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The scientific journal News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences has been indexed in the international abstract and citation database Scopus since 2016 and demonstrates stable bibliometric performance.

The journal is also included in the Emerging Sources Citation Index (ESCI) of the Web of Science platform (Clarivate Analytics, since 2018).

Indexing in ESCI confirms the journal's compliance with international standards of scientific peer review and editorial ethics and is considered by Clarivate Analytics as part of the evaluation process for potential inclusion in the Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI), and Arts & Humanities Citation Index (AHCI).

Indexing in Scopus and Web of Science ensures high international visibility of publications, promotes citation growth, and reflects the editorial board's commitment to publishing relevant, original, and scientifically significant research in the fields of geology and technical sciences.

«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық реферативтік және ғылымиметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.

Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық реферативтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.

ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылмды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.

Scopus және Web of Science дерекқорларында индекстелуі жарияланымдардың халықаралық деңгейде жоғары сұранысқа ие болуын қамтамасыз етеді, олардың дәйексөз алу көрсеткіштерінің артуына ықпал етеді және редакциялық алқаның геология мен техникалық ғылымдар саласындағы өзекті, бірегей және ғылыми тұрғыдан маңызды зерттеулерді жариялауға ұмтылысын айқындайды.

Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.

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).

Индексирование в Scopus и Web of Science обеспечивает высокую международную востребованность публикаций, способствует росту цитируемости и подтверждает стремление редакционной коллегии публиковать актуальные, оригинальные и научно значимые исследования в области геологии и технических наук.

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MATHEMATICAL MODELING OF THE DEPENDENCE OF OPEN-PIT EXCAVATOR PRODUCTIVITY ON PARTICLE SIZE DISTRIBUTION AND THE LOOSENING COEFFICIENT OF BLASTED ROCK MASS

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Abstract. Relevance. The degree of fragmentation of the rock mass directly determines the efficiency of subsequent excavation and haulage operations. It should be noted that existing methods for calculating productivity usually account for blast quality only at a qualitative level, without providing its precise numerical description in terms of particle-size distribution and the bulking factor. Hence, there is a scientific problem of quantitatively assessing the effect of the particle-size distribution of blasted rock on the productivity of loading-and-excavating equipment. **Objective.** The aim of this study is to develop a generalized integral mathematical model linking particle-size distribution parameters to the productivity of open-pit excavators. **Methods.** A mathematical model quantitatively linking the particle-size distribution of blasted rock mass is developed, and generalized relationships with the productivity of open-pit excavators are established. The Kuznetsov–Cunningham model (Kuz-Ram) is used to predict fragmentation. **Results.** Analytical expressions for the bucket fill factor K_r and the digging time t_k are obtained in terms of the parameters of the Rosin–Rammler distribution. The

bucket fill model explicitly incorporates the effect of over-fragmentation (fine-fraction spillage), while the model branches at $d_{50}/d_3=0.7$ are coupled continuously and smoothly. An integral calculation procedure is developed that makes it possible to determine the optimal conditioned lump size d^* for a specific excavator model. *Conclusions.* Accordingly, the proposed approach makes it possible to obtain adequate quantitative indicators characterizing the size distribution of fragmented rock material and to identify the optimal range of blasting intensity at which the productivity of excavation equipment reaches its maximum. The relationships established in the study provide a basis for accounting for the quality of rock mass preparation for excavation by blasting when evaluating the efficiency and optimizing the operating parameters of mining and haulage systems employing both road and rail transport under specific mining-technical, geological, geometric, organizational, and economic operating conditions.

Keywords: open-pit excavator, particle size distribution, bucket fill factor, digging time, target fragment size, Kuz-Ram, Rosin–Rammler distribution, ECG, productivity, blast preparation

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КАРЬЕРЛІК ЭКСКАВАТОРЛАР ӨНІМДІЛІГІНІҢ ЖАРЫЛЫСПЕН ДАЙЫНДАЛҒАН ТАУ-КЕН МАССАСЫНЫҢ ГРАНУЛОМЕТРИЯЛЫҚ ҚҰРАМЫ МЕН ҚОПСЫТУ КОЭФФИЦИЕНТІНЕ ТӘУЕЛДІЛІГІН МАТЕМАТИКАЛЫҚ МОДЕЛЬДЕУ

