level.max}$, bottom mode of loading, excavator Komatsu PC1250, moving pitch L_{mp} = 1,81 m) technology parameters do not allow the excavator to work with maximum productivity during excavation of each pair of face blocks, because the total excavated volume of rock mass exceeds the dump truck capacity by 24%. In such working conditions, after completion of excavation of the next face blocks (upper and lower) at the maximum possible step of excavator moving pitch Lmp = 1,81 m in face blocks, about 24% of unexcavated coal will remain. At the loading of the next dump truck, it will lead to the discrepancy of continuous work of the excavator in time: first, the volume of coal remaining in the face blocks will be worked out, and then the excavator will move to a new position, and only after that will finish loading of the dump truck, leaving in the next "batch" of face blocks already 48% of unworked volume. This mode of operation will lead to a sharp decrease in the productivity of both the excavator and the dump truck due to the increased technological downtime.

The question arises about the stabilization of excavator-automobile complex operation in the considered conditions, i.e. selection of such parameters of mining technology, at which the volume of excavated without downtime and movements of rock mass (coal) will be a multiple of the whole number of dump truck body volumes.

At the same time, mining only by lower or only by upper digging is not considered due to the impossibility of loading dump truck with coal volume only from the upper or only from the lower block without moving the excavator along the axis of its stroke during dump truck loading.

The following may be subject to change under these conditions:

- the digging height of the lower block (digging depth $H_{dig.low}$);
- height of the upper block (digging height $H_{dig.up}$);
- excavator moving pitch L_{mp}.

Increasing the digging height H_{dig} by increasing the height of the bottom layer will lead to "pushing" the dump truck away from the excavator. In this case, ensuring the uniformity and completeness of the dump truck body's loading with rock mass will be impossible. It is also impossible to increase the digging height H_{dig} because, in this case, a "blinder" or prism of non-digging will be formed in the upper part of the face, which is unacceptable under the conditions of safe mining operations or under the condition of compliance with the standard of mineral losses. It is also impossible to increase the moving pitch, which was mentioned above.

Proceeding from this, the regulation of the parameters of the technological scheme is possible only in the direction of reducing excavated volumes of rock mass within the limits of its "surplus" of 24%.

Based on this, it can be argued that the most rational from the point of view of managing the stability of the considered excavator-automobile complex is to reduce the moving pitch when excavating coal from the seam by upper digging and lower digging to its full maximum possible thickness by the technical parameters of the excavator longitudinal stroke. Let's analyze this situation in detail.

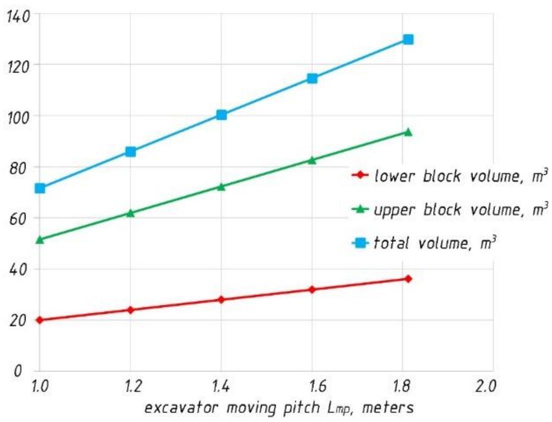


Fig. 6. Dependence of the volume of excavated rock mass on the moving pitch of the excavator when working at the maximum digging radius by excavating the upper and lower face blocks

When the moving pitch of the excavator decreases, the "thickness" of face blocks along the seam strike will inevitably decrease, and consequently, their volume will decrease. Figure 6 shows the change in the volume of coal removed from the upper and lower blocks when the moving pitch is changed from 1.81 m to 1.0 m.

