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*Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).*

*Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).*

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# JUSTIFICATION OF TECHNOLOGICAL PARAMETERS AND ENERGY CONSUMPTION OF QUARRY EXCAVATORS, TAKING INTO ACCOUNT THE QUALITY OF ROCK PREPARATION FOR EXCAVATION

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**Abstract.** The current methodological framework for substantiating the main technical and economic indicators of geotechnological systems performance, applied during both the design and operational stages, differs significantly. During the design phase, generalized and simplified methods and approaches are used in calculating the main indicators and substantiating choices regarding key mining and transport equipment, as well as schemes and sequences for deposit development. This often leads to substantial imbalances during the operational stage, increased costs of mining and transport operations, and reduced profitability of resource development overall.

At the operational stage, more effective methods of analysis, evaluation, and optimization of functioning geotechnological systems are increasingly applied. These methods are based on a process-oriented approach and include adapted tools such as simulation modeling, which enable the step-by-step analysis and study of subsystem and element interactions–even in complex, large-scale systems. A critically important shortcoming in this area is the lack of capacity for dynamic

accounting of such a key characteristic of the extracted rock mass as its degree and quality of readiness for excavation. This results in a loss of the dynamic interrelation between two sequential processes involved in rock mass extraction: drilling and blasting, and mining and transport.

**Keywords:** geotechnological complex, energy efficiency, process management, process management economics, efficiency, simulation modeling, environmental friendliness

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## ТАУ ЖЫНЫСТАРЫН ҚАЗУҒА ДАЙЫНДЫҚ САПАСЫН ЕСКЕРУМЕН КАРЬЕР ЭКСКАВАТОРЛАРЫНЫҢ ТЕХНОЛОГИЯЛЫҚ ПАРАМЕТРЛЕРІН ЖӘНЕ ЭНЕРГИЯ ТҰТЫНУЫН НЕГІЗДЕУ

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**Сарсенбаев Ербол** — инженер, Қазақстан Республикасының минералдық шикізатты кешенді қайта өңдеу жөніндегі ұлттық орталығының филиалы Д. А. Қонаев атындағы тау-кен ісі институты, Алматы, Қазақстан,
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**Аннотация.** Қазіргі заманғы геотехнологиялық кешендердің жұмыс істеуінің негізгі техникалық-экономикалық көрсеткіштерін негіздеу үшін қолданылатын әдіснамалық базасы олардың жобалау және пайдалану кезеңдерінде айтарлықтай ерекшеленеді. Жобалау кезеңінде негізгі көрсеткіштерді есептеу және негізгі тау-кен және тасымалдау жабдықтарын, кен орнын ашу сүлбелері мен тәртібін таңдаудың әртүрлі нұсқаларын негіздеуде ұлғайтылған және қарапайым әдістер мен тәсілдер қолданылады, бұл олардың пайдалану кезеңінде елеулі дисбаланстарға, тау-кен тасымалдау жұмыстарының өзіндік құнының артуына және игерудің жалпы тиімділігін төмендеуіне әкеп соғады. Пайдалану кезеңдерінде тиімдірек талдау, бағалау және жұмыс істейтін геотехнологиялық кешендердің параметрлерін оңтайландыру әдістері кеңінен қолданылуда, ол процестік тәсілдерге негізделген, осындай тапсырмаларды шешуге бейімделген имитациялық моделдеу сияқты әдістер қолданылады, бұл күрделі және ауқымды жүйелердің ішкі жүйелері мен элементтерінің өзара әрекеттесуін операциялар бойынша зерттеуге мүмкіндік береді. Осы бағыттағы принципті маңызды кемшіліктердің бірі – алынатын тау-кен массасының экскавацияға дайындық шамасы мен сапасын динамикалық түрде ескерудің мүмкін еместігі болып табылады. Бұл екі: бұрғылау жару және тау-кен тасымалдау кезеңдік тау-кен массасын өңдеу процесінің өзара бірізділік байланысын жоғалтады.

