Estimation of Hydraulic Backhoes Productivity for Overburden Removing at Kuzbass Open Pits

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In a recent decade in the countries which increased the volume of solid mineral resource production the vector of mining equipment upgrading for overburden and resource extracting operations was directed towards the replacement of depreciated shovels with more productive and flexible in operation hydraulic excavators. Their mass introduction at coal open pit mines of Russia, China, Australia and Canada is expected to increase the efficiency of excavation and loading operations and reduce the total cost of rock mass extracting. This can be achieved by reducing coal losses during mining operations and faster loading the volume of the blasted rock mass when the best configuration of excavator's face and dump track positioning is provided. The key parameter of selection of hydraulic backhoe model and optimising the technological schemes of its application, along with mining and geological conditions, is the backhoe's performance. For calculating the performance of the hydraulic backhoe the parameterisation of technological schemes of excavator using has the particular importance for mining and overburden removing works. In particular, it is necessary to determine the minimum duration of a single face block mining during a single pass of the excavator, and the height of processed layer in order to achieve maximum efficiency of the hydraulic backhoe. This article describes the method of determining the effective productivity of hydraulic excavator when developing face unit in a single pass, depending on the layer's thickness and loading dump truck position respectively to the level of excavator's installation.

Keywords: *hydraulic backhoe, open-pit mining, effective productivity, thickness of the layer*

Introduction

At present, hydraulic excavators take an important place in the range of extracting and loading equipment for coal open pit mines (Tyulenev et al., 2017). Replacing traditional rope shovels, hydraulic excavators impose new requirements on another open pit mining processes like drilling and blasting, transporting the rock mass (Hrehova et al., 2012). Using mobile and productive hydraulic backhoes can also improve the fullness of coal extraction from the seam. That favourably influences on the extraction of whole estimated deposit within the quarry field (Cehlár et al., 2017).

Despite rope shovels and draglines have been known as high-productive open pit mining equipment (Alabuzhev et al., 1966; Matushenko, 1975; Demirel et al., 2009; Molotilov et al., 2009; Demirel, 2011; Hummel, 2012; Mattis et al., 2012; Prakash et al., 2013). In general, this is due to both the flexibility of their application and the ability to modify the technical schemes of overburden removing and coal mining operations, and a large assortment of hydraulic excavators in the quarry equipment market. Among the manufacturers of quarry hydraulic shovels, such companies as Komatsu, Hitachi (Japan), Terex (USA), Liebherr (Germany) are leading. For the years 2005-2012 the distribution of mining excavators' sales in the world market among the largest manufacturers showed: Hitachi - 38.3 %, Terex - 21.8 %, Liebherr - 15.3 %, Komatsu - 15.1 %, Caterpillar - 9.5 % (Tyulenev et al., 2016). The presence of several large suppliers in the world market of hydraulic excavators has led to the situation that the invariance of parameters directly influencing the performance of hydraulic excavators is quite high due to the wide range of their models offered by several large manufacturers and the spread of their operating parameters. Therefore, the choice of a specific hydraulic excavator for given mining-and-geological conditions must be accompanied, on the one hand, by an assessment of excavator's effective productivity, and on the other hand – by an analysis of the parameters determining this productivity.

The main design advantage which determines the high efficiency of hydraulic excavators in comparison with mechanical shovels is the presence of a volumetric hydraulic drive (Bhaveshkumar, 2013). This makes it possible to apply more compact schemes of working equipment, add additional degrees of freedom to bucket motion, which is especially in demand for selective excavation. All this together leads to a reduction in the total mass of the hydraulic excavator in comparison with the mechanical shovels and a decrease in pressure on the ground. At the same time, working equipment of hydraulic excavators is produced in two versions – "shovel" and "backhoe", which also extends their technological capabilities.