The total excavated volume of rock mass (in the pillar) grows linearly with increasing moving pitch; this change is adequately described by the relationship:

$$V = 71.627 \cdot L_{mp} + 0.0201 \tag{3}$$

To find the required moving pitch in general case, it is necessary to consider the degree of loosening of the rock mass in the dump truck body. It will be different for different lithotypes of coal because the degree of crushing of coal and uniformity of its particle size distribution during excavation and loading depends on its strength, structural properties, and maceral composition. For this purpose, it is necessary to construct a surface of the form:

$$V = f(L_{mp}, C_{loose}), \tag{4}$$

where C_{loose} is the coefficient of loosening of the rock mass in the dump truck body.

The loosening factor C_{loose} will be different for coal, sediment and blasted rock. Field measurements have shown that the value of the rock loosening coefficient in the dump truck body C_{loose} varies within a wide enough range – from 1.1 for soft cohesive rocks with low moisture content to 1.5 and more for difficult-to-explode large-block rocks. For coals of the Kuznetsk coal basin, this coefficient, on average, takes values close to 1.35.

Figure 7 shows the surface describing the change in the volume of rock mass in the dump truck body depending on its loosening coefficient and the moving pitch of the excavator, based on the results of the analysis of the total volume of excavated face blocks, taking into account its loosening in the dump truck body.

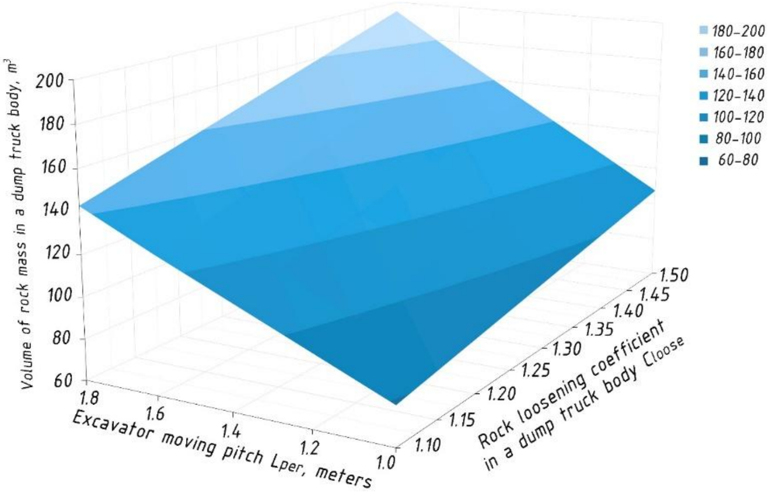


Fig. 7. Change of rock mass volume in the dump truck body depending on its loosening and moving pitch (when mining a face block at the maximum digging radius)

The surface shown in the figure can be roughly described by a plane equation of the form:

$$V = \frac{34 \cdot L_{mp} - 25.7 \cdot C_{loose}}{0.3} + 43.6 \text{ , m}^3. \tag{5}$$

This equation does not accurately describe the available surface (the deviation of calculated values of coal volume from the volume values presented in Figure 7 is 15-20%), so let us proceed to find the equation of the second-order surface approximating the obtained results. In the first approximation, the presented change in the volume of the rock mass is described by the surface equation:

$$V = A \cdot C_{loose}^2 + B \cdot C_{loose} \cdot L_{mp} + C \cdot L_{mp}^2 + D \cdot L_{mp} + E \cdot C_{loose} + F \text{ , m}^3, \tag{6}$$

where *A, B, C, D, E, and F* are the coefficients determining the shape of the approximating model surface.

The solution of equation (6) is reduced to the solution of a system of linear equations, after solving which and finding the desired coefficients, equation (6) takes the form:

$$V = -1.39 \cdot C_{loose}^2 + 71.63 \cdot C_{loose} \cdot L_{mp} + 0.38 \cdot L_{mp}^2 - 1.07 \cdot L_{mp} + 3.62 \cdot C_{loose} - 1.6 \text{ , m}^3. \quad (7)$$

Analysis of the invariants of this equation shows that it describes the surface of a hyperbolic paraboloid. The volumes calculated by formula (7) are shown in Table 1.

