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PRELIMINARY ASSESSMENT OF ROADHEADERS EFFICIENCY BASED ON EMPIRICAL METHODS AND INDEX OF EQUIVALENT ROCK STRENGTH

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ABSTRACT

Purpose. The choice of a proper roadheader is a critically important step in planning of a project or some of its stages. Nowadays various manufacturers produce numerous models of these vehicles, hence it is unreasonable to conduct a thorough analysis of each model's parameters in terms of their adequacy for the successful implementation of the project. Therefore, it is necessary to develop quite simple and easy-to-use assessment of roadheaders efficiency at the project preliminary stages.

Methods. The widely used model of the Colorado School of Mines based on numerous laboratory tests has been applied as the basic model for determining theoretical efficiency of rock mass destruction. Since domestic scientists are accustomed to using rock strength parameters, which differ from values σ_c and σ_t accepted everywhere (including Russia), we represented dependencies that allow to convert values of some indicators to the values of other indicators.

Findings. Calculating the efficiency of roadheaders' use for each geological section with homogeneous rock can take unreasonably long time. Thus, it is necessary to have a simple integrated strength index for the whole excavation or even enterprise, which can be interpreted through the generally accepted values such as the uniaxial compressive strength σ_c and tensile strength σ_t. Jointing of rocks is also an important parameter in a feasibility study of roadheaders' efficiency.

Originality. The equivalent rock strength index was applied as a simple integrated strength index for the whole excavation. This parameter is established on the basis of integrated assessment index of mining operations complexity, which comprises the sum of the uniaxial compressive strength σ_c and rock jointing for the whole excavation or even mining enterprise.

Practical implications. The results of this paper can serve as a preliminary scientifically grounded method of selecting equipment for a particular project in mining industry or underground construction by the efficiency criterion. Its main advantage is simplicity and clarity. However, it should be noted that this method should not be applied at the stage of the project final feasibility study, especially without considering other production factors (compatibility with other equipment, availability of the personnel with adequate qualification for operation and maintenance of the chosen machine etc.).

Keywords: *roadheader, efficiency, empirical method, preliminary assessment, integrated complexity assessment, equivalent strength*

1. INTRODUCTION

High advance rate of excavation works allows early access to mineral deposits in mining or fast construction of such socially significant infrastructure objects in civil engineering as subways, tunnels, engineering communications, and utilities lines. Thus, advance rate is an important parameter for feasibility study in the practice of mining and civil construction companies (Seker & Ocak, 2017; Zhabin, Polyakov, & Averin, 2018b). One of the most wide-spread technical means for excavation is roadheaders. Their main advantages are mobility, flexibility, and selective mining ability, while the disadvantage is relatively limited destructive force in respect to the rock of strength up to 100 – 120 MPa of uniaxial compressive strength σ_c (Ozfirat, Malli, Ozfirat, & Kahraman, 2017).

The choice of a proper roadheader is a critically important step in planning a project or some of its stages. The variety of models of these machines produced by various manufacturers at present is large, which makes it unreasonable to carefully analyze each model from the point of view of its adequacy for successful implementation of the project parameters. Therefore, there is a need in a sufficiently simple and easy-to-use assessment of roadheaders' efficiency at preliminary stages of the project implementation in mining and civil construction.

2. ANALYSIS AND CHOICE OF A BASIC EMPIRICAL METHOD

The task described above is usually solved by decision-makers on the basis of their experience of designing mining enterprises, which are highly individual and subjective. Therefore, it may lead to a non-optimal decision taken. At the same time, over the past decades, a great deal of scientific and practical experience has been accumulated that allows to build statistically valid mathematical models to determin the productivity of mining operations depending on the key parameters (Table 1).

Table 1 presents the following parameters: P_{inst} – the roadheader's installed cutterhead power; k – the energy transfer ratio; σ_t – the Brazilian tensile strength; σ_c – the uniaxial compressive strength; RQD – the rock quality designation.

As seen from the Table 1, universal methods for determination of roadheaders performance include such parameters as installed cutterhead power and the energy transfer ratio, which depends on the cutterhead type.

As the basic model for determining the net cutting rate of the destruction of a rock massif, one can use the formula proposed in (Rostami, Ozdemir, & Neil, 1994) – the model of the Colorado School of Mines, which is based on numerous laboratory tests and has been widely used in practice:

$$ICR = k \cdot \frac{P_{inst}}{SE_{opt}}, \tag{1}$$

where:

ICR – the instantaneous (net) cutting rate, m^3/h;

P_{inst} – the installed roadheader power, kW;

SE_{opt} – the optimum specific energy obtained from full-scale linear cutting tests, $kW \cdot h/m^3$;

k – energy transfer coefficient.