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Аннотация. *Өзектілігі.* Тау массасының ұсақталу дәрежесі кейінгі қазу және тасымалдау операцияларының тиімділігін тікелей айқындайды. Атап өту қажет, өнімділікті есептеудің қолданыстағы әдістемелері жару дайындығының сапасын тек сапалық деңгейде ғана ескереді, оның гранулометриялық құрам мен копсыту коэффициенті арқылы нақты сандық сипаттамасын бермейді. Осыдан жарылған тау массасының гранулометриялық құрамының қазыптисеу жабдықтарының өнімділігіне әсерін сандық бағалаудың ғылыми міндеті туындайды. *Мақсаты.* Осы жұмыстың мақсаты — гранулометриялық құрам параметрлерін карьерлік экскаваторлардың өнімділігімен байланыстыратын жалпыланған интегралдық математикалық модель әзірлеу. *Әдістер.* Бұл жұмыста жарылған тау массасының гранулометриялық құрамын сандық түрде байланыстыратын математикалық модель әзірленді, карьерлік экскаваторлардың өнімділігімен жалпыланған тәуелділіктер анықталды. *Нәтижелер.* Розин–Раммлер үлестірімінің параметрлері арқылы шөміштің толу коэффициенті K_t және қазу уақыты t_k үшін аналитикалық өрнектер алынды. Артық ұсақтау әсері (ұсақ фракцияның «майдалану» қозғалысы) толтыру коэффициенті моделіне тікелей енгізілген, ал модельдің тармақтары $d_{50}/d_c=0,7$ нүктесінде үздіксіз әрі бірқалыпты жалғасады. Гранулометрияны болжау үшін Кузнецов–Каннингем моделі (Kuz-Ram) қолданылады. Ұсақтау біркелкілігінің n көрсеткішіне байланысты өнімділік функциясының $d^*/d_c = 0,19-0,25$ аралығында бір ішкі максимумға ие болатыны көрсетілген. Нақты экскаватор моделі үшін кесектің оңтайлы кондициялық өлшемі d^* -ты анықтауға мүмкіндік беретін интегралдық есептеу рәсімі әзірленді. *Қорытынды.* Осылайша, ұсынылған тәсіл кесектердің мөлшер бойынша таралуын сипаттайтын барабар сандық көрсеткіштерді алуға мүмкіндік береді. Зерттеуде жүргізілген сезімталдық талдауы жару арқылы ұсақтау қарқындылығының қазу жабдығының өнімділігі максимумға жететін оңтайлы диапазоны бар екенін көрсетеді. Осы диапазоннан тыс шығу — ұсақталмау (ірі кондициялық емес кесектер, негабарит) жағына да, шектен тыс уақталу жағына да — шөміштің толу коэффициентінің төмендеуіне, демек, өнімділіктің төмендеуіне әкеледі. Зерттеу нәтижесінде алынған тәуелділіктер тау жыныстарын жарып қазуға дайындау сапасын автомобиль және теміржол көлігі бар тау-көлік кешендерінің жұмысының тиімділігін бағалау мен параметрлерін оңтайландыру кезінде оларды пайдаланудың нақты тау-техникалық, тау-геологиялық, тау-геометриялық, ұйымдастырушылық және экономикалық жағдайларында ескеруге мүмкіндік береді.

Түйін сөздер: карьерлік экскаватор, гранулометриялық құрам, шөміштің толу коэффициенті, қазу уақыты, кондициялық кесек өлшемі, Kuz-Ram, Розин–Раммлер таралуы, ЭКГ, өнімділік, жарылыспен дайындау

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МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ ЗАВИСИМОСТИ ПРОИЗВОДИТЕЛЬНОСТИ КАРЬЕРНЫХ ЭКСКАВАТОРОВ ОТ ГРАНУЛОМЕТРИЧЕСКОГО СОСТАВА И КОЭФФИЦИЕНТА РАЗРЫХЛЕНИЯ ВЗОРВАННОЙ ГОРНОЙ МАССЫ

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Аннотация. *Актуальность.* Степень дробления горной массы оказывает существенное влияние на эффективность последующих процессов экскавации и транспортирования. Существующие методики расчета производительности карьерных экскаваторов, как правило, учитывают качество взрывной подготовки горной массы преимущественно на качественном уровне, не обеспечивая достаточно точной количественной оценки влияния гранулометрического состава и коэффициента разрыхления на эффективность выемочно-погрузочных работ. В связи с этим актуальной научной задачей является разработка математических методов количественной оценки зависимости производительности карьерных экскаваторов от характеристик гранулометрического состава взорванной горной массы. *Цель.* Разработать интегральную математическую модель, устанавливающую количественную зависимость производительности карьерных экскаваторов от параметров гранулометрического состава взорванной горной массы и позволяющую определять оптимальные характеристики ее дробления. *Методы.* Исследование основано на математическом моделировании зависимости производительности карьерных экскаваторов от гранулометрического состава

взорванной горной массы. Для прогнозирования гранулометрического состава использована модель Кузнецова — Каннингема (Kuz-Ram). Распределение размеров кусков горной массы описано с использованием функции Розина — Раммлера. На основе аналитического подхода установлены зависимости коэффициента наполнения ковша и времени черпания от параметров гранулометрического распределения. Разработана интегральная расчетная процедура определения оптимального размера куска горной массы с учетом характеристик экскавационного оборудования. *Результаты.* Получены аналитические выражения, характеризующие зависимости коэффициента наполнения ковша K_n и времени черпания $t_{\text{ч}}$ от параметров распределения Розина — Раммлера. В математическую модель коэффициента наполнения ковша включен эффект переизмельчения горной массы, сопровождающийся пересыпанием мелких фракций. Обеспечены непрерывность и гладкость сопряжения ветвей модели при $d_{50}/d_c=0,7$. Установлено, что функция производительности имеет единственный внутренний максимум при $d^*/d_c = 0,19-0,25$ в зависимости от показателя равномерности дробления $\backslash(n\backslash)$. Разработана интегральная процедура расчета, позволяющая определять оптимальный кондиционный размер куска $\backslash(d^*\backslash)$ для конкретной модели карьерного экскаватора. *Выводы.* Разработанный подход позволяет количественно оценивать влияние гранулометрического состава взорванной горной массы на производительность карьерных экскаваторов и определять оптимальный диапазон интенсивности взрывного дробления, обеспечивающий максимальную эффективность выемочно-погрузочных работ. Полученные аналитические зависимости создают методическую основу для учета качества взрывной подготовки горных пород при оценке эффективности и оптимизации параметров функционирования горнотранспортных комплексов с автомобильным и железнодорожным транспортом. Предложенная модель может применяться с учетом конкретных горнотехнических, горно-геологических, геометрических, организационных и экономических условий эксплуатации карьерного оборудования.