Tab. 1. Results of calculating the volume of mined loosened rock mass V depending on the moving pitch of excavator L_{mp} and loosening coefficient C_{loose} in the dump truck body.

		loosening coefficient C_{loose} in the dump truck body								
		1.10	1.15	1.20	1.25	1.30	1.35	1.40	1.45	1.50
moving pitch of excavator Lmp, [meters]	1.81	142.84	149.36	155.87	162.37	168.87	175.36	181.84	188.32	194.79
	1.60	126.04	131.79	137.54	143.28	149.02	154.74	160.46	166.18	171.88
	1.40	110.26	115.30	120.33	125.36	130.38	135.39	140.39	145.39	150.38
	1.20	94.52	98.84	103.16	107.47	111.77	116.07	120.35	124.63	128.91
	1.00	78.81	82.42	86.02	89.61	93.19	96.77	100.34	103.91	107.47

Note: the volume values are given when working with the maximum value of the digging radius when excavating the upper face block

To calculate the moving pitch, formula (7) can be modified by expressing L_{mp} through the other parameters:

$$L_{mp} = \frac{1.07 - 71.63 \cdot C_{loose} + \sqrt{5132.62 \cdot C_{loose}^2 - 159.04 \cdot C_{loose} + 1.53 \cdot V + 2.44}}{0.76}. \quad (8)$$

Using the proposed model, it is possible to estimate either the moving pitch of the excavator depending on the mined volume and coal loosening factor by formula (8) or to determine the mined volume at a given moving pitch and loosening factor by formula (7).

For example, for the considered platform based on BELAZ 75310 with the body loaded "with a cap" 2:1 with the volume of coal V = 141 m³ with the coefficient of its loosening in the body C_{loose} = 1,35, moving pitch in the considered mining-geological and mining-technical conditions it will be expedient to choose L_{mp} = 1,45 m under the condition of work on the maximum possible digging radius $R_{dig.level.max}$. Such value of moving pitch will provide rhythmicity and continuity of excavator operation, as in the time interval of excavator moving will be simultaneously exchanged dump truck.

Consider the work of the excavator at the minimum possible value of digging radius at the placement level $R_{dig.level.min} = 4.18 \approx 4.2$ m. This value is true for the considered mining-geological and mining-technical conditions: the thickness of the layer is 4 m, and its dip angle is 30º and is determined by the trajectory of the bucket teeth and the position of the axis of the excavator stroke relative to the bottom of the layer (Figure 1). The axis of the excavator stroke relative to the formation roof (this is the upper edge of the excavator installation site) remains at a constant minimum possible distance equal to the width of the possible collapse prism.

If, in such conditions, the geometry of the face block below the level of excavator placement does not change (Figure 2), the geometry of the face block above the level of excavator placement undergoes significant changes: a large volume (up to 1 m³) of non-digging prism is formed, which is completely taken away after excavator movement; a flat face block surface is formed across the strike of the seam (Figure 3, b). Due to the change in the position of the centre of mass of the upper block relative to the point of its unloading into the dump truck body, the angle of rotation of the excavator and the type of its change when changing the moving pitch – with increasing moving pitch it decreases (Figure 5, b), in contrast to the increasing angle of rotation when increasing the moving pitch when working at maximum $R_{dig.level.max}$.

The change in the volume of excavated rock mass depending on the moving pitch when working at the minimum possible values of $R_{dig.level.min}$ is presented in Figure 8.

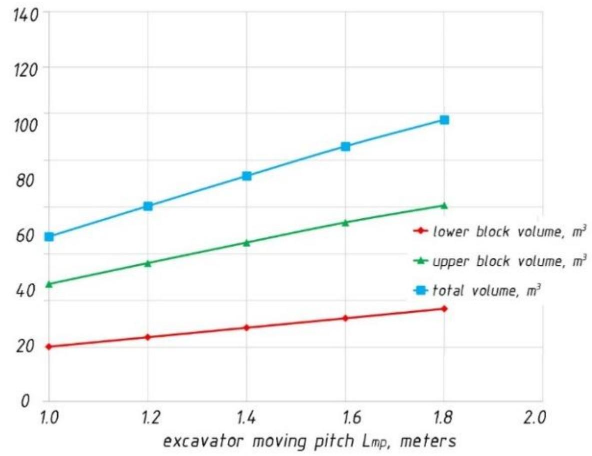


Fig. 8. Dependence of the volume of excavated rock mass on the moving pitch of the excavator when working at the minimum digging radius when excavating the upper and lower face blocks