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State of the Problem

In Russian mining industry, the modernisation of quarry excavators' park began with a delay of 20-25 years from technologically advanced countries, mainly in the form of replacing worn out obsolete ECG excavators (rope shovels) at operating and under construction coal open pits. As an alternative to old rope excavators, coal companies have been importing hydraulic excavators with a working weight up to 500 tons or more. At the present time, some hydraulic backhoes exploitation experience has been gained in various coal-mining regions of Russia, including the largest of them – Kuzbass (Oparin et al., 2012).

Since 2001, hydraulic backhoes of relatively small unit capacity (with a bucket of up to 4 cubic meters) have been working, for example, at the open pit mines of coal company JSC "Kuzbass Razrez Ugol" ("Open Pit Coal Mining of Kuzbass", the second largest coal mining company in Russia). The use of hydraulic backhoes in difficult geological conditions makes it possible to reduce coal losses and reduce its dilution due to selective excavation. This also makes it possible to extract coal from thin seams that are inaccessible for shovels (named ECG in Russian, which means "quarry excavators on caterpillars") by hydraulic backhoes, mainly due to more complex bucket trajectory.

The renewal of the excavator park of JSC “Kuzbass Razrez Ugol” company became a part of a long-term program for large coal-mining enterprises modernisation, mainly to improve equipment productivity, the efficiency of extracting-and-loading operations and coal losses reduction. Moreover, with the increase in coal production and the expansion of overburden removing, the issue of switching to a new autonomous excavation equipment of a large unit capacity becomes particularly urgent, what is proved by the history of open pit mining developing (Lokhanov et al., 1967; Scott et al., 2010). This led to the expansion of hydraulic excavators (mainly backhoes), not only for mining but also overburden removing operations (Fig. 1) (Agafonov et al., 2017; Zhironkin et al., 2017; Kapitskaya et al., 2017).

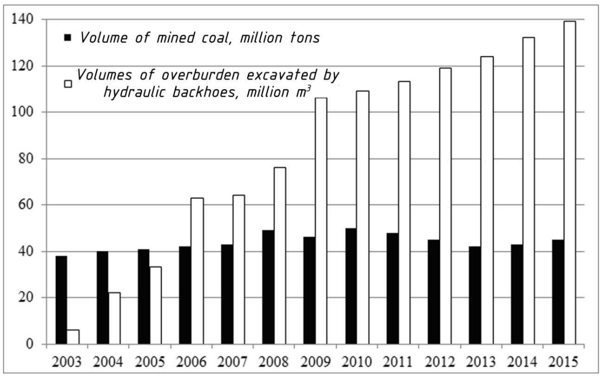

Fig. 1. The dynamics of coal mining and overburden removing carried out by hydraulic excavators at the enterprises of JSC “Kuzbass Razrez Ugol” company.

As it follows from Fig. 1, modernisation of the excavators' park and subsequent increase in coal production at the open pits of the largest coal holding company in Kuzbass led to the active use of hydraulic excavators in overburden removing. As a result of 13 years - from 2003 to 2015 - the volumes of overburden excavated by hydraulic excavators increased in 23 times - from 6 to 139 million m^3.

For example, the overburden removing complex launched in 2008 at Taldinsky coal open pit mine includes hydraulic excavator Hitachi EX-3600 (backhoe) with a bucket capacity of 20 m^3, wheel bulldozer CAT-834 and caterpillar bulldozer CAT D-10, dump truck BelAZ 7536 with a capacity of 220 tons, a heavy grader CAT 24M and drilling machine Ingersoll-Rand DML-1200. The hydraulic backhoe Hitachi EX-3600 productivity reached 18,000 m^3 per day.

Used methods

From a technological point of view, as a relatively new type of extracting-and-loading equipment, hydraulic backhoes require adaptation for Kuzbass coal open pit mines conditions, mainly for the process of justifying rational technological parameters of excavator-dump truck complexes.

In particular, it is necessary to determine the volumes and duration of mining the face block as the main components in calculating the effective productivity of each model of the hydraulic backhoe and to justify the rational height of excavated layer.