Table 1. Summary of empirical methods to determine roadheader performance

Reference	Mining & geological parameters	Roadheader's parameters	Comments
Gehring, 1989	σ_c	—	Developed for heavy-weight axial and transverse road-head-ders operating in coal bearing strata. It needs correction for lighter roadheaders and other rock masses. It also needs size correction for UCS values.
Natau, Mutschler, & Lempp, 1991	σ_c, σ_t	P_{inst}	Developed for transverse roadheaders in different power classes and different types of rocks. It needs correction for axial roadheaders.
Rostami, Ozdemir, & Neil, 1994	SE_{opt}	P_{inst}, k	Developed for axial and transverse roadheaders in different power and weight classes, and different types of rocks. The type of roadheader is not specified. k value of 0.45 works for axial type and the value of 0.55 works for transverse type.
Copur, Ozdemir, & Rostami, 1998	σ_c	P_{inst}, weight	Developed for transverse roadheaders in different power and weight classes for excavation of especially evaporitic (nonabrasive) rocks with up to 60 MPa compressive resistance.
Çopur, Tunçdemir, Bilgin, & Dinçer, 2001	σ_c, σ_t	P_{inst}, k	Developed for different types of massive rocks. It works for transverse types of roadheaders.
Balci, Demircin, Copur, & Tuncdemir, 2004	σ_c, σ_t	P_{inst}, k	Developed for axial and transverse roadheaders in different, weight, power classes, and different types of rocks. Dynamic and static elasticity modulus, and Schmidt hammer can also be used in the model.
Bilgin et al., 2006	σ_c or σ_t	P_{inst}, k	Developed for axial and transverse roadheaders in different weight and power classes, and different types of rocks. The type of roadheader is not specified. Dynamic and static elasticity modulus, as well as Schmidt hammer values can also be used in the model.
Ocak & Bilgin, 2010	σ_c	—	Developed for only one type of transverse roadheader and different types of rocks. It needs correction for other types and classes of roadheaders.
Ebrahimabadi, Goshtasbi, Shahriar, & Seifabad, 2011	σ_c, σ_t, RQD	—	Developed for only one type of light-weight axial roadheader and coal bearing strata. It needs correction for other types, weight, and power classes of roadheaders, and other rock masses.

The value of the coefficient k should be 0.45 for axial type and 0.55 – for transverse type. Limitations for each type of the machines should also be taken into account: axial roadheaders are capable of destroying rocks with a compressive strength of up to 60 – 80 MPa (effective range 40 – 60 MPa), and transverse roadheaders – up to 100 – 120 MPa (effective range of 60 – 80 MPa) (Ozfirat, Malli, Ozfirat, & Kahraman, 2017).

The value of SE_{opt} in respect to rock properties can be obtained from the following equation (Çopur, Tunçdemir, Bilgin, & Dinçer, 2001):

$$SE_{opt} = 0.027 \cdot \sigma_c \cdot \sigma_t + 0.675 . \quad (2)$$

3. DEVELOPMENT OF THE METHOD FOR PRELIMINARY ESTIMATION OF ROADHEADER PERFORMANCE IN A PROJECT

Uniaxial compressive strength and Brazilian tensile strength in Eq. (2) are broadly applied worldwide including Russia, which is also evidenced by the state standards for determining these values (GOST 21153.3-85 and GOST 21153.2-84) acting in this country. However, in practice, domestic specialists also often use such strength indicators as the contact strength P_k and the spall fracture toughness P_{sp}. For the contact strength and spall fracture toughness, the following correlation dependencies with the uniaxial compressive strength have been established (Nistratova, 1998), which can be used for calculations in the presented model:

$$P_k = 13 \cdot \sigma_c^{0.94} ; \quad (3)$$

$$P_{sp} = 4.22 \cdot \sigma_c^{1.25} . \quad (4)$$

Correlation indexes for Eqs. (3) and (4) are 0.82 and 0.86 respectively.

All these indicators reflect the strength properties of only one rock formation, and therefore are applicable in a limited section of working or mining enterprise. Calculating the efficiency of roadheaders use for each such section with subsequent separation or, conversely, integration of the relevant information can take unreasonably long time. Hence, it is necessary to have a simple integrated strength index for the whole excavation or even enterprise, which can be interpreted through the generally accepted value such as the uniaxial compressive strength σ_c. Equivalent rock strength can be applied as such indicator (Zhabin, Averin, & Polyakov, 2018) which is established by integrated assessment of the complexity of mining operations at the site (Zhabin, Averin, & Polyakov, 2017).

