карьера, может использоваться инженерами-проектировщиками уже на стадии проектирования для определения оптимального варианта режима горных работ и производительности карьера по руде с учетом их взаимосвязи. На примере Анновского карьера ПАО „СевГОК“ доказана возможность сравнительной оценки режима горных работ и производительности карьера по предложенному технологическому критерию.

Ключевые слова: *карьер, режим горных работ, производительность карьеров, критерий оценки*

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STATISTICAL RESEARCH OF SHOVEL EXCAVATOR PERFORMANCE DURING LOADING OF ROCK MASS OF DIFFERENT CRUSHING QUALITY

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СТАТИСТИЧНІ ДОСЛІДЖЕННЯ ПРОДУКТИВНОСТІ ОДНОКОВШЕВИХ ЕКСКАВАТОРІВ ПРИ НАГРУЖЕННІ ГІРНИЧОЇ МАСИ РІЗНОЇ ЯКОСТІ ДРОБЛЕННЯ

Purpose. Applying technical means to control excavator performance and quality of rock crushing by explosion. Establishing the dependence of time consumption required for rock mass excavation on its particle size distribution and mathematical description of this dependence as a function of two variables.

Methodology. The methodological basis to solve the problem is a comprehensive approach including research by means of IGS-5M devices, applying mathematical statistics methods and analysing the results in the mathematical package.

Findings. The possibility to maintain operational control of the time consumption required for rock mass excavation and direct measurement of its particle size distribution at the same time has been implemented. The concept of cycle rate has been introduced and its dependence on the mean diameter of the piece has been determined. The empirical formula to determine excavator technical performance as a function of two variables that uniquely characterize the quality of rock mass fragmentation has been obtained.

Originality. For the first time in the practice of mining the hardware specifically designed for operational control of excavators and crushing of rocks by explosion has been used (IGS-5M devices is in the invention stage). A two-parameter distribution function of the rock mass particle size distribution was proposed where one parameter is the size of the dominant fraction, the other one is the fraction in the test volume of blasted rock. The formula to determine excavator technical performance as a function of specified parameters has been obtained.

Practical value. Applying specified devices while organizing and carrying out mining operations will allow using technically feasible solutions at the design stage of mass explosions. Using the formula to calculate excavator technical performance in specific conditions will help improve planning technological processes, especially the rational distribution of freight flows. In the long view, the above mentioned formula will be a critical part of the mathematical model while optimizing basic technological processes at the open pits.

Keywords: *open pit, excavator, performance, particle size distribution, rock mass*

Introduction. The priority trend to improve the extraction and processing of rock minerals by opencast mining is establishing and practically applying optimal methods to control the main industrial processes.

It is well-known that production costs required for performing the whole technological process greatly depend on the crushing quality of rocks developed by explosion, which is usually characterized by particle size distribution of obtained rock mass, i. e. by the content of individual cubs (fractions) in its volume. Intensive mineral crushing reduces the costs of loading and transport operations and mechanical crushing, but results in increasing costs of drilling and blasting operations (D&B). Conversely, decreasing D&B costs contributes to coarse crushing, and therefore increases the cost of the subsequent technological operations. Optimizing drilling, blasting, loading and transport operations and mechanical crushing provides such quality of the rock mass fragmentation that the total operations cost will be minimal. This implies that the process of choosing the best parameters to control D&B complex should be carried out by special algorithm based on solving a mathematical model dealing with the influence of particle size distribution of the rock mass on the technical and economic parameters of these processes. The dependence of the shovel excavator performance on the quality of the rock mass fragmentation is the model component, so its determination is an intermediate goal of the optimization process. The problem of searching the unambiguous function between these variables can be solved based on statistical processing of impersonal information continuously obtained within a certain period of time and dealing with the monitored value status, as well as applying a mathematical description of the actual rock mass lumpiness distribution in its volume being acceptable for analytic transformation and practical application.

