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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.

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«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.

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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).

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METHODS FOR CALCULATING TRANSPORT ENERGY CONSUMPTION AND ROCK EXCAVATION PRODUCTIVITY USING AN INERTIAL ROTOR

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Abstract. *Relevance.* Full-rotation boom rotary excavators play a leading role in ensuring high efficiency of excavation and transportation operations using continuous-action equipment. These excavators are being improved by increasing their unit power within optimal limits while simultaneously changing their dimensions, metal consumption, energy consumption and reducing the cost per unit of excavated material. *Objective.* The article provides a comparative analysis of methods for calculating the energy costs of transporting rock excavated by an inertial rotor, considering the cut material along the profile of the worked layer as a continuous flow of variable mass, and in the second case, representing the same cut volume in the working process as constant within the rotor transport sector. *Methods.* At the same time, both of these calculation methods boil down to simple, simplified engineering calculations, which allows for the analysis of their values over a wide range depending on the rotor diameter and the parameters of the cutting and transport elements, as well as the digging speed. *Results.* Such analysis confirms the acceptability of the calculation methods for practical use and helps to determine the basic parameters and location of the cutting and transport elements on the rotor shell. *Conclusions.* One of the promising areas for the development of excavation and transport machines is the unconventional process of processing rock with a rotor from top to bottom, with the collapse and transport of the cut material along the face, chute, and subsequent discharge onto the receiving conveyor belt as the rotor rotates. In the inertial rotor, the buckets are replaced by a pair of knives located at an angle to the generating shell. The unconventional process of rock excavation and the new design of the working body for continuous-action excavators discussed in the article are, in general, of certain interest for further research.

Keywords: inertial rotor, bucket rotor, bucketless rotor, cutting and transportation elements, digging energy consumption, excavated rock masses, removable layer of rock

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КӨЛІКТІК ЭНЕРГИЯ ШЫҒЫНЫН ЖӘНЕ ТАУ ЖЫНЫСТАРЫН ИНЕРЦИЯЛЫҚ РОТОРМЕН ҚАЗУ ӨНІМДІЛІГІН ЕСЕПТЕУ ӘДІСТЕРІ

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Аннотация. *Өзектілігі.* Үздіксіз әрекет ету техникасын пайдалана отырып, экскавациялық-көлік жұмыстарының жоғары тиімділігін қамтамасыз етуде толық айналмалы жебелі роторлы экскаваторлар жетекші рөл атқарады, оларды жетілдіру габариттерді, металл сыйымдылығын, энергия сыйымдылығын бір мезгілде өзгерту және экскавариацияланатын материал бірлігінің құнын төмендету кезінде олардың бірлік қуатының оңтайлы шегінде арттыру жолымен жүреді. *Мақсаты.* Мақалада тау жыныстарын инерциялық ротормен экскавациялаудың көліктік энергия шығындарын есептеу әдістеріне салыстырмалы талдау жасалады, өңделетін қабаттың профилі бойынша кесілген материалды айнымалы массаның үздіксіз ағыны ретінде қарастырады, ал екінші жағдайда жұмыс процесінде бірдей кесілген көлемді ротормен көлік секторы шегінде тұрақты түрде ұсынады. *Әдістері.* Сонымен қатар, бұл есептеу әдістерінің екеуі де ротордың диаметріне және кесу-тасымалдау элементтерінің параметрлеріне, сондай-ақ қазу жылдамдығына байланысты олардың мәндерін кең ауқымда талдауға мүмкіндік беретін қарапайым жеңілдетілген инженерлік есептеулерге дейін азаяды. *Нәтижелері.* Мұндай талдау есептеу әдістерінің практикалық қолдануға жарамдылығын растайды және ротордың қабығындағы кесу және тасымалдау элементтерінің негізгі параметрлері мен орналасуын анықтауға көмектеседі. *Қорытындылар.* Экскавациялық-көліктік машиналарды дамытудың перспективалы бағыттарының бірі – ротордың айналу барысы бойынша кесілген материалдың кенжар, науа бойынша құлауымен және тасымалдануымен және кейіннен оны қабылдау конвейерінің лентасына лақтырумен тау жыныстарын жоғарыдан төмен қарай ротормен өңдеудің дәстүрлі емес процесі. Инерциялық роторда шөміштер пайда болған қабыққа бұрышпен орналасқан жұп пышақтармен ауыстырылады. Мақалада қарастырылған тау жыныстарын экскавациялаудың мұндай дәстүрлі емес процесі және үздіксіз экскавациялық машиналар үшін жұмыс органының жаңа конструктивті орындалуы, жалпы алғанда, одан әрі зерттеуге белгілі бір қызығушылық тудырады.