The volume of the face block (rock extracted from the face of one excavator's move) depends on the following parameters: the step of the excavator's moving (a, m), the maximum value of digging radius at the level of excavated layer’s bottom (R_d, m) and the height of excavated layer (h_l). In turn, the value of maximum step of backhoe’s shifting (a_{max}, m) depends on the calculated height of excavated layer, the distance from the upper edge of the layer to the tracks of the hydraulic excavator, and the temporal stability angle of excavating face in the process of working the layer (Fig. 2).

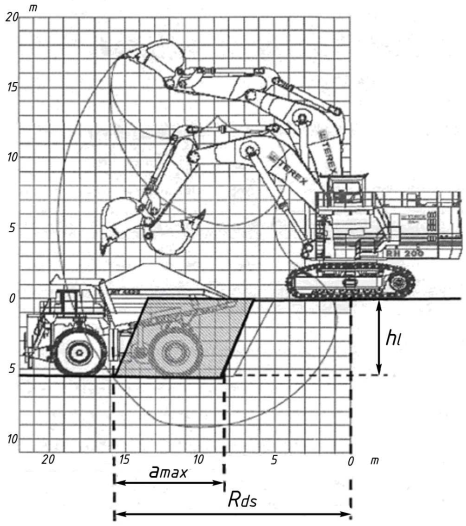

Fig. 2. The relationship between the parameters of the face of hydraulic backhoe in mining the rock layer

The study carried out at Open Pit Mining Department of T.F. Gorbachev Kuzbass State Technical University (Kemerovo, Russian Federation) and National Research Tomsk Polytechnic University (Tomsk, Russian Federation) allowed approximating the maximum step of the backhoe's shifting expressed in the following way (1):

$$a_{\max} = R_d - 1.4 \times h_i - 3 \tag{1}$$

R_d - digging radius of the excavator at the level of excavated layer's bottom [m];

h_l – the height of excavated layer [m].

The calculations showed that the values of the step of backhoe's shifting, obtained using formula (1), as a result of approximation, have high reliability (0.95-0.98 for hydraulic backhoes Liebherr-984C, 994, Terex RH-200 and layer thickness: $2 < h_l < 8$). We explain it by the fact that the trajectory of the backhoe bucket's movement was determined in accordance with strict mathematical laws, approximated with a sufficiently high accuracy.

Chronometric observations over the operation of hydraulic excavators at open pits of JSC "Kuzbass Razrez Ugol" showed that the actual value of shifting a is always less than the calculated value a_{max}. If they equalise, in this case, the approach of dump trucks for loading will be hampered by scattered rock pieces from the face that the excavator will not be able to clean. The actual distance of backhoe's shifting is (0.5-0.75) a_{max}, so for the following calculations we take:

$$a = c \times (R_d - 1.4 h_l - 3) \tag{2}$$

where: c_1 – correction coefficient (0.5–0.75).

Approximation of the dependence of maximum digging radius of the backhoe at the level of dump truck installation (the bottom of the layer) from the layer's height allowed drawing the following formula (3):

$$R_d = R_{ds} - 0.84 \times h_l + 2 \tag{3}$$

where: R_{ds} is the digging radius at the standing level [m].

It should be noted that the term "digging at the level of standing" is in a certain sense conventional, since the rock mass scooping by backhoe's bucket comes from the catch pit, into which the blasted rock mass falls under stability angle. Such a catch pit is necessary for filling the bucket more fully, so it moves along with the excavator.

The width of the backhoe pass (A_P) was accepted according to the classic recommendations:

$$A_p = 1.5 \times R_{ds} \tag{4}$$

Consequently, the volume of the rock mass loaded by the hydraulic excavator within the limits of one step of the shifting V_{pass}, m^3 is expediently defined as follows (calculated on the dense state):

$$V_{pass} = \frac{c \times 1.5\left(R_{ds} - 1.4 \times h_l - 3\right) \times \left(R_{ds} - 0.84 \times h_l + 2\right) \times h_l}{K_f} \tag{5}$$

where: K_f – the degree of fragmentation of rock in the backhoe's bucket.