Ключевые слова: карьерный экскаватор, гранулометрический состав, коэффициент наполнения ковша, время черпания, кондиционный кусок, Kuz-Ram, распределение Розина–Раммлера, ЭКГ, производительность, взрывная подготовка

Introduction. The performance of excavator–truck complexes (ETC) in open-pit mines is determined by a set of interrelated factors, among which the quality of blast preparation of the rock mass plays a key role. This is because the particle size distribution of the blasted muckpile directly affects three fundamental and interrelated parameters of the excavator cycle: bucket fill factor K_n , digging time $t_{\text{ч}}$, and specific digging resistance K_1 (Adushkin and Kryukov, 2014; Brunton et al., 2003). For excavator–truck and excavator–rail complexes as a whole, the same factor similarly affects the fill factor of the truck body or dump car and the volume of loaded rock mass.

At the same time, most existing normative productivity calculation methods account for fragmentation only through a binary qualitative classification of “well/poorly blasted” rock. A similar limitation is noted in foreign commercial methods developed by Hitachi, Caterpillar, and Komatsu (Caterpillar Performance Handbook, 2022). This makes the development of quantitative models that explicitly link fragmentation parameters with excavator productivity and the performance of mining and transport complexes an important task. The problem is extensive and multifactorial, which makes its mathematical description difficult to implement. Therefore, the aim of the present study was to construct an abstract integral mathematical model of the “blasting → fragmentation → excavation” system that can: (1) predict muckpile particle size distribution from blast design parameters; (2) analytically estimate the bucket fill factor (K_n) and digging time (t_d) using characteristic muckpile dimensions-the characteristic fragment size (d_p), the 80th-percentile size (P_{80}), and the uniformity index (n) of the size distribution; and (3) determine the optimum target fragment size (d^*) for a specific excavator size class. The resulting relationships can be effectively used to establish the relationship between the degree of rock loosening and the efficiency of the mining and transport complex using simulation, logical-statistical, and object-oriented modeling methods (Galiyev et al., 2026; Galiyev et al., 2026; Galiyev et al., 2023).

Materials and Methods. Basic excavator productivity model. The theoretical productivity (m^3/h) of a single-bucket power-shovel excavator is determined by the classical expression (Kuznetsov, 1973):

$$Q_r = \frac{3600 \cdot E \cdot K_n}{K_r \cdot t_d}, \quad (2.1)$$

where E is the bucket capacity, m^3 ; K_n is the bucket fill factor; K_r is the rock loosening coefficient; and t_d is the duration of the working cycle, s.

The value of K_r is directly and rather strongly determined by the particle size distribution of the blasted rock mass. As fragment size and heterogeneity increase, the packing density of the rock in the bucket decreases, causing the loosening coefficient to increase. According to experimental data (Yanchenko, 2019), when the share of the fine fraction (0–25 cm) decreases from 65% to 14% and the share of coarse fractions (100–180 cm) increases accordingly, the loosening coefficient in the excavator bucket increases from 1.27–1.38 to 1.76–1.98. Since productivity in Eq. (2.1) is expressed as the in-situ rock volume, an increase in K_r at the same geometric bucket capacity reduces the in-situ rock volume represented by one excavation cycle. This dependence of the loosening coefficient on muckpile fragmentation, together with rock strength and bulk density, determines the physical meaning of K_r in the denominator of Eq. (2.1).

The cycle duration is decomposed into the following components:

$$t_d = t_d + t_{noe} + t_p + t_{noe}' + t_{ep}, \quad (2.2)$$

where t_d is the digging time; $t_{пов}$ and $t_{пов}'$ are the rotation times of the loaded and empty buckets; t_p is the dumping time; and $t_{вп}$ is the auxiliary-operation time. Under normal operating conditions, $t_{пов} + t_{пов}' + t_p + t_{вп} = \text{const} \approx 25\text{--}30$ s for ECG-8I... ECG-18 excavators. Thus, fragmentation affects t_d mainly through t_d and K_n .

Operational productivity accounting for working-time utilization:

$$Q_3 = Q_T \cdot K_{сп} \cdot K_{tex} \quad (2.3)$$

where K_n is the working-time utilization coefficient (0.75–0.85); $K_{тр}$ is the technical availability coefficient (0.80–0.92).

Muckpile particle size distribution model (Kuz-Ram)

Mean fragment size equation

The Kuznetsov–Cunningham (Kuz-Ram) model (Kuznetsov, 1973; Cunningham, 2005) is used to predict the particle size distribution of blasted rock mass. The mean fragment size is determined from the Kuznetsov equation:

$$d_{50} = A \cdot \left(\frac{f}{10}\right)^{0.8} \cdot (E_{всп})^{-0.633}, \quad (3.1)$$

where A is the coefficient accounting for rock-mass structure (5–13); f is the Protodyakonov rock-strength coefficient; and q is the specific explosive consumption, kg/m³.