Analysis of the recent research and publications. Searching optimal solutions to manage mining operations at the quarries is particularly relevant nowadays, as techno-economic calculation allows finding additional opportunities to increase profits. Work [1] points out that higher requirements specify a rock crushing quality implying the lumpiness meeting the terms of the efficient mining equipment usage. It was found that the distribution of the rock mass grain composition follows the law of log-normal distribution. This law is characterized by an average lump size and logarithmic variance. A correlation equation taking into account these characteristics has been obtained.

The results of studies dealing with the influence of rock mass crushing intensity on the technical and economic indicators of career and transport equipment are presented in [2]. Statistical analysis of the particle size distribution of blasted overburden blocks found that the probability density of the lump distribution follows the Weibull law. Practical recommendations of the most effective usage of the mining equipment in the overburden operations management in Kryvbas quarries are given.

Work [3] introduces an excavation ratio reflecting the impact of the rock mass lumpiness on the time consumption during the process of loading. It proposes the technique to forecast excavator-automobile complex performance and implementation of organizational and technical measures aimed at ensuring the effective operation of all mining equipment.

Unsolved aspects of the problem. As a rule, impersonal information obtained by applying techniques commonly used in mining industry, is used in the research works investigating the dependence of excavator performance on the quality of rock mass fragmentation. Following this methodology, determining rock mass particle size distribution is carried out by a photoplanimetric way where it is necessary to take a lot of pictures of surface collapse followed by computing the linear dimensions of the lumps and their distribution in the plane of each photo [2]. Chronometer observation of such excavator performance within a long period of time as loading more than 2,000 dump trucks is also carried out [1]. Such methods of research information support are laborious and not always reliable, and the issue of their improvement aimed at eliminating these disadvantages, has not been solved at the appropriate level yet.

Objectives of the article involve the following: practical application of technical means to provide efficient control of the excavator operation and direct measurement of the rock mass size distribution; statistical studies of obtained information and function definition to show unambiguous dependence of excavator performance on the quality of rock mass fragmentation. Estimation of the mean lump diameter used in these studies is carried out using the parameters characterizing the yield and the dominant fraction content in the rock mass volume.

Presentation of the main research. As we know, theoretical excavator performance corresponds to the full usage of its design capacity, $\frac{\text{m}^3}{\text{hour}}$

$$Q_T = \frac{3600 \cdot \vartheta_s}{t_{ct}}, \tag{1}$$

where ϑ_s is geometric volume of an excavator shovel trough m^3; t_{ct} is theoretical cycle time, sec.

Its value is determined by calculation, based on the excavator design data with the face height equal to the height of the pressure shaft location, with rotation angle of 90° and unloading rocks into the mine dump. The value Q_T is indicated in the passport of the excavator. Technical excavator performance is its maximum possibility in continuous operation in specific geological conditions, $\frac{\text{m}^3}{\text{hour}}$

$$Q = \frac{3600 \cdot \vartheta_s \cdot K_f}{t_c \cdot K_l}, \tag{2}$$

where t_c is actual cycle time depending mainly on the rock mass lumpiness, s; K_f is filling ratio of an excavator shovel trough; K_l is degree of rock fragmentation in the excavator shovel trough from (1) and (2) we obtain

$$Q = \frac{Q_T \cdot K_c \cdot K_f}{K_l}, \tag{3}$$

where $K_c = \frac{t_{ct}}{t_c}$. K_c is cycle ratio reflecting the influence of the rock mass fragmentation quality on the theoretical cycle time of a particular excavator, i.e. its dependence on the average lump diameter $K_c = K_c(d_m)$, thus $d_m = \frac{1}{\vartheta} \cdot \sum_{i=1}^{n} x_i \cdot y_i$, where x_i, y_i are respectively the linear dimension and output of the i-fraction; ϑ is the amount of the aggregate consideration (selective and general).

Research of time consumption dependence on rock mass excavation having varied lumpiness is performed using operational information obtained as a result of applying technical means of control.