2024-2026 жылдарға арналған ҚР Ғылым және жоғары білім министрлігінің Ғылым комитеті тарапынан қаржыландырылатын мақсатты бағдарламасы аясында, «Минералды және техногендік шикізатты өндіру мен кешенді қайта өңдеудің инновациялық ресурсты үнемдейтін технологияларын құру» бағдарламасы бойынша, зерттеудің мақсаты мен міндеті – ҒЗЖ жобасы аясында «Карьерлердің геотехнологиялық кешендерінің жұмыс істеуін аудиттеу ақпараттық жүйесін құру» тақырыбы бойынша ғылыми зерттеу жұмысы жүзеге асырылуда.

**Түйін сөздер:** геотехнологиялық кешен, карьер, энергиялық тиімділік, үдерістік басқару, үдерістік басқарудың экономикасы, тиімділік, имитациялық үлгілеу, экологиялығы

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## ОБОСНОВАНИЕ ТЕХНОЛОГИЧЕСКИХ ПАРАМЕТРОВ И ЭНЕРГОРАСХОДА КАРЬЕРНЫХ ЭКСКАВАТОРОВ С УЧЁТОМ КАЧЕСТВА ПОДГОТОВКИ ГОРНЫХ ПОРОД К ВЫЕМКЕ

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**Аннотация.** Современная методологическая база обоснования основных технико-экономических показателей функционирования геотехнологических комплексов, применяемая на стадиях их проектирования и эксплуатации, существенно различается. На стадии проектирования используются укрупнённые и упрощённые методы расчёта основных показателей и обоснования вариантов выбора горного и транспортного оборудования, схем и порядка вскрытия месторождений. Это приводит к дисбалансам на стадии эксплуатации, росту себестоимости горнотранспортных работ и снижению рентабельности освоения месторождений в целом. На стадии эксплуатации применяются более эффективные методы анализа, оценки и оптимизации параметров функционирующих геотехнологических комплексов. Всё более востребованными становятся подходы, основанные на процессном анализе, включая адаптированные методы имитационного моделирования, которые позволяют пооперационно рассматривать и исследовать взаимодействие подсистем и элементов даже сложных и масштабных систем. Одним из принципиально важных недостатков данного направления остаётся отсутствие возможности динамического учёта такой характеристики извлекаемой горной массы, как степень и качество её готовности к экскавации. В результате теряется динамическая взаимосвязь двух последовательных процессов подготовки и перемещения горной массы - буровзрывного и горнотранспортного. Цель и задача исследования - создание информационной системы аудита функционирования геотехнологических комплексов карьеров в рамках программы «Создание инновационных ресурсосберегающих технологий добычи и комплексной переработки минерального и техногенного сырья», реализуемой по программе целевого финансирования Комитетом науки Министерства науки и высшего образования Республики Казахстан на 2024–2026 гг.

**Ключевые слова:** геотехнологический комплекс, энергоэффективность, управление процессами, экономика управления процессами, эффективность, имитационное моделирование, экологичность

**Introduction.** One of the key challenges in improving the quality of design, as well as in evaluating the effectiveness of mining and transport operations and the functioning of geotechnological complexes in open-pit mining, is the adequate

accounting of energy consumption based on the quality of the rock mass preparation for excavation. This impacts the efficiency of open-pit mining complexes and the profitability of developing hard mineral deposits.

The existing methodological framework does not fully allow for the accounting of the relationship between key technical and economic performance indicators of excavators and the degree of loosening of the rock masses they excavate. This shortcoming reduces the quality of scientific and practical research aimed at improving economic efficiency, energy efficiency, and at reducing the environmental impact of mining and transport operations on the surrounding environment. In this regard, one effective solution to this pressing issue is the application of dynamic approaches implemented through simulation modeling, which are based on process-oriented management approaches in the operation of geotechnological complexes.