Rosin–Rammler distribution

The cumulative fragment-size distribution is described by the two-parameter Rosin–Rammler law:

$$F(d) = 1 - \exp\left[-\left(\frac{d}{d_p}\right)^n\right], \quad (3.2)$$

where d_p is the characteristic size (d for which $F = 1 - 1/e \approx 0.632$); n is the fragmentation uniformity index. The characteristic size d_p is related to the mean size by:

$$d_p = \frac{d_{50}}{(\ln 2)^{1/n}}. \quad (3.3)$$

The uniformity index n is determined using the Blastek–Cunningham formula:

$$n = 2,2 - 14 \cdot \frac{B}{D} \cdot \left(1 - \frac{W}{B}\right)^2 \cdot \left(\frac{L_c}{L}\right)^{0,1}, \quad (3.4)$$

where B is the spacing between blasthole rows, m; D is the blasthole diameter, m; W is the burden, m; L_c is the explosive charge length, m; and L is the blasthole length, m.

Target size class

The percentage of fragments larger than d_k (oversize fragments) is determined from (3.2):

$$R(d_k) = \exp \left[- \left(\frac{d_k}{d_p} \right)^n \right]. \quad (3.5)$$

The target fragment size d_k is taken as ..., where ... is the linear opening size of the bucket (Chung and Katsabanis, 2000):

$$d_k = 0,6 \cdot d_3 = 0,6 \cdot \left(\frac{2E}{\pi} \right)^{1/3}. \quad (3.6)$$

Let the dimensionless fragment size be $\xi = d_{50}/d_3$. Taking Eqs. (3.3) and (3.6) into account, the oversize fraction can be expressed explicitly in terms of ξ :

$$R(\xi) = \exp \left[- \ln 2 \cdot \left(\frac{0,6}{\xi} \right)^n \right]. \quad (3.7)$$

MAIN PART: Analytical models of K_n and t_4 as functions of fragmentation
Bucket fill factor

Based on a generalization of field observations (Brunton et al., 2003; Osanloo and Hekmat, 2005),

The bucket fill factor is represented as the product of two factors reflecting opposing effects: reduced filling as fragment size increases and filling losses caused by over-fragmentation of the rock mass:

$$K_n(\xi) = K_n^0 \cdot [1 - \kappa \cdot F_f(\xi)] \cdot G(\xi), \quad (4.1)$$

where K_n^0 is the baseline bucket fill factor (determined by rock density and bucket design: 0.90–0.97 for soft rocks and 0.82–0.90 for strong rocks).

The factor $G(\xi)$ describes the decrease in bucket filling as fragment size increases. Based on a generalization of field observations [2, 8], the following regression relationship was obtained for $\xi \in [0; 0.7]$:

$$G(\xi) = 1 - \alpha_1 \xi - \alpha_2 \xi^2, \quad 0 \leq \xi \leq 0,7, \quad (4.1a)$$

where $\alpha_1 = 0.18$ and $\alpha_2 = 0.35$ are regression coefficients.

For $\xi > 0.7$, K_n decreases sharply because large fragments hang up in the bucket (the “arching” effect). To avoid a discontinuity at the branch junction, this branch is written so that both the function value and its first derivative coincide at $\xi = 0.7$:

$$G(\xi) = G(0,7) \cdot \exp[-\lambda(\xi - 0,7) - \beta(\xi - 0,7)^2], \quad \xi > 0,7, \quad (4.2)$$

where $G(0.7) = 1 - 0.7\alpha_1 - 0.49\alpha_2 = 0.7025$; $\lambda = (\alpha_1 + 1.4\alpha_2)/G(0.7) = 0.954$ is the coefficient ensuring equality of derivatives at the junction; $\beta = 3.8$.

The factor $[1 - \kappa \cdot F_f(\xi)]$ accounts for over-fragmentation: fine material is retained less effectively in the bucket and partly spills during lifting and swinging (“spillage”). The fine-fraction share is determined from the Rosin–Rammler distribution (3.2):

$$F_f(\xi) = 1 - \exp \left[-\ln 2 \cdot \left(\frac{\xi_f}{\xi} \right)^n \right], \quad (4.16)$$

where $\xi_f = df/d\phi$ is the relative fine-fraction threshold ($\xi_f = 0.15$ is adopted); κ is the fill-loss coefficient due to the fine fraction ($\kappa = 0.3$ is adopted).

Digging time

Digging time is determined by the crowd-force mechanism power, specific digging resistance, and face characteristics. The generalized model is:

$$t_d(\xi) = t_d^0 \cdot [1 + \gamma_1 \xi + \gamma_2 \xi^{1.5} R(\xi)], \quad (4.3)$$

where t_d^0 is the baseline digging time for finely fragmented rock, s; $\gamma_1 = 0.22$ and $\gamma_2 = 0.58$ are empirical coefficients; $R(\xi)$ is the fraction of oversize fragments according to Eq. (3.7).

The physical meaning of the terms is as follows: the first term (γ_1) reflects the increase in resistance force with increasing mean fragment size; the second term ($\gamma_2 \cdot R$) represents the additional time required to break and move oversize fragments.