Chronometer data of the cyclic operation of excavators are obtained using the spring type weight DVR-2 sensors mounted on the boom hoist winch rope. Fixing the changes of a rope strain from the load, the sensor continuously gave out information of each cycle of the rock mass excavation. Output signals after a direct current amplifier were fed to the recording device input. Typical waveforms of individual cycles, which are statistically different in their characteristics, are shown in Fig. 1. The use of objective control of excavator work on different blocks of rocks allowed determining their actual time consumption in each case accurately. In parallel with these observations the quality of the rock mass crushing was continuously monitored directly in the process of excavation.

For this purpose a device named IGS-5M (Fig. 2) created at the level of invention [4] and successfully tested on the EKG-4,6 and EKG-8I excavators was used.

The basis of the device lies in the dependence of the total energy consumption while digging the rock mass on its particle size distribution.

IGS-5M work is based on the time conversion of an input signal received at each excavation cycle. The pulse generated by the value and duration of the load, is registered in the count channel, which corresponds to a predetermined range of linear pieces dimensions that are in the rock mass collapse. Total five intervals are given: less

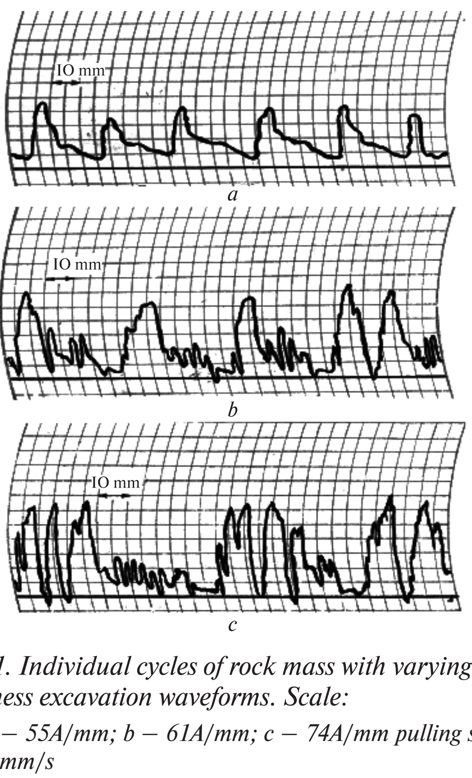

Fig. 1. Individual cycles of rock mass with varying lumpiness excavation waveforms. Scale:

a – 55A/mm; b – 61A/mm; c – 74A/mm pulling speed is 1 mm/s

Fig. 2. The IGS-5M device for rapid measurement of the rock mass particle size distribution

than 200 (200), 201–400 (400), 401–600 (600), 601–800 (800) more then 800 (1000) mm. Their designations are marked on the device front panel in parentheses. Each pulse is reflected on the display of the corresponding interval in the cumulative sum; therefore, the distribution of the impulse amounts along these intervals is the empirical distribution of the rock mass lumpiness in its controlled volume.

As a result of statistical processing of all information obtained within a long period of time, the quantitative ratio of cycle coefficient and average piece diameter has been found. Based on this, rock crushing by explosion is conveniently divided into three groups: small, medium and large (Table). From Table it is clear that the relationship $K_c(d_m)$ is not linear. There is a point of a curve inflection. The abscissa d_b, according to experimental data, is close by its significance to half of a sub-standard fractions ("oversized") diameter, and the ordinate is $(0.5–0.55)K_c$, that is $d_b = 0.5d_{sub}$ where d_{sub} is the amount of off-spec fractions and $d_{sub} = 0{,}8 \cdot \sqrt[3]{\vartheta_s}$.

In addition, this dependence follows theoretical restrictions: $K_c \to 0$ if $d_m \to \infty$ (rock mass consists of pieces exceeding the "outsized"); $K_c \to 1$ if $d_m \to 0$ (excavation of loose ground $t_c \approx t_{cl}$).