Түйін сөздер: инерциялық ротор, шөмішті ротор, шөмішсіз ротор, кесу-тасымалдау элементтері, қазудың энергия шығыны, экскавацияланатын тау массалары, алынатын тау жынысының қабаты

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МЕТОДЫ РАСЧЕТА ТРАНСПОРТНЫХ ЭНЕРГОЗАТРАТ И ПРОИЗВОДИТЕЛЬНОСТИ КОПАНИЯ ГОРНЫХ ПОРОД ИНЕРЦИОННЫМ РОТОРОМ

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Аннотация. *Актуальность.* Ведущую роль в обеспечении высокой эффективности экскавационно-транспортных работ с применением техники непрерывного действия играют полноповоротные стреловые роторные экскаваторы. Их совершенствование направлено на повышение единичной мощности в оптимальных пределах при одновременном изменении габаритных параметров, металлоёмкости и энергоёмкости, а также снижении затрат на экскавацию единицы горной массы. *Цель.* Провести сравнительный анализ методов расчёта транспортных энергозатрат и производительности экскавации горных пород инерционным ротором на основе двух подходов к представлению срезаемого материала: как непрерывного потока переменной массы и как постоянного объёма в пределах транспортирующего сектора ротора. *Методы.* Первый метод основан на представлении материала, срезанного по профилю разрабатываемого слоя, в виде непрерывного потока переменной массы. Второй метод предполагает рассмотрение того же объёма срезанного материала как постоянной массы в пределах транспортирующего сектора ротора. Оба метода сводятся к упрощённым инженерным расчётам, что позволяет анализировать полученные значения в широком диапазоне изменения диаметра ротора, параметров режуще-транспортных элементов и скорости копания. *Результаты.* Проведённый анализ подтвердил применимость предложенных методов расчёта в инженерной практике. Полученные зависимости позволяют определять основные параметры режуще-транспортных элементов и обосновывать их рациональное расположение на обечайке ротора. *Выводы*. Одним из перспективных направлений развития экскавационно-транспортных машин является применение нетрадиционного процесса разработки горных пород инерционным ротором сверху вниз. Этот процесс предусматривает обрушение и транспортирование срезаемого материала по забою и лотку с последующим его выбросом на ленту приёмного конвейера по направлению вращения ротора. В конструкции инерционного ротора ковши заменены парой ножей, расположенных под углом к образующей поверхности обечайки. Рассмотренные процесс экскавации горных пород и конструктивное исполнение рабочего органа представляют практический и научный интерес для дальнейшего совершенствования экскавационных машин непрерывного действия.

Ключевые слова: инерционный ротор; ковшовый ротор; бесковшовый ротор; режуще-транспортные элементы; энергозатраты копания; экскавируемая горная масса; снимаемый слой горной породы

Introduction. Continuous operation technology, and primarily rotary excavators, plays a significant role in the intensification of open-pit mining worldwide. The spread of this technology is facilitated by the well-known advantages of such machines: continuity of the working process, significantly higher productivity, and lower energy consumption compared to single-bucket excavators. The technological advantages of rotary excavators include the possibility of using flow technology, selective excavation, and obtaining the required lumpiness of the mined rock (Abramov, 2012; Balovnev, 1981).

In Kazakhstan, full-turn swing rotary excavators have become widespread at the Ekibastuz coal mines, which operate the most modern excavators, including, for example, the largest rotary complex, the ERShRD-5000, which can load 70 railway cars in half an hour (Liberman et al., 2024; Berezhnoi, 1979).