Overall productivity function

Substituting Eqs. (4.1)–(4.3) into Eqs. (2.1) and (2.2) gives productivity as a function of the fragmentation parameters:

$$Q_T(\xi, n) = \frac{3600 \cdot E \cdot K_H(\xi, n)}{K_p \cdot [t_d(\xi, n) + t_{const}]}. \quad (4.4)$$

As $\xi \rightarrow 0$, productivity decreases because of the factor $[1 - \kappa F_f]$, whereas at large ξ it decreases because $G(\xi)$ declines and t_d increases. Therefore, the $Q_T(\xi)$ function has a single interior maximum at $\xi = \xi^* = d^*/d\phi$, determined from the condition $dQ_T/d\xi = 0$.

Figures 1 and 2 present the results calculated from Eq. (4.4) for the following parameters: $K_n^0 = 0.92$; $\alpha_1 = 0.18$; $\alpha_2 = 0.35$; $\beta = 3.8$; $\lambda = 0.954$; $\kappa = 0.3$; $\xi_f = 0.15$; $E = 8 \text{ m}^3$; $K_r = 1.35$; $t_{const} = 20 \text{ s}$; $t_d^0 = 18 \text{ s}$; $\gamma_1 = 0.22$; $\gamma_2 = 0.58$.

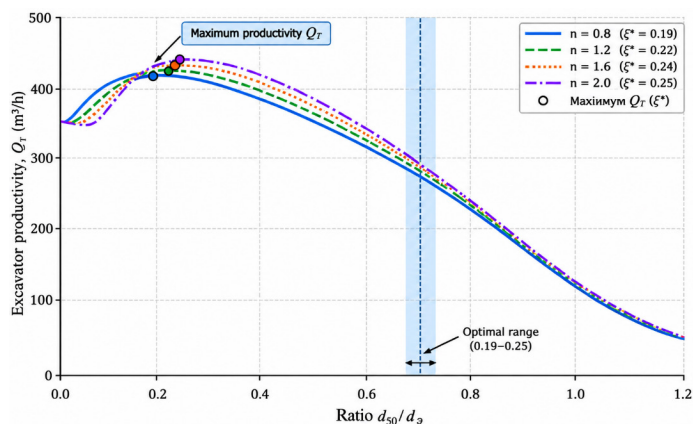


Figure 1. “Dependence of $Q_T(d_{50})$ for different values of n ”.

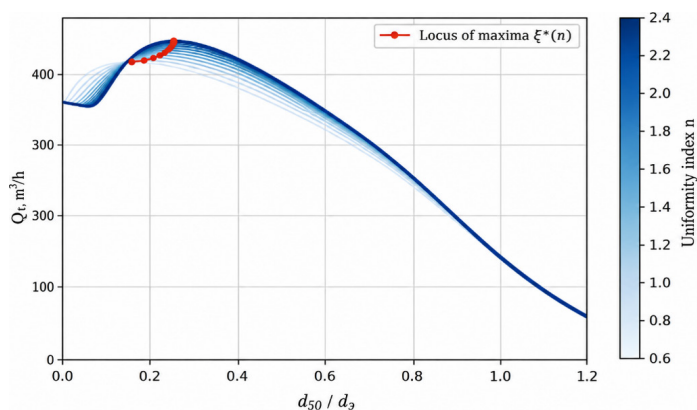


Figure 2. Family of cross-sections of the $Q_T(d_{50}/d_0, n)$ surface and the locus of maxima $\xi^*(n)$.

As shown in Figures 1 and 2, the $Q_T(\xi)$ curves are continuous over the entire interval, including the branch-junction point $\xi = 0.7$. The productivity maximum shifts toward larger ξ as the uniformity index n increases: $\xi^* = 0.19, 0.22, 0.24$, and 0.25 for $n = 0.8, 1.2, 1.6$, and 2.0 , respectively. More uniform fragmentation (higher n) provides not only a higher maximum Q_T but also a narrower over-fragmentation zone.

Determination of the optimum target fragment size d^*

The condition $dQ_T/d\xi = 0$ for model (4.4), taking Eqs. (4.1)–(4.3) into account, leads to the following transcendental equation for ξ^* :

$$\frac{\Phi'(\xi)}{\Phi(\xi)} + \frac{G'(\xi)}{G(\xi)} = \frac{t_v'(\xi)}{t_v(\xi) + t_{const}}, \quad (3.1)$$

where $\Phi = 1 - \kappa Ff(\xi)$, the derivatives have the form:

$$\begin{aligned}\Phi'(\xi) &= \kappa \cdot \ln 2 \cdot n \cdot \frac{1}{\xi} \left(\frac{\xi_f}{\xi} \right)^n \exp \left[-\ln 2 \cdot \left(\frac{\xi_f}{\xi} \right)^n \right], \\ G'(\xi) &= -(\alpha_1 + 2\alpha_2 \xi), \quad 0 \leq \xi \leq 0,7, \\ t_{\varphi}'(\xi) &= t_{\varphi}^0 \left[\gamma_1 + \gamma_2 R(\xi) \xi^{0,5} \left(1,5 + n \ln 2 \left(\frac{0,6}{\xi} \right)^n \right) \right].\end{aligned}$$

The left-hand side of Eq. (5.1) is positive at small ξ (the over-fragmentation effect dominates) and negative at large ξ , whereas the right-hand side is always positive; therefore, the equation has a unique root within the interval. Equation (5.1) is solved by the bisection method for each excavator class; the optimum fragment size is $d^* = \xi^* \cdot d_0$. The numerical solutions for the range of machines are given in Table 1.