Imagine cycle coefficient K_c as an empirical function

$$K_c = \frac{a}{b + c \cdot e^{\left(\frac{d_m}{d_b}\right)^2}}, \quad (4)$$

where a, b, c are real numbers, and $a = b + c$ if $d_m = 0$.

The values of a, b, c can be defined by function investigation on the existence of inflection points

Table

Relations between the average diameter of the lump and the cycle ratio for each rocks group

Parameters / values	Rocks crushing		
	small	average	big
d_m (mm)	less than 400	400–600	more than 600
K_c	1.0–0.8	0.8–0.6	less than 0.6

$$d_m = d_b \frac{d^2\left(K_c\right)}{d\left(d_m\right)^2} =$$

$$= \frac{2a\cdot c\cdot e^{\left(\frac{d_m}{d_b}\right)^2}\cdot\left(b+2b\left(\frac{d_m}{d_b}\right)^2 + c\cdot e^{\left(\frac{d_m}{d_b}\right)^2} - 2c\left(\frac{d_m}{d_b}\right)^2\cdot e^{\left(\frac{d_m}{d_b}\right)^2}\right)}{d_b\cdot\left(b+c\cdot e^{\left(\frac{d_m}{d_b}\right)^2}\right)^3}.$$

Further

$$\begin{cases} b\cdot\left(1+2\left(\frac{d_m}{d_b}\right)^2\right) + c\cdot e^{\left(\frac{d_m}{d_b}\right)^2}\cdot\left(1-2\left(\frac{d_m}{d_b}\right)^2\right) = 0 \\ b+c\cdot e^{\left(\frac{d_m}{d_b}\right)^2} \neq 0, \quad d_b \neq 0 \end{cases}.$$

From whence

$$c = \frac{3b}{e}; \quad a = \frac{b\cdot(e+3)}{e}.$$

Taking into account the errors of less than 3 %, which is acceptable in the mathematical modelling of processes in the mining industry, we get

$$K_c = \frac{2}{1+e^{\left(\frac{d_m}{d_b}\right)^2}}. \tag{5}$$

For EKG-4,6 excavator

$$K_c = \frac{2}{1+e^{\left(\frac{d_m}{650}\right)^2}}.$$

This dependence is shown in Fig. 3.

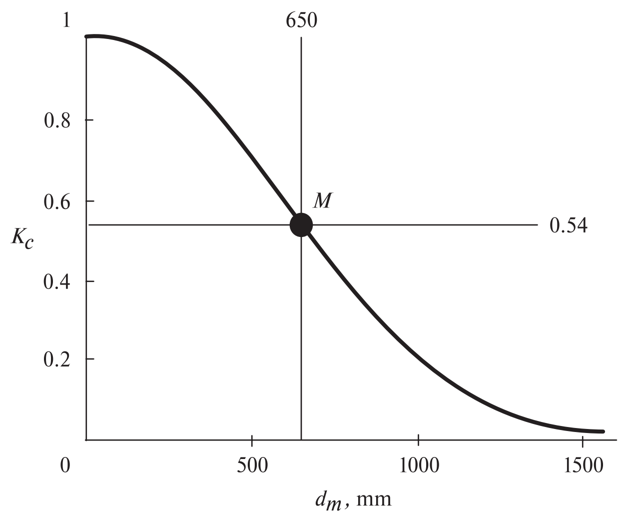

Fig. 3. Graph of cycle ratio (CR) depending on the mean diameter of the rock mass lumps (d_m). The point M (650; 0.54) is an inflection point

By analysing the curve shape shown in Fig. 3, we conclude that adopted function (4) corresponds to the specified conditions and restrictions and its values are close to the experimental data. Using only one of statistical distribution number characteristics (in this case the average diameter of the lump d_m), as it is known, does not give a complete understanding of this distribution, which explains the need to apply more representative assessment of rock mass crushing quality.