The total change in the excavated volume is described by the expression:

$$V = 62.6 \cdot L_{mp} + 5.2 \text{, m}^3. \quad (9)$$

By analogy with the considered case of operation at the maximum digging radius, let us draw a surface in coordinates (C_{loose}, L_{mp}, V) for the minimum digging radius when excavating both upper and lower face blocks (Figure 9).

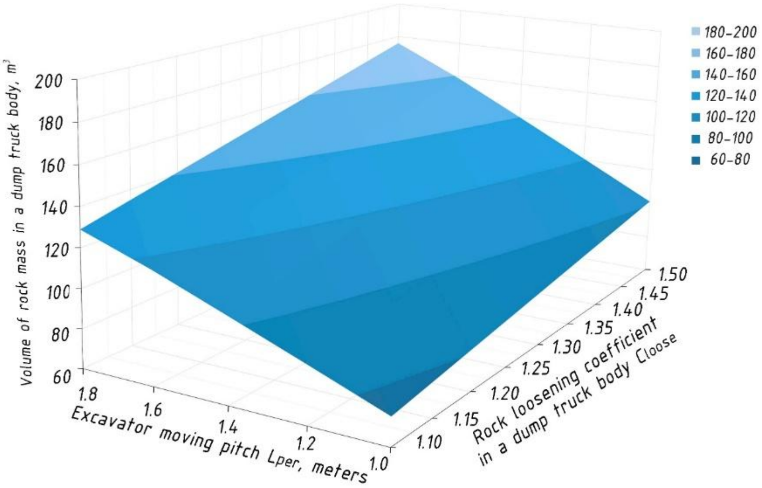


Fig. 9. Change of rock mass volume in the dump truck body depending on its loosening and moving pitch (when mining a face block at the minimum digging radius)

Similarly to equation (7) we obtain the equation of the surface shown in Figure 9:

$$V = 81.47 \cdot C_{loose}^2 + 62.31 \cdot C_{loose} \cdot L_{mp} - 31.72 \cdot L_{mp}^2 + 88.82 \cdot L_{mp} - 206.75 \cdot C_{loose} + 77.33 \text{,m}^3. \quad (10)$$

The volumes calculated by formula (7) are shown in Table 2.

Tab. 2. Results of calculating the volume of mined loosened rock mass V when working with the minimum possible digging radius

		loosening coefficient C_{loose} in the dump truck body								
		1.10	1.15	1.20	1.25	1.30	1.35	1.40	1.45	1.50
moving pitch of excavator L_{mp}, [meters]	1.81	128.95	133.39	138.23	143.48	149.14	155.21	161.68	168.56	175.85
	1.60	119.05	122.87	127.09	131.71	136.75	142.19	148.04	154.30	160.96
	1.40	106.61	109.80	113.40	117.41	121.82	126.64	131.86	137.50	143.54
	1.20	91.64	94.20	97.18	100.56	104.35	108.54	113.15	118.16	123.58
	1.00	74.12	76.07	78.42	81.18	84.34	87.91	91.89	96.28	101.08

Analysis of the results of calculating the volumes of loosened rock mass using the proposed models shows their deviation in the range of ±0.06% for model (7) and ±3.9% for model (10) with respect to the results obtained using the geometry of face blocks and technology parameters (Figures 7 and 9, respectively). This allows us to judge the adequacy of the proposed mathematical models and methods of their construction.