To obtain this assessment, all excavations of the project are divided into sections that are relatively homogeneous in terms of mining-geological conditions. Then the difficulty of mining each section c_i is evaluated. For this purpose, sections are assigned a category after dividing the compressive strength by 30 and rounding the resulting value to the nearest bigger integer (if $\sigma_c > 270$ MPa, then the category is 10). Then, the category is amended according to the criterion of rock fracturing at the excavation site:

Competent rocks	+1
Slightly fractured rocks	+1
Fractured rocks	±0
Highly fractured rocks	–1
Extremely fractured rocks	–1

The integrated assessment is determined by the following equation:

$$C_{Int} = \sum_{i=1}^{n} \frac{l_i \cdot c_i}{L} , \quad (5)$$

where:

C_{Int} – the integrated assessment of the whole excavation complexity;

i – the number of an excavation site;

n – the total number of excavation sites;

l_i – the length of i-excavation site;

c_i – the assessment of complexity for i-excavation site;

L – the length of the whole excavation.

The value obtained from Eq. (5) should be multiplied by 30 (since values of uniaxial compressive strength σ_c of rocks for each excavation site were previously divided by 30). This is the index of equivalent rock strength:

$$\sigma_c^{eq} = 30 \cdot C_{Int} . \quad (6)$$

For evaluation of Brazilian tensile strength, it is reasonable to use recommendations given in (Kahraman, Fener, & Kozman, 2012). It states that there is linear correlation between uniaxial compressive strength and Brazilian tensile strength for different rocks. Specifically, the value of Brazilian tensile strength is 10.61 times less than uniaxial compressive strength. Satisfactory results from the use of this formula were confirmed in (Nazir, Momeni, Armaghani, & Amin, 2013).

After performing the calculation using Eq. (6), and, if necessary Eqs. (3) or (4), and then successively Eqs. (2) and (1), we get an approximate value of the theoretical performance of the roadheader during the project. Knowing the value of the instantaneous (net) cutting rate, we can determine the volume of the destroyed rock in cubic meters per day of work:

$$V_{exc} = ICR \cdot MUT \cdot S_{day} \cdot H_{shift} , \quad (7)$$

where:

MUT – the machine utilization time, %/100;

S_{day} – the number of working shifts per day;

H_{shift} – the duration of a working shift, hours.

Machine utilization time MUT shows a part from the total time spent on doing the work, which is spent only on mining operations. This coefficient depends on many factors and is usually 0.25 – 0.50 (Kahraman & Kahraman, 2016).

Then daily mining rate is:

$$AR = \frac{V_{exc}}{A_{face}} , \quad (8)$$

where:

A_{face} – the face cross-section area, m^2.

4. CONCLUSIONS

The discussed method, which takes into account the generalized international experience in the field of mi-ning operations with the use of roadheaders, can serve as a preliminary scientifically grounded approach to selecting equipment for a particular project in mining industry or underground construction by the performance criterion. Its main advantage is simplicity and clarity. For domestic specialists who are accustomed to the use of rock strength parameters in their activities, which differ from everywhere (including Russia), the accepted values of σ_c and σ_t are the dependencies that allow to convert the values of some indicators to the values of other indicators. However, it should be noted that the above metho-dology should not be applied at the stage of the project final feasibility study, especially without considering other production factors (compatibility with other equipment, availability of the personnel with adequate qualification for operation and maintenance of the chosen machine etc.).

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ПОПЕРЕДНЯ ОЦІНКА ПРОДУКТИВНОСТІ ПРОХІДНИЦЬКИХ КОМБАЙНІВ НА ОСНОВІ ЕМПІРИЧНИХ МЕТОДІВ ТА ЕКВІВАЛЕНТНОЇ МІЦНОСТІ ГІРСЬКИХ ПОРІД

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Мета. Вибір конкретного прохідницького комбайна є критично важливим кроком у плануванні робіт по проекту або будь-якого з його етапів. При цьому номенклатура машин, що випускаються різними виробниками в даний час, надзвичайно велика, що робить недоцільним ретельний аналіз кожної моделі комбайна з точки зору його адекватності необхідним для успішної реалізації проекту параметрам. Таким чином, виникає необхідність у досить простій і швидко проводимій попередній оцінці машин уже на передпроектній стадії.

Методика. В якості основної моделі для визначення теоретичної продуктивності руйнування гірського масиву була використана методика Колорадського гірничого університету, яка заснована на численних лабораторних випробуваннях і пройшла широку апробацію на практиці. Для вітчизняних фахівців, що звикли до використання у своїй діяльності міцнісних показників гірських порід, що відрізняються від повсюдно (у тому числі в Росії) прийнятих величин $\sigma_{ст}$ і $\sigma_р$ представлені залежності, що дозволяють проводити перерахунок значень одних показників до значень інших показників.