**Literary review.** Currently, within the methodology used for the design and planning of mining operations, excavator productivity is calculated in a highly generalized manner. This is due to the complexity of mathematically or analytically reproducing the mechanisms of energy transfer during excavation operations. To simplify the process of accounting for the energy costs of excavator operation, the following types of calculations are applied to the main technical and technological indicators of excavation and loading equipment (see Table 1). In this case, correction factors—typically determined empirically—such as the time and speed of filling the bucket with rock, are of particular interest.

To determine the hourly technical productivity of the excavator, factors such as bucket capacity ($E_k$), cycle time ($t^c$), and the excavation coefficient ($K_e$) are taken into account. The excavation coefficient expresses the ratio of the bucket filling coefficient ($K_n$) to the rock loosening coefficient ($K_r$). This indicator allows for an assessment of the impact of the degree of rock loosening on technical productivity, but does not reflect the energy intensity of this process. Additionally, this approach does not adequately establish the productivity of the excavator under specific mining, geological, organizational, and economic conditions. In simplified terms, this issue is addressed using the shift time utilization coefficient of the excavator, which makes this approach applicable at the stage of generalized calculations during the design phase. However, this method leads to significant errors (up to 10-15% or more), which is a substantial drawback in the process of optimizing mining and transport operations. The other formulas represent similar calculations over larger time periods of excavator operation.

Table 1. - Parameters of excavator performance indicators: for ore and overburden

| №№ | Parameters of excavator performance indicators: for ore and overburden | |
|---|---|---|
| 1 | Technical productivity of the excavator, м³ | $Q\text{тех.} = \frac{3600}{\text{Е} \times t\text{ц} \times \text{Кэ}}$ |
| 2 | Hourly productivity considering effective excavator operation, м³/т | $Q\text{час.}\,(\text{м}^3) = \text{Ки.э} \times Q\text{тех.}$<br>$Q\text{час.}\,(\text{т}) = \frac{\gamma}{Q\text{hours.}\,(\text{м}^3) \times \text{Тсм}}$ |

| | | |
|---|---|---|
| 3 | Shift productivity, м³/т | $Q\text{час.}\,(\text{м}^3) = \text{Ки.э} \times Q\text{тех.}$<br>$Q\text{час.}\,(\text{т}) = \frac{\gamma}{Q\text{hours.}\,(\text{м}^3) \times \text{Тсм}}$ |
| 4 | Daily productivity, м³/т | $Q\text{сут.}\,(\text{м}^3) = 2 \times Q\text{см.}$<br>$Q\text{сут.}\,(\text{т}) = 2 \times Q\text{см}\,(\text{т}).$ |
| 5 | Average monthly productivity, м³/т | $Q\text{ср.м.}\,(\text{м}^3) = \frac{Q\text{ср.г.}\,(\text{м}^3)}{12}$<br>$Q\text{ср.м.}\,(\text{т}) = \frac{Q\text{ср.г.}\,(\text{т})}{12}$ |
| 6 | Average annual productivity, м³/т | $Q\text{ср.г.}\,(\text{м}^3) = 355 \times \text{Кг.т} \times Q\text{сут.}\,(\text{м}^3)$<br>$Q\text{ср.г.}\,(\text{т}) = 355 \times \text{Кг.т} \times Q\text{сут.}\,(\text{т})$ |
| 7 | Average monthly operating, м/hours | $E\text{ср.м.} = \frac{E\text{ср.г.}}{12}$ |
| 8 | Average annual operating, м/hours | $E\text{ср.г.} = 355 \times 24 \times \text{Кг.т} \times \text{Ки.с}$ |

where $E_к$ - nominal bucket capacity, м³;
$t_ц$ - average time of the excavator working cycle, sec;
$K_н$ - bucket filling factor;
$K_р$ - rock loosening factor in the excavator bucket;
$K_е$ - excavation factor;
$K_{и.э}$ - factor of utilization of the excavator working time during effective work during an hour;
$K_{ми.\,см}$ - factor of utilization of the excavator during a shift;
$K_{т.г}$ - factor of technical support of equipment;
$T_{СМ}$ - shift duration, hour;
$\gamma$ - specific gravity of the rock mass, м³/t.