The principle of operation of a boom rotary excavator is based on the rotation of buckets attached to a rotary wheel. The rotor digs into the rock, filling the buckets with rock. The buckets of a rotary excavator can be unloaded in two ways: by gravity or by centrifugal force. The rock is unloaded onto a conveyor located on the side of the excavator, after which it is fed onto the unloading conveyor by means of a transfer system.

The rock mass is excavated in two independent movements: relative movement, which involves the repeated continuous movement of buckets or their replacement elements together with the working body along a closed trajectory relative to the supporting frame, and transfer movement, which involves the movement of the frame together with the working body, also known as feed. At the same time, unlike a single-bucket excavator, in which all operations of the working process are performed sequentially with the mandatory participation of the bucket, in a continuous-action excavator, the same operations are combined in time and functionally divided between the buckets and the transporting device (Blouin et al., 2001; Hartlieb and Bock, 2018; Korneev et al., 1990).

The boom rotary excavator is equipped with emergency lighting systems, fire extinguishing systems for electrical equipment rooms, dust suppression (irrigation) systems in areas where rock is loaded and unloaded and in the excavation zone, as well as a heating system for the loading and unloading units of the conveyor line and the gearboxes of the main mechanisms. The control cabins and electrical equipment rooms are equipped with ventilation, heating, and air conditioning systems.

To date, the reserves for further increasing the productivity and digging force of existing rotary excavators have been exhausted, since the gravity rotors with which the excavators are equipped limit the increase in rotation speed and digging force due to design and technological reasons: the buckets are unloaded in the upper position under the weight of the rock they contain, and the chips are separated when the rotor rotates from bottom to top relative to the face (Kozbagarov et al., 2026; Kuznetsova and Savinkin, 2017; Labutin et al., 2005).

With the growing volume of excavation and transportation work, estimated at tens of billions of cubic meters per year in the Commonwealth of Independent States, in the mining industry, it is necessary to make wider use of new continuous-action equipment that offers high productivity and mobility with low specific weight and is capable of developing high-density rock masses with reduced specific energy consumption (Lieberman et al., 2022; Machniak and Koziol, 2017).

The intensification of mining operations is mainly carried out on the basis of the creation and introduction into production of fundamentally new technologies and materials, the creation of machines with high unit power and productivity, and units operating on the basis of new technical effects. The implementation of these provisions is based on improving the efficiency of research and reducing the time required to introduce scientific and technological achievements into production (Bugaric et al., 2020; Konyrbekov, 2015; Kozbagarov et al., 2022).

For large-scale mining operations and open-pit mining, continuous-action equipment with rotary excavators as the main machines has become widely used both abroad and in our country. The use of this high-performance equipment contributes to the introduction of progressive and effective technological schemes for conducting work, allows for a significant improvement in conditions and increased labor productivity, and more clearly resolves issues of non-emergency impact on the environment (Kozbagarov et al., 2023b).

Continuous working process of rotary excavators allows to apply the most effective flow technology in the production of works. The practice of excavation and surface mining works shows that the most effective use of rotary excavators in the development of soft and medium hardness soils, rocks and coals.

At the same time, the area of application of rotary excavators in recent years is significantly expanding. Nowadays rotary excavators are spread in many countries of the world, they are operated in various climatic conditions and are used in different branches of production.

Along with open-pit mining, rotary excavators are widely used in various types of earthmoving operations in construction: road construction, hydraulic engineering, quarries of construction materials, as well as in loading and unloading operations, etc. Rotary excavators used in construction are characterized by small size, low weight, increased mobility and maneuverability, which allows their use even in tight spaces and facilitates transfer from site to site.

In recent years in rotary excavator construction a number of highly efficient working bodies have been created, operating at high speeds with increased digging forces and having a large transport capacity. All these requirements of the technical improvement of continuous technology are met by the inertial rotor of bottom discharge with a non-traditional method of face mining (Bugaric et al., 2025; Kozbagarov et al., 2023a).

The use of an inertial rotor for layer-by-layer mining will enable the creation of a new generation of high-performance continuous mining machines capable of mining rock with a wide range of densities without explosive preparation or moisture.

The process of overloading (Figure 1) of excavated material from buckets of conventional rotors to the belt of the receiving conveyor of boom excavators is performed mainly under the action of gravitational or centrifugal forces, so they are called as machines with gravity or centrifugal rotors (Bugaric et al., 2020; Gomilanovic et al., 2024).