To calculate the moving pitch, we can modify the formula (10) by expressing L_{mp} through the other parameters:

$$L_{mp} = \frac{-62.3 \cdot C_{loose} - 88.8 + \sqrt{14220.8 \cdot C_{loose}^2 - 15164.95 \cdot C_{loose} - 126.883 \cdot V + 17700.7}}{-63.4}, \text{ m.} \quad (11)$$

If when working at the maximum possible value of $R_{dig.level.max}$ prisms of under extraction at the bottom of the seam in the upper block are practically not formed (their volume is within 0.005-0.02 m³) and they can be neglected, then when reducing the digging radius, their volume begins to increase to 0.5 m³ and more. Since the increase in losses of mineral resources due to the imperfection of the applied technological schemes is inadmissible, the rational reduction of the top layer height by 0.5-1 m (depending on the geometry of the formed slope of the face and the formed prisms of under extraction) will allow selecting these prisms after the next movement of the excavator (Figure 3, b), which will lead to the complete elimination of losses without changing the productivity of the excavator-automobile complex.

Simultaneously with an insignificant (up to 10%) reduction of the bench height, there is a displacement of the upper face block to the excavator with a reduction of its volume at comparable values of the excavator movement at its operation at the maximum digging radius. A decrease in the volume of the upper face block with a decrease in the height of the top layer and value of $R_{dig.level.min}$ should be compensated by an increase in the moving pitch of the excavator, which will inevitably lead to an increase in the volume of the lower face block.

Since the speed of the excavator moving is within the range of 2.1-3.2 km/h, the time spent on moving to L_{mp} = 1.5 m (about 2 seconds) is incomparably small with the time of dump truck exchange (30-50 seconds). Thus, mining the top layer with a small value of $R_{dig.level.min}$ is much more favourable in terms of excavator productivity than its mining with increased values of $R_{dig.level.min}$.

The productivity of the excavator affects not only the angle of rotation but also the distance of movement of rock mass from the face to the point of unloading – the smaller this distance, the shorter the cycle time of the excavator.

Taking as the point of unloading the highest point of rock in the body of the loaded "with a cap" 2:1 dump truck, we will see that the distance between the centre of mass of the upper face block and the point of unloading when moving the rock mass from the upper block at the maximum value of $R_{dig.level}$ = 9.9 m, and moving pitch 1.8 m is 19.6 m, and at the minimum value of $R_{dig.level}$ = 6 m, it is 16.6 m (a decrease of 16%). The increase in the angle of rotation when working with the minimum value of $R_{dig.level}$ is 14% (138º at $R_{dig.level.min}$ = 6 m; 119º at $R_{dig.level.max}$ = 9.9 m).

Also, the performance of the excavator can indirectly affect the distance from the face to the attachment elements of the handle, boom, central trunnion, support roller wheel and hydraulic cylinders – the greater it is, the greater the forces and moments of forces in the elements of these units arising during the digging operation, and hence the wear of friction pairs. A higher wear rate will inevitably lead to shorter repair intervals and increase the number of repair downtimes.

Conclusions

1. The volume of the face block below the level of excavator placement $V_{fb.low}$, moving pitch of excavator for extraction of each subsequent block L_{mp} when increasing the minimum digging radius at the level of excavator placement $R_{dig.level.min}$ do not change.

2. Dependence of the excavator rotation angle on the minimum digging radius when excavating a face block by bottom digging in the described mining-geological and mining-technical conditions is described by the expression $\beta_n = 1.76 R_{dig.level.min} + 64.01$, taking values in the range of 68-74°.

3. In order to maintain the productivity of the excavator-automobile complex, it is inexpedient to increase the minimum digging radius at the level of excavator positioning, as it does not affect the excavated volume of rock mass from the bottom face block but increases the angle of excavator rotation for unloading, which leads to increased idle time of dump truck under loading and loss of excavator productivity.

4. The excavator rotation angle at face block extraction above the level of excavator placement when working with maximum digging radius increases from 116° to 119° and falls from 143° to 138° when moving pitch increases from 1.0 to 1.8 m in the described mining-geological and mining-technical conditions.

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