Clearly, in the context of a dynamic approach to studying the interdependence of excavator operational parameters and the degree of rock mass loosening, a corresponding calculation method is required that ensures adequate accounting of the energy costs of this process in the relevant mining, geological, economic, organizational, and geo-technical situations.

**Materials and methods.** One of the directions for the dynamic approach to accounting for the degree of loosening of the excavated rock mass is the dynamic approach to forming the total excavator cycle time ($T_ц$), which is calculated by summing the time of all operations:

$$T_ц = t_1 + t_2 + t_3 + t_4 + t_5. \quad (9)$$

where $t_1$ – time to fill the bucket with rock from the face, sec.;
$t_2$ - time to rotate the bucket to the unloading location, sec.;
$t_3$ – time to unload the rock mass, sec.;
$t_4$ - time to rotate the bucket back to the digging location, sec.;
$t_5$ – time to lower the bucket into the face, sec.

For single-bucket excavators used in open-pit mining, the bucket filling operation is one of the most complex of all the excavator cycle operations. In equation (9), the most sensitive part to the degree of loosening of the extracted rock mass is the time required to fill the excavator bucket during excavation *($t_p$)*. This dependence is determined by the excavation resistance forces, the physicochemical properties of the excavated rock mass, the parameters of the excavator, the height of the working bench (the height of the rock pile after blasting operations), and other factors. According to scientific and practical studies, this operation time accounts for a significant portion (up to 30-40%) of the total excavator cycle time, which depends on the rock loosening coefficient, the bucket filling coefficient, climatic conditions, equipment condition, bench height, etc. (Dodis et al., 2007; Komissarov et al., 2022; Khoroshavin et al., 2023; Letnev et al., 2023).

It should be noted that during excavation, the resistance of the rock mass *($F_{сопр}$)* can depend on several of its properties, such as dryness, viscosity, looseness, density, moisture capacity, crack formation, etc. A simplified model of the resistance force of the rock mass can be created by applying the friction law, for example:

$$F_{сопр} = K_{тр} \cdot S \cdot \sigma, \tag{10}$$

where $F_{сопр}$ — resistance force; $K_{тр}$ — friction coefficient; $S$ — area of contact between the bucket and the rock mass; σ — rock stress.

The formula for excavator productivity considering loosening is as follows:

$$Q = \frac{V \cdot n \cdot K_n \, K_р}{60}, \tag{11}$$

where Q — productivity (m³/h); V — nominal (geometric) bucket volume (m³); n — number of excavator cycles per hour (cycles per hour); Kn — bucket filling coefficient (typically 0.8-0.95 depending on rock categories). Kp — rock loosening coefficient (a value < 1, accounting for the increase in volume during excavation).

The productivity of the open-pit excavator is significantly influenced by the loosening coefficient, as loosened material occupies more volume compared to dense material. Based on this, the excavator will require more cycles to perform the same volume of work, which reduces the overall productivity of the excavator.

In mining literature, the subsequent evolution of productivity calculations for single-bucket open-pit excavators solidified an approach focused on the static method for accounting for the physical and mechanical properties of the excavated rocks, creating a set of solutions based on the methodology for determining calculated loads on the excavator's working parts.

Methods for determining the calculated loads on the excavator's working parts based on the characteristics of the developed face are presented in the works of A.Ya. Zelinin, N.G. Dombrovsky, R.Kh. Sharipov, and others.

The forces acting on the excavator's hoisting cable when digging the rock mass are given by:

$$F_{\text{п}} = F_{k+p} \cdot e^{0{,}014\frac{K_F \cdot E}{H_B \cdot K_P} \cdot K_v}, \quad (12)$$

where *Fк+p* - force from the weight of the bucket and boom; *KF* - coefficient of rock resistance to excavation; *E* -bucket capacity; *HB* - height to the axis of the excavator's support shaft; *Kp* - rock loosening coefficient; *Kv* - coefficient of increased stress when changing the bucket lifting speed (the coefficient is equal to the absolute value of the bucket lifting speed).