To solve a pressing scientific and technical problem, the authors of the article propose a new design for a bottom discharge inertial rotor, based on many years of research. The proposed design for continuous-action machines is based on the use of a fundamentally new working body-a bucketless rotor with inertial discharge of rock in the lower position (Kozbagarov et al., 2023b).

In the proposed new working body (Figure 2, a), the layer is worked “from top to bottom” (“towards oneself”), and the variable-mass material excavated by it is transported by the rotor along the cut surfaces and the chute and is discharged onto the conveyor belt in a continuous flow, flying in the plane of rotation of the working body under the action of centrifugal, mass, and inertial forces of the quantity of movements acquired from the cutting and transporting elements, therefore, it can be classified as an inertial rotor, which can be made in bucket and bucketless designs (Kozbagarov et al., 2023b; Kozbagarov et al., 2026; Nurakov and Awwad, 2019).

A gearless inertial rotor, which has two rows of blades instead of buckets and develops the face with the front cutting edge of these blades and transports the cut material in a continuous flow, is the most promising.

Figure 1. Inertia rotor in operation.

Having all the advantages of the centrifugal rotor with top discharge, the inertial rotor has a number of advantages, the main of which are:

1) ability to operate at both low and high rotational speeds, allowing any required performance to be achieved and rock of varying densities to be excavated;

2) small size and weight of the rotor and unloading effect from the reaction of the rock mass during operation, which reduces loads on the metal structure, improves dynamics and stability of the working process;

3) feeding excavated material onto the conveyor at a significant initial speed in the direction of belt movement.

Such a design allows to use its great potential for increasing productivity by increasing the rotor speed to values significantly exceeding the critical ones (Kozbagarov et al., 2023b; Kozbagarov et al., 2026; Savkovic and et al., 2022).

Materials and methods. Total energy consumption of digging by the inertial rotor consists of the cost of cutting, transportation of cut material on the surfaces of the worked layer and the trough, as well as the work of its subsequent ejection on the conveyor located behind the trough in the plane of rotation of the working body (Kozbagarov et al., 2023b; Kozbagarov et al., 2026).

In the present study, the fragmented rock mass transported by the inertial rotor is represented as an equivalent continuous medium with averaged physical and mechanical properties. This assumption makes it possible to derive engineering relationships for estimating transport energy consumption and excavation productivity. The proposed analytical model does not explicitly consider the particle size distribution of fragmented rock, dynamic self-compaction, internal shear friction, moisture content, material adhesion or possible jamming of individual rock fragments between adjacent blades. These factors are assumed to have a secondary influence within the investigated operating conditions and define the applicability limits of the proposed model.

Experimental verification of the proposed calculation method was performed using a full-scale inertial rotor prototype operating under field conditions. The experimental setup included an inertial rotor mounted on a test rig equipped with a drive system, supporting frame and loading mechanism. During the tests, the power consumption of the drive, rotor torque, rotational speed and excavation productivity were determined using calibrated measuring instruments. The obtained experimental data were used to verify the adequacy of the developed analytical relationships presented in this paper.

For the purpose of analytical modelling, the fragmented rock transported by the inertial rotor is represented as an equivalent continuous medium moving along the excavation face and the discharge chute. The proposed model neglects the additional resistance associated with friction between the accumulated fragmented material and the lower part of the excavation face, as well as the possible formation of a rock cushion at the bottom of the excavation. These simplifying assumptions make it possible to derive engineering relationships for estimating transport energy consumption and excavation productivity within the investigated operating conditions. The influence of these factors on transport resistance under specific mining conditions requires the development of a more detailed coupled mechanical model and is considered a subject for future research.

Calculation of power spent on digging by the inertial rotor taking into account the influence of speed is made by the formula:

$$N = N_p^v + N_{mp} \tag{1}$$

where N – power consumed for digging taking into account the effect of speed, kW; N_p^v - power consumed for clean cutting taking into account speed, kW; N_{mp} - power consumed for transporting broken rock mass by the rotor along the face and chute, taking into account the influence of speed, kW.