Результати. Обчислення ефективності використання прохідницьких комбайнів для кожної геологічної ділянки з однорідними породами може зайняти невиправдано багато часу. У зв'язку з чим виникає необхідність у простому, інтегральному для всієї виробки або гірничого підприємства, показника міцності, який може бути інтерпретований через загальноприйняті величини – межу міцності на стиск $\sigma_{ст}$ і межу міцності на розтяг $\sigma_р$. Також важливим параметром у техніко-економічному обґрунтуванні ефективності прохідницьких комбайнів є тріщинуватість гірських порід.

Наукова новизна. В якості найпростішого інтегрального показника міцності порід по всій виробці використовувався показник еквівалентної міцності гірських порід. Цей параметр визначається на основі показника інтегральної оцінки складності гірничопрохідницьких робіт, заснованої на підсумовуванні межі міцності на стиск $\sigma_{ст}$ і тріщинуватості гірських порід по всій виробці або навіть гірничому підприємству.

Практична значимість. Отримані результати можуть слугувати в якості попереднього науково обґрунтованого способу відбору техніки для конкретного проекту в гірничодобувній галузі або підземному будівництві за критерієм продуктивності. Її основною перевагою є простота і зрозумілість. Однак варто зазначити, що розглянуту методику не слід застосовувати на етапі остаточного техніко-економічного обґрунтування проекту, тим більше у відриві від інших виробничих факторів (сумісність з іншим обладнанням, наявність персоналу з необхідною для експлуатації та обслуговування обраної машини кваліфікацією і т.д.).

Ключові слова: *прохідницький комбайн, продуктивність, емпіричний метод, попередня оцінка, інтегральна оцінка складності, еквівалентна міцність*

ПРЕДВАРИТЕЛЬНАЯ ОЦЕНКА ПРОИЗВОДИТЕЛЬНОСТИ ПРОХОДЧЕСКИХ КОМБАЙНОВ НА ОСНОВЕ ЭМПИРИЧЕСКИХ МЕТОДОВ И ЭКВИВАЛЕНТНОЙ ПРОЧНОСТИ ГОРНЫХ ПОРОД

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Цель. Выбор конкретного проходческого комбайна является критически важным шагом в планировании работ по проекту или какому-либо из его этапов. При этом номенклатура машин, выпускаемых различными производителями в настоящее время, необычайно велика, что делает нецелесообразным тщательный анализ каждой модели комбайна с точки зрения его адекватности требуемым для успешной реализации проекта параметрам. Таким образом, возникает необходимость в достаточно простой и быстро проводимой предварительной оценке машин уже на предпроектной стадии.

Методика. В качестве основной модели для определения теоретической производительности разрушения горного массива была использована методика Колорадского горного университета, которая основана на многочисленных лабораторных испытаниях и прошла широкую апробацию на практике. Для отечественных специалистов, привыкших к использованию в своей деятельности прочностных показателей горных пород, отличающихся от повсеместно (в том числе в России) принятых величин $\sigma_{сж}$ и $\sigma_р$ представлены зависимости, позволяющие производить перерасчет значений одних показателей к значениям других показателей.

Результаты. Вычисление эффективности использования проходческих комбайнов для каждого геологического участка с однородными породами может занять неоправданно много времени. В связи с чем возникает необходимость в простом, интегральном для всей выработки или горного предприятия, прочностном показателе, который может быть интерпретирован через общепринятые величины – предел прочности на сжатие $\sigma_{сж}$ и предел прочности на растяжение $\sigma_р$. Также важным параметром в технико-экономическом обосновании эффективности проходческих комбайнов является трещиноватость горных пород.

Научная новизна. В качестве простейшего интегрального показателя прочности пород по всей выработке использовался показатель эквивалентной прочности горных пород. Этот параметр определяется на основе показателя интегральной оценки сложности горнопроходческих работ, основанной на суммировании предела прочности на сжатие $\sigma_{сж}$ и трещиноватости горных пород по всей выработке или даже горному предприятию.

Практическая значимость. Полученные результаты могут служить в качестве предварительного научно обоснованного способа отбора техники для конкретного проекта в горнодобывающей отрасли или подземном строительстве по критерию производительности. Ее основным достоинством является простота и понятность. Однако стоит отметить, что рассмотренную методику не следует применять на этапе окончательного технико-экономического обоснования проекта, тем более в отрыве от других производственных факторов (совместимость с прочим оборудованием, наличие персонала с необходимой для эксплуатации и обслуживания выбираемой машины квалификацией и т.д.).

Ключевые слова: *проходческий комбайн, производительность, эмпирический метод, предварительная оценка, интегральная оценка сложности, эквивалентная прочность*

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