Table 1. Optimum target fragment size and expected productivity for a range of excavators (rock strength $f = 8\text{--}10$, $n = 1.2$).

Excavator	Bucket capacity, m^3	d_0 , m	dk , m	Q_T , m^3/h	$K_n(d^*)$	d^* , m
ECG-5A	5	1.47	0.88	265	0.78	0.33
ECG-8И	8	1.72	1.03	425	0.78	0.38
ECG-12	12	1.97	1.18	637	0.78	0.44
ECG-18	18	2.25	1.35	955	0.78	0.50
ECG-32P	32	2.73	1.64	1698	0.78	0.61
WK-20	20	2..34	1.40	1061	0.78	0.52
WK-35	35	2.81	1.69	1857	0.78	0.62
PC-8000	38	2.89	1.74	2017	0.78	0.64

Note: $d_0 = (2E/\pi)^{1/3}$; $dk = 0.6 \cdot d_0$; $d^* = \xi^* \cdot d_0$, $\xi^* = 0.222$, obtained by solving Eq. (5.1) for $n = 1.2$. Q_T values were calculated using the same $t_{\varphi 0} = 18$ s, $t_{\text{const}} = 20$ s, and $K_r = 1.35$ for all machines and are intended for comparison; for a specific machine, they should be refined using the manufacturer-specified cycle time.

Numerical study and model verification

Effect of d_{50}/d_0 on K_n , t_{φ} , and Q_T

A parametric study was performed for the ECG-8И excavator ($E = 8 \text{ m}^3$, $d_0 = 1.72$ m, $n = 1.2$) based on equations (4.1)–(4.4). The results are presented in Table 2.

Table 2. Effect of the dimensionless fragment size d_{50}/d_0 on excavation parameters (ECG-8И).

d_{50}/d_0	d_{50} , m	K_n	t_{φ} , s
0.10	0.17	0.72	18.4
0.22 (ξ^*)	0.38	0.78	19.0
0.30	0.52	0.78	19.5
0.50	0.86	0.72	21.5
0.70	1.20	0.63	24.2
0.90	1.55	0.45	27.4

The table shows that productivity reaches a maximum at $d_{50}/d^* \approx 0.22$, corresponding to $d^* \approx 0.38$ m for the ECG-8I. Within $\xi = 0.15\text{--}0.30$, productivity differs from the maximum by no more than 2–3%, i.e., the optimum is relatively flat. With over-fragmentation ($\xi = 0.10$), Q_T decreases by 6% because of filling losses, whereas increasing the muckpile size to $\xi > 0.7$ reduces productivity by more than 29% because t_T increases and K_n decreases. Validation using data from operating mines

To assess the adequacy of the proposed mathematical model (4.1)–(4.4), calculated optimum median fragment sizes d^* were compared with published field data from operating mines developing hard rock.

Three independent sources containing documented field studies of the effect of blasted-rock fragmentation on loading-equipment productivity were used as the validation basis.

Source 1. Brunton, Thornton, Brunton & Péré (2003) — Granny Smith mine, Western Australia. The study was conducted using a Liebherr 994 hydraulic excavator (14 m³ bucket) in hard rock ($f = 8\text{--}10$). Fragmentation was determined using Split Desktop for each truck haul. A reduction in P_{80} from 600 to 200 mm increased productivity by 26%; optimum bucket loading was achieved at $P_{50} \approx 0.38\text{--}0.42$ m [Brunton et al., 2003].

Source 2. Beyglou, Johansson & Schunnesson (2017) — Aitik mine, Sweden (Boliden Mineral AB). This is the largest open-pit mine in Northern Europe, producing copper-porphyry ores ($f = 6\text{--}9$). Correlation analysis of 225 loading cycles showed that rope-shovel loading efficiency decreases sharply at $P_{80} > 800$ mm; the target value is $P_{80} = 600\text{--}800$ mm, corresponding to $P_{50} \approx 0.36\text{--}0.40$ m [Beyglou et al., 2017].

Source 3. Osanloo & Hekmat (2005) — Gol-e-Gohar mine, Iran. Based on a modified Rosin–Rammler–Bennett distribution and image analysis, excavator productivity was found to decrease by up to 38% when P_{80} increased from 400 to 800 mm. The bucket fill factor, which depends on fragmentation and operator skill, was identified as the main productivity-determining factor (Osanloo and Hekmat, 2005).

Table 3. Comparison of calculated and actual d^* based on data from operating mines (sources: (Osanloo & Hekmat, 2005; Brunton et al., 2003; Beyglou et al., 2017)).

Mine (country)	Rock, f	Excavator, E , m ³	d_0 , m	Calculated d^* , m ($n = 0.8\text{--}1.6$)	Actual d^* , m ¹
Granny Smith (Australia) ²	8–10	Liebherr 994, 14	2,07	0,39–0,50	0,40
Aitik (Sweden) ³	6–9	-	-	-	~0,36–0,40
Gol-e-Gohar (Iran) ⁴	10–14	-	-	-	0,40–0,80

Notes to Table 3:

¹ Actual d^* values are presented as P_{50} of the blasted rock mass based on image analysis (Split Desktop / WipFrag).