It has been established that when excavating rock with a speed greater than 0.55 m/s, the stresses in the boom exceed the allowable limit (Lyashenko et al., 2016).

Example of excavator productivity calculation approach based on the number of loaded dump trucks per hour, Komatsu Company:

$$t_T = \left(\frac{Tq}{Bc \cdot \text{К} \cdot Ploose}\right) * \cdot t_c, \quad (13)$$

where $B_c$ – excavator bucket capacity (m³); $T_q$ – dump truck payload capacity; $K$ – bucket filling coefficient (%); $t_c$ – cycle time (sec); $P_{loose}$ – bulk density (loose state), t/m³; the asterisk (*) indicates that the result in parentheses should be rounded to the nearest whole number (Litvin et al., 2022). In this case, there is no correction factor for the physical and technical properties of the rock mass.

An increase in the rock loosening coefficient ($K_p$) typically reduces excavation resistance but increases the volume of rock that needs to be moved, which in turn reduces overall productivity.

Let's establish an inverse proportional relationship between digging time and the loosening coefficient within a certain range (for example, the higher $K_p$, the lower the digging time), but this will be an approximate assumption requiring experimental confirmation.

Variant for determining excavator digging time considering loosening coefficient:

$$T\text{Ч} = \frac{V \cdot \text{Кр}}{Q\text{экс} \cdot \text{Кз}}, \quad (14)$$

where $Q_{экс}$ - operational productivity of the excavator (m³/s); $T_ч$ - digging time (sec); $V$ - volume of excavated material (m³); $K_p$ - loosening coefficient; $K_з$ bucket loading coefficient

or

$$T\text{Ч} = \frac{3600}{n} - (t_2 + t_3 + t_4 + t_5). \quad (15)$$

where n — number of excavator cycles per hour (cycles per hour).

It is known that the loosening coefficient of the rock mass ($K_p$) influences the digging force ($F_п$), as shown in the formula above. Increasing $K_p$ typically reduces

excavation resistance (Letnev K. Yu et al., 2016; Poderini R. Yu et al., 2013; Methodical et al., 2003; Malafeev et al., 2020; Tarasov et al., 2015).

For a more accurate determination of the relationship between digging time and the loosening coefficient, as well as other factors, it is necessary to apply approaches based on the results of experimental studies and the use of specialized software systems for simulating excavator operation, which take into account the mechanics of rock mass and the dynamics of the machine's operation. One such approach involves using the dependence of the excavator's digging coefficient $(K_ч)$ on the obtained values of the rock mass loosening coefficient, as shown in Figure 1.