The time of working the face block by the backhoe with the loading of rock into a dump truck located in one step of shifting from the excavator (T_{bl}) includes the excavation time itself, the total time spent on face cleanup, waiting for the dump truck and the backhoe movement (6).

$$T_{bl} = \frac{V_{pass}}{K_e \times E} \times \left(K_b \frac{60}{t_c} \right) + T_{wait} + T_{face} + T_{pass} \tag{6}$$

where: T_{bl} – time of block excavation [min];
E - geometric capacity of the backhoe's bucket, m^3;
K_e - coefficient of excavation;
K_b – degree of bucket filling;
t_c – time of excavation cycle [seconds];
T_{wait} - waiting time for the dump truck [minutes];
T_{face} - time of face cleanup [minutes];
T_{pass} - time of backhoe shifting [minutes].

Results and discussion

The calculation of working time of the excavator within a single move with a different layer's height is summarised in Tab. 1.

Tab. 1. The operating time of hydraulic backhoe within the limits of one shifting step for different values of layer's height to be worked [minutes].

Layer's height (h_l) [m]	**Model of hydraulic backhoe**		
	Liebherr-984C	**Liebherr-994**	**Terex RH-200**
With truck loading lower than the excavator is positioned			
2.0	51.5	44.7	40.1
2.5	55.2	49.0	44.4
3.0	56.5	51.6	47.4
3.5	56.1	52.7	49.2
4.0	55.9	52.5	50.0
4.5	54.0	52.9	49.9
5.0	50.5	52.5	50.3
5.5	45.4	51.1	50.5
6.0	38.8	48.7	49.9
6.5	30.9	45.2	48.6
7.0	21.8	40.9	46.6
With truck loading lower than the excavator is positioned			
2.0	65.9	56.8	50.2
2.5	72.0	63.1	56.4
3.0	77.3	67.5	61.0
3.5	79.9	71.6	64.2
4.0	79.9	74.5	67.4
4.5	77.4	75.7	70.0
5.0	72.5	75.4	71.5
5.5	65.1	73.4	71.8
6.0	55.4	69.9	71.1
6.5	43.6	64.9	69.2
7.0	29.8	58.4	66.3

The data from Tab. 1 indicate that the operating time of the hydraulic excavators of considered models will be the largest for the layer's height of 3.0-4.0 m (upper loading) and the height of 3.5-5.5 m (lower loading) within the same shifting of the backhoe.

The volume of rock mass per one shifting move of the excavator (5) and the time of its development (6) allow determining backhoe's effective productivity taking into account the auxiliary operations (Q_{ef}). The effective productivity of a hydraulic backhoe for the face block working can be achieved when the condition of rational quality of the rock mass explosive preparation is fulfilled taking into account the influence of the rate of bucket filling and the duration of this process. In general, the effective productivity of the excavator (hydraulic backhoe) can be calculated by the following formula (7)

$$Q_{ef} = \frac{60V_{pass}}{T_{bl}} \tag{7}$$

where: Q_{ef} - backhoe's effective productivity [m_3 / hour].

The data used for simulation calculations are presented in Tab. 2.

Tab. 2. The initial data for calculation backhoe effective productivity.

Parameters	**Initial Data (lower /upper dump trick's position)**	**Data range**	
		min	**max**
Angle of backhoe turn [degrees]	30/90	10	180
Height of the dump truck [m]	3	2	7
Time of face cleanup [min]	7	2	15
Time of dump truck waiting [minutes]	0.5	0	2
Backhoe shifting speed [km/h]	2	0.5	4
Degree of rock fragmentation in the shotpile	1.30	1.1	1.4
Degree of rock fragmentation in the bucket	1.5	1.1	1.5
Degree of bucket filling	0.9	0.5	1.2

The calculations of effective productivity of a number of hydraulic backhoes being used at Kuzbass open pit mines for different values of working layer's height are shown in Fig. 3.