The function of rock mass particle size distribution, whose parameters correspond to only specific lump ratio in each of its volume, has been proposed. In addition, their definition in terms of production does not cause any difficulties, even with visual evaluation of mass explosion results

$$f(x) = \frac{e\cdot y_{\max}}{\Delta}\cdot\left(\frac{x}{x_{\max}}\right)^n\cdot e^{-\left(\frac{x}{x_{\max}}\right)^n}, \tag{6}$$

where $x_{\max}$, $y_{\max}$ are parameters, the size of the dominant fraction and its content in the rock mass volume (mode and the modal value of the function) respectively; x is the current size of fraction, mm; Δ is the interval between neighbouring values of the size fractions; n is a normalizing factor determined by the condition.

$$\frac{e\cdot y_{\max}}{\Delta\cdot\left(x_{\max}\right)^n}\cdot\int_0^\infty x^n\cdot e^{-\left(\frac{x}{x_{\max}}\right)^n}\cdot dx = 1.$$

Let us apply the well-known method of calculating improper integrals by using a gamma function, then

$$\frac{e\cdot y_{\max}\cdot x_{\max}}{\Delta\cdot n}\cdot\Gamma\left(\frac{n+1}{n}\right) = 1.$$

The average value of a random variable, according to the main provisions of the statistics, can be estimated by the expectation of this quantity. Consequently,

$$d_m(x_{\max}, y_{\max}) = \frac{e\cdot y_{\max}}{\Delta\cdot\left(x_{\max}\right)^n}\cdot\int_0^\infty x^{n+1}\cdot e^{-\left(\frac{x}{x_{\max}}\right)^n}\cdot dx, \tag{7}$$

where $d_m(x_{\max}, y_{\max})$ is the average diameter of a lump, depending on the distribution parameters. Using the gamma function, we get

$$d_m\left(x_{\max}, y_{\max}\right) = \frac{e\cdot y_{\max}\cdot\left(x_{\max}\right)^2}{\Delta\cdot n}\cdot\Gamma\left(\frac{n+2}{n}\right). \tag{8}$$

In view of this expression, a cycle ratio as a function of the distribution parameters is

$$K_c(x_{\max}, y_{\max}) = \frac{2}{1+e^{\left(\frac{d_m(x_{\max}, y_{\max})}{d_b}\right)^2}}. \tag{9}$$

Using formulas (3, 9), we obtain the formula to calculate shovel excavator technical performance while loading rock mass having varying lumpiness.

$$Q = \frac{2 \cdot Q_Ò \cdot K_f}{\left(1 + e^{\left(\frac{d_m(x_{\max}, y_{\max})}{d_b}\right)^2}\right) \cdot K_l}. \quad (10)$$

Validity check of the formula (10) dealing with the dependence reflection existing in the real world has been carried out for a large number of cases recorded for each group of rock crushing. To calculate and visualize the results the computer algebra system (MathCad 15) was used.

Based on a comparison of calculated and empirical data it was revealed that an average square deviation between them does not exceed 8 %. This confirms the reliability of applying formula (10) to assess and predict technical excavator performance.

Conclusions and recommendations for further research.

1. The device to provide continuous monitoring of the excavator performance and the IGS-5M device (Fig. 2) allow obtaining operational information about the rock mass size distribution and time consumption required for its excavation. The expediency of their practical application at the initial stage of mining operations optimization is explained by the ability to take more expert decisions while designing drilling and blasting operations.

2. A function of distributing grain size composition of rock mass (6) was proposed, whose parameters are the size and the dominant fraction content in its particular entirety. The evaluation of these parameters that are clear to any technologists does not cause any difficulties even during visual inspection of the mass explosion results.

3. The concept of a cycle ratio reflecting the influence degree of the rock mass crushing quality on the theoretical cycle time of a particular excavator has been introduced.

4. The empirical formula (10) to determine the dependence of excavator technical performance on the rock mass fragmentation quality has been obtained. The unambiguity of this formula is explained by the fact that rock mass quality is characterized not by an average lump diameter but by the size and predominant fraction content in the blasted rocks volume.