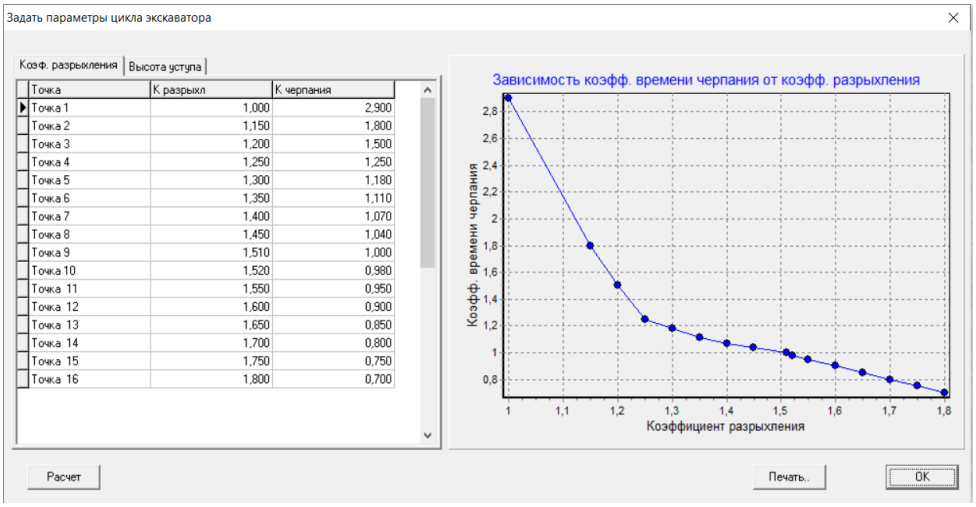


Figure 1 – Mechanism of simulation modeling of the impact of the rock loosening degree on the excavator's digging time.

This approach assumes that indicators such as the bulk density and moisture content of the rock mass remain constant during specific studies, and that the loosening degree does not significantly impact the other operations in the excavation cycle. Therefore, the methodology assumes that the times for other cycle operations remain constant. The reference to the current situation is based on three facts: First, for a given rock loosening coefficient in the enterprise or project for the development of a deposit, the digging coefficient is taken as one - this is the baseline scenario in the research process; when the loosening coefficient is equal to 1 (natural rock mass), the digging time tends to infinity, but the starting point is taken as the case in which excavation is possible (based on the rock strength coefficient), and maximum loosening is limited by physical capabilities. Another aspect that allows for maximum consideration of the current situation is taking the actual or project-based cycle time as the baseline value (usually the passport specification), which ensures that the considered excavator models align with the actual excavated rock mass in a specific face. This approach allows for increasing or decreasing the digging time based on the loosening coefficient of the rock mass

within technologically acceptable ranges and minimizes the calculation error. In this case, the loosening coefficient for ore mass and overburden can vary.

Currently, insufficient attention is being paid to the issues of forming the main parameters of the primary mechanisms and improving the efficiency of open-pit excavators' operation (Komissarov et al., 2018).

When the volumetric characteristics of rocks change due to their destruction, additional loosening of initially loose rocks, changes in moisture content both in positive and negative temperatures, the time spent in a loose state can reach considerable values (Yanchenko et al., 2019).

Thus, the proposed approach allows for the adequate consideration of the impact of the degree of loosening of the rock mass on the efficiency of the operated or designed geotechnological complex under the given mining, geological, geometrical, organizational, and economic conditions. This is achieved within the framework of a process approach using the most effective method of simulation modeling to solve such dynamic tasks.

One of the remaining drawbacks is the approximate accounting of energy consumption in such research. The main indicators characterizing the efficiency of the operation of excavator and truck complexes are the shift productivity of the complex and fuel consumption. (Zhilinkov et al., 2022).

**Conclusion.** The research conducted has substantiated and proposed an approach and mechanism for solving the problem of adequately accounting for the key parameters of the functioning of geotechnological complexes in open-pit mining with respect to the quality of the extracted rock mass preparation. This task is being addressed for the first time within a unified geotechnological complex framework, focusing on excavation processes, based on a process approach using simulation logic-statistical modeling methods. In the proposed approach, the cycle time of excavator operation is calculated dynamically within the context of a mining transport system under specific mining, geological, geometrical, economic, and organizational conditions, depending on the loosening coefficient of the rock mass. For this, a transition coefficient is proposed that ensures the dynamic accounting of the effect of the excavation operation time within the excavator's working cycle, and further, on the entire excavation cycle time, with respect to the loosening coefficient of the extracted rock mass.

The scientific and practical novelty of the proposed approach lies in the fact that this task is being solved for the first time within the dynamic consideration of the geotechnological complex's functioning as a whole, which allows for designing the main parameters of its operation at a higher methodological level. This, in turn, improves the quality of selecting the main mining and transport equipment models depending on the preparation level of the rock mass for extraction.

Solving this problem is fundamental within the outlined systematic approach and will allow, in the future, to move towards solving the issue of adequately accounting for energy consumption in the dynamics of the excavation process based on the quality of the rock mass preparation for extraction.

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