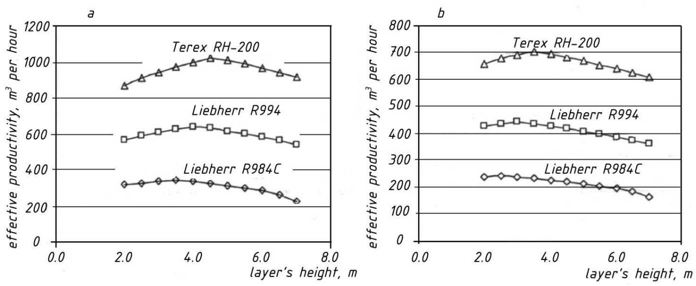

Fig. 3. The dependence of hydraulic backhoe effective productivity for various ways of dump truck loading: (a) for the installation of a dump truck below the level of backhoe's position, (b) upper the level of backhoe's position.

Conducted multivariate simulation calculations of the effective excavator productivity showed that its maximum is achieved with a layer's height 3.0-5.0 m and 2.5-4.0 m, respectively when dump trucks are installed lower the excavator's position. Calculation of the excavation cycle is based on timekeeping observations that are approximated with a sufficiently high degree of reliability (at least 0.9). Thus, for applying in practice of excavation and loading operations at open coal pits using hydraulic excavators, we recommend the values of the rational excavating layer's height, presented in Tab. 3.

Tab. 3. The rational values of excavated layer's height, corresponding to the maximum effective productivity of the backhoe.

Ways of dump truck positioning	**Liebherr 984C**	**Liebherr 994**	**Terex RH-200**
Lower than the backhoe [m]	3.0–3.5	4.0–4.5	4.5–5.0
Upper than the backhoe [m]	2.0–2.5	3.0–3.5	3.5–4.0

The results of data analysis for multivariate simulation calculations of effective productivity of hydraulic excavator dependence on the layer's height were approximated by the expression for its average value (8):

$$\bar{h}_l = 5.3 \times \left[\exp\left(-\frac{R_{ds}}{13,5}\right)\right]^{3,5} \tag{8}$$

Application of formula (8) to determine the average value of the layer's height requires schematization of installation for each model of the excavator, similar to that shown in Fig. 2. It was found that when layering the rock shotpile, the maximum productivity of hydraulic backhoes is achieved with a layer's height equal to 0.5 of maximum digging depth for a lower dump truck installation and 0.4 maximum digging depth for the installation of a dump truck at the level of excavator's position.

This is confirmed by the distribution of volumes of rock mass excavated in one step of excavator's shifting, depending on the layer's height.

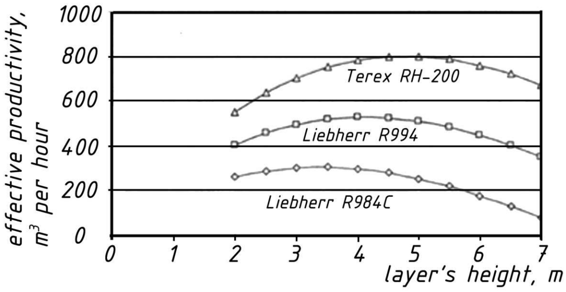

Fig. 4. The dependence of volumes of rock mass excavated in one step of the backhoe shifting, on the layer's height.

As it follows from Fig. 4, the maximum value of the excavated rock volume (780 m^3 for Terex RH-200, 560 m^3 for Liebherr-994 and 310 m^3 for Liebherr -984 C) corresponds to the height of the layer in 3.5-5.0 m, which actually lies within 0.4-0.5 of the maximum digging depth of these backhoes.

Conclusion

The volume of the face block has its maximum value depending on the height of the layer of overburden rock or coal being excavated by the backhoe. The layer's height corresponding to the maximum volume of the face block does not depend on the actual backhoe's shifting step. The maximum effective productivity of the hydraulic backhoes can be achieved with a working layer's height equal to 0.5 of the digging depth with a lower dump truck setting and 0.4 depth of digging with the dump truck installed at the level of the excavator's position on the bench.

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