² Brunton et al. (2003): Granny Smith mine, Placer Dome Asia Pacific, Western Australia. Liebherr 994 (14 m³). P_{80} varied from 200 to 1200 mm; reducing P_{80} from 600 to 200 mm increased productivity by 26%.

³ Beyglou, Johansson & Schunnesson (2017): Aitik mine, Boliden Mineral AB, Sweden. Target P_{80}

= 600–800 mm for maximum loading efficiency; P_{50} was estimated from the P_{50}/P_{80} correlation ≈ 0.45 – 0.50 .

⁴ Osanloo & Hekmat (2005): Gol-e-Gohar mine, Iran. Direct P_{50} data are not provided in the source; the range was estimated using the modified Rosin–Rammler–Bennett distribution.

⁵ Field data for P_{50} are unavailable; only calculated values from the proposed model are provided.

For the Granny Smith mine, for which the most complete primary data are available, the actual $P_{50} = 0.40$ m lies within the calculated d^* range of 0.39 – 0.50 m and corresponds to the lower end of $n \approx 0.8$ – 1.0 , which is characteristic of strong fractured rocks. For the Aitik and Gol-e-Gohar mines, the reported optimum sizes (0.36 – 0.80 m) are of the same order of magnitude as the calculated d^* values for excavators with 10 – 40 m³ buckets (0.36 – 0.66 m, Table 1); quantitative comparison requires bucket-capacity and n data.

Sensitivity analysis of productivity to blast-design parameters

The sensitivity analysis was performed to establish a quantitative relationship between specific explosive consumption (q , kg/m³) and the technical productivity of the ECG-12 excavator (Q_T). The Kuz-Ram model is used as the link, allowing the median fragment size d_{50} to be expressed as a function of q , rock-mass characteristics, and blast-pattern geometry.

The calculation was performed under fixed geotechnical conditions: Protodyakonov strength $f = 10$ – 12 , bench height $H = 12$ m, blasthole diameter $d = 250$ mm, and emulsion explosive type EM-1. The range of specific explosive consumption was $q = 0.30$ – 0.70 kg/m³.

Dependence of d_{50} on specific explosive consumption

According to the Kuz-Ram model (Cunningham, 1983), the mean fragment size is determined by:

$$d_{50} = A \cdot \left(\frac{V_0}{Q_{RR}} \right)^{0.8} \cdot Q_{BB}^{1/6} \cdot \left(\frac{115}{E_{OTK}} \right)^{19/30}, \quad (6.1)$$

where A is the rock coefficient ($A = 7$ – 13 for hard rocks); V_0 is the rock volume per blasthole, m³; Q_{BB} is the explosive charge mass in the blasthole, kg; and E_{rel} is the relative explosive energy compared with ANFO.

As specific explosive consumption increases from $q = 0.35$ to 0.55 kg/m³, the median fragment size d_{50} decreases from 0.58 to 0.37 (Table 4) m. Further increasing explosive consumption above $q > 0.60$ kg/m³ reduces d_{50} by less than 0.05 m for each 0.05 kg/m³ increase in specific consumption, indicating saturation of the fragmentation effect.

Effect of specific explosive consumption on ECG-12 productivity

Substituting the dependence $d_{50}(q)$ into equation (4.4) allows excavator productivity to be expressed directly as a function of specific explosive consumption: $Q_T = Q_T(d_{50}(q))$. The calculation results for ECG-12 ($E = 12$ m³, $d_3 = 1.97$ m, $n = 1.2$) are presented in Table 4.

Table 4. Dependence of EKG-12 productivity on specific explosive consumption.

q, kg/m ³	d ₅₀ , m	d ₅₀ /d ₃	K _n	Q _T , m ³ /h	ΔQ _T , %
0.30	0.65	0.33	0.77	621	-1.3
0.35	0.58	0.29	0.78	629	—
0.40	0.51	0.26	0.78	635	+0.9
0.45	0.45	0.23	0.78	637	+1.2
0.50	0.40	0.20	0.77	636	+1.2
0.52	0.39	0.20	0.77	636	+1.1
0.55	0.37	0.19	0.77	635	+0.9
0.60	0.33	0.17	0.76	631	+0.3
0.70	0.27	0.14	0.75	620	-1.4

Note: ΔQ_T is the change relative to the baseline case q = 0.35 kg/m³.

The data in Table 4 show that technical productivity Q_T reaches a maximum at q ≈ 0.45–0.50 kg/m³ (d₅₀ = 0.40–0.45 m, d₅₀/d₃ ≈ 0.20–0.23), which corresponds to the solution of Eq. (5.1) for EKG-12 (d* ≈ 0.44 m, Table 1). At the same time, over q = 0.35–0.60 kg/m³ the muckpile remains within a broad, flat optimum, and the productivity increase does not exceed 1.2%. At q > 0.55 kg/m³, productivity begins to decrease because of over-fragmentation (d₅₀/d₃ < 0.19) and an increased share of fine material, which is retained less effectively in the bucket (the “spillage” effect).