5. In the long view, the formula (10) will be used in the mathematical model while optimizing basic technological processes at the open pits. The volume of excavated rock mass can be determined previously using numerical simulation of controlled rock failure [5].

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Мета. Застосування технічних засобів оперативного контролю роботи екскаваторів і якості дроблення гірських порід вибухом. Встановлення залежності витрат часу на екскавацію гірської маси від її гранулометричного складу, математичний опис цієї залежності у вигляді функції двох змінних.

Методика. Методологічною основою вирішення поставленого завдання є комплексний підхід, що включає дослідження за допомогою пристрою ІГС-5М, використання методів математичної статистики, аналіз результатів у математичному пакеті.

Результати. Реалізована можливість ведення оперативного контролю витрат часу на екскавацію гірської маси одночасно з безпосереднім виміром її гранулометричного складу. Уведено поняття коефіцієнта циклу та встановлена його залежність від середнього діаметра шматка. Отримана емпірична формула для визначення технічної продуктивності екскаваторів у вигляді функції двох змінних, що однозначно характеризують якість дроблення гірської маси.

Наукова новизна. Уперше у практиці ведення гірських робіт застосовані технічні засоби, спеціально створені для оперативного контролю роботи екскаваторів і якості дроблення гірських порід вибухом (пристрій ІГС-5М на рівні винаходу). Запропонована двопараметрична функція розподілу гранулометричного складу гірської маси, у якій один параметр представляє розмір фракції, що переважає, другий – зміст фракції в досліджуваному обсязі підірваних порід. Отримана формула для визначення технічної продуктивності екскаваторів у вигляді функції зазначених параметрів.

Практична значимість. Використання представлених пристроїв при організації та веденні гірських робіт дозволить застосовувати технічно обґрунтовані рішення на стадії проектування масових вибухів. Використання формули для обчислення технічної продуктивності екскаваторів у конкретних умовах буде сприяти поліпшенню планування технологічних процесів, особливо раціональному розподілу вантажопотоків. У перспективі вищевказана формула стане найважливішою частиною математичної моделі оптимізації основних технологічних процесів у кар'єрах.

Ключові слова: *кар'єр, екскаватор, продуктивність, гранулометричний склад, гірська маса*

Цель. Применение технических средств оперативного контроля работы экскаваторов и качества дробления горных пород взрывом. Установление зависимости затрат времени на экскавацию горной массы от ее гранулометрического состава, математическое описание этой зависимости в виде функции двух переменных.

Методика. Методологической основой решения поставленной задачи является комплексный подход, включающий исследования с помощью устройства ИГС-5М, использование методов математической статистики, анализ результатов в математическом пакете.

Результаты. Реализована возможность ведения оперативного контроля затрат времени на экскавацию горной массы одновременно с непосредственным измерением ее гранулометрического состава. Введено понятие коэффициента цикла и установлена его зависимость от среднего диаметра куска. Получена эмпирическая формула для определения технической производительности экскаваторов в виде функции двух переменных, однозначно характеризующих качество дробления горной массы.

Научная новизна. Впервые в практике ведения горных работ применены технические средства, специально созданные для оперативного контроля работы экскаваторов и качества дробления горных пород взрывом (устройство ИГС-5М на уровне изобретения). Предложена двухпараметрическая функция распределения гранулометрического состава горной массы, у которой один параметр представляет размер преобладающей фракции, второй – содержание фракции в исследуемом объеме взорванных пород. Получена формула для определения технической производительности экскаваторов в виде функции указанных параметров.

Практическая значимость. Использование представленных устройств при организации и ведении горных работ позволит применять технически обоснованные решения на стадии проектирования массовых взрывов. Использование формулы для вычисления технической производительности экскаваторов в конкретных условиях будет способствовать улучшению планирования технологических процессов, особенно рациональному распределению грузопотоков. В перспективе вышеуказанная формула станет важнейшей частью математической модели оптимизации основных технологических процессов на карьерах.

Ключевые слова: *карьер, экскаватор, производительность, гранулометрический состав, горная масса*

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