Optimum specific explosive consumption

From an economic perspective, the optimum specific explosive consumption q* is determined by minimizing the total unit costs of blasting and excavation:

$$C(q) = q \cdot C_{\text{ББ}} + \frac{C_{\text{Маш}}}{Q_{\text{T}}(q)} \rightarrow \min, \quad \frac{dC}{dq} = 0 \Rightarrow C_{\text{ББ}} = \frac{C_{\text{Маш}}}{Q_{\text{T}}^2} \cdot \frac{dQ_{\text{T}}}{dq}, \quad (6.2)$$

where C_{ББ} is the explosive cost, RUB/kg; C_{Маш} is the excavator machine-hour cost, RUB/h.

For open-pit conditions using emulsion explosives, with an explosive cost of approximately RUB 850/kg and an EKG-12 machine-hour cost of approximately RUB 18,000/h, increasing q by 0.10 kg/m³ raises explosive costs by approximately RUB 85/m³, whereas the excavation saving due to the increase in Q_T (Table 4) is less than RUB 0.5/m³. Therefore, considering the excavation stage alone, increasing q beyond the value required to reach the flat optimum zone is not economically justified, and the technical optimum

$$q_{\text{T}}^* \approx 0,45-0,50 \text{ кг/м}^3, \quad d_{50}(q_{\text{T}}^*) \approx 0,40-0,45 \text{ м} \quad (6.3)$$

should be considered the upper bound of the rational specific explosive consumption. The final choice of q* requires consideration of downstream processes (transportation, crushing, and secondary crushing of oversize), which is beyond the scope of the present study and is a subject for further research. The cost

parameters given are indicative and should be refined for the specific conditions of the deposit being developed.

Thus, the sensitivity analysis demonstrates that there is an optimum range of blast fragmentation intensity at which excavator technical productivity reaches a maximum. Exceeding this range either toward insufficient fragmentation (large oversize fragments) or toward excessive fragmentation leads to a decrease in the bucket fill factor and, consequently, a reduction in productivity.

Results and Discussions. The proposed model has several fundamental advantages over normative methods: it explicitly accounts for the continuous fragment-size distribution rather than a binary qualitative assessment, links blast-design parameters to productivity through physically justified equations, and allows analytical optimization without iterative simulation. Incorporation of the over-fragmentation effect and smooth coupling of the bucket-fill branches ensure the existence of a single interior productivity maximum.

The limitations of the model arise from the following assumptions: (1) isotropic fragmentation (constant n throughout the muckpile); (2) neglect of the effects of moisture and temperature on rock rheology; and (3) linear approximation of digging resistance at small d/d_0 ; and (4) the over-fragmentation parameters κ and ξ_f are based on preliminary estimates and require calibration against field observations. Limitations (1) and (2) can be addressed by integrating DEM-based blast modeling with ML prediction of rock-mass parameters [Hamdi and Mouza, 2005].

The results are consistent with field studies of Osanloo and Hekmat (2005) and Beyglou et al. (2017), according to which the best loading performance is achieved at a median fragment size of approximately 0.36–0.42 m for excavators with 10–40 m³ buckets, although the exact values depend on excavator type and the physical and mechanical properties of the rock.

The study established abstract relationships between excavator productivity and the fragmentation of blasted rock mass. The limitations include the lack of adequate consideration of the influence of useful bucket load on digging time and, consequently, excavator productivity, as well as the traction forces and energy consumption associated with excavation. However, the results provide a basis for further qualitative treatment of these issues, which are necessary for optimizing excavator productivity and the performance of mining and transport complexes as a whole (Shibanov et al., 2024; Annakulov et al., 2023; Annakulov et al., 2023).

Conclusion. A mathematical model has been developed that quantitatively relates the particle size distribution of blasted rock mass to the productivity of single-bucket open-pit excavators. The main scientific results are:

1. Analytical expressions for K_n and t_4 were obtained as functions of the dimensionless ratio d_{50}/d_0 and the oversize fraction $R(d_k)$ based on the Rosin–Rammler distribution; the over-fragmentation effect was incorporated into the K_n model, and the model branches were coupled continuously and smoothly.

2. A procedure was developed to determine the optimum target fragment size d^* from a transcendental equation (5.1), solved for each excavator size class.

3. The relative optimum fragment size was found to be $d^*/d_0 = 0.19\text{--}0.25$ and to increase with the uniformity index n ; for eight excavator types ($E = 5\text{--}38 \text{ m}^3$), $d^* = 0.33\text{--}0.64 \text{ m}$ at $n = 1.2$.

4. For the Granny Smith mine, the actual $P50 = 0.40 \text{ m}$ lies within the calculated d^* range of $0.39\text{--}0.50 \text{ m}$; data from the other mines are consistent with the calculations in order of magnitude

5. For strong rocks ($f = 8\text{--}12$), technical excavator productivity reaches a maximum at $q \approx 0.45\text{--}0.50 \text{ kg/m}^3$, while further increases in specific explosive consumption do not increase productivity and are not economically justified.

The practical significance of the study lies in the possibility of applying the developed algorithm in blast-design planning at open-pit mines in Uzbekistan, including the conditions of Almalyk Mining and Metallurgical Complex (AMMC), to coordinate blast parameters with ETC productivity.

The relationships obtained in this study make it possible to account for the quality of rock preparation for excavation by blasting when evaluating the efficiency and optimizing the operating parameters of mining and transport complexes using truck and rail haulage under specific geotechnical, geological, geometric, organizational, and economic operating conditions.

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