The net cutting power is determined from the expression

$$N_p^v = K_v + N_p^o \tag{2}$$

where K_v – velocity influence coefficient determined experimentally, MPa; N_p^o - net cutting power at speeds of V_o to 2 m/s.

The authors suggest determining the power N_{mp} expended on transportation by taking into account the reactive component of transportation resistance arising from the variability of the mass of excavated material in the rotor.

As can be seen from the formula (1), the total energy consumption of digging by the inertial rotor consists of the costs of cutting (Figure 2, a) and transportation of the cut material on the surfaces of the worked layer and trough (Figure 2, b, c, d). It is convenient to determine the power consumption for transporting excavated rock mass by the rotor through torque. The torque on the rotor shaft expended for material transportation is proposed to be determined by two methods. In the first method, the volume of material to be transported is assumed to be constant. The second method takes into account the mass variability in the rotor of bucket or bucketless design. The action of external forces for the bucketless inertial rotor is shown in Figure 2, b and d, bucket rotor in Figure 2, c. These figures show the following external forces acting on the bucket and bucketless rotors: $\overline{G}$ - the force of gravity; $\overline{P_y}$ - centrifugal force of inertia; $\overline{F_{mp}}$ - the force of friction of the transported material on the surface of the developed layer and the trough; $\overline{N}$ - the normal force of resistance to soil destruction; $\overline{F}$ - the force of normal pressure on the radial surface (Kozbagarov et al., 2023b; Kozbagarov et al., 2026; Nurakov and Awwad, 2019).

In order to establish the applicability and accuracy of both methods, it became necessary to make comparisons between them.

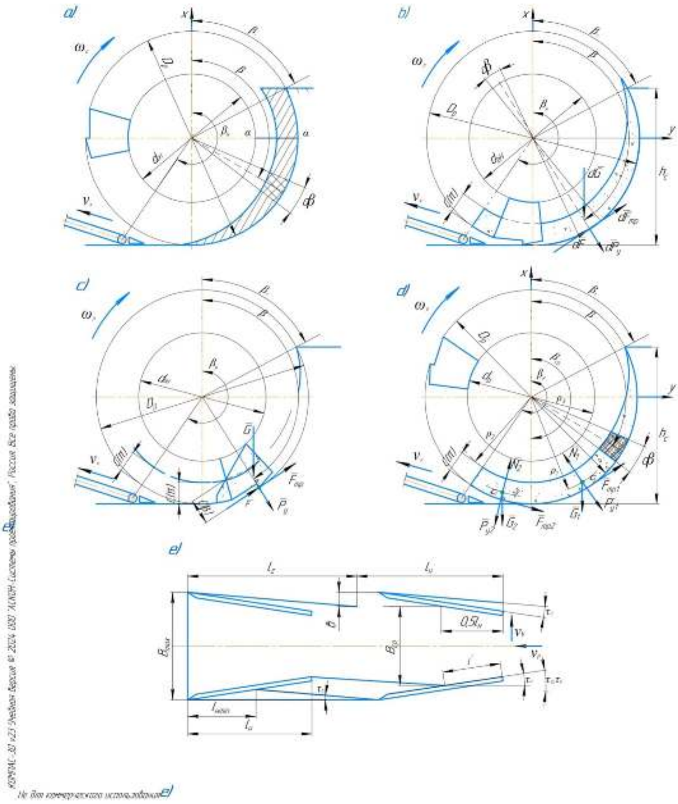

Figure 2. Calculation schemes of soil development and transportation by inertial bottom discharge rotor, a) face development,
b) transportation by bucketless rotor at variable material weight, c) transportation by bucket at variable weight, d) transportation by bucketless rotor at constant weight, e) rotor shell reaming.

The torque on the rotor shaft expended on transporting the cut material is considered using the theorem on the change in kinetic moment of a variable mass point $d\overline{K} \cdot dt^{-1}$, as the sum of the moments of all active and reactive forces (Kozbagarov et al., 2023b; Kozbagarov et al., 2026)

$$d\overline{K} \cdot dt^{-1} = \overline{M} + \overline{M}_r \tag{3}$$

where $\overline{M}$ - the main moment of all external forces, which consists of the moment from the action of mass forces M_b, friction forces of excavated material on the profile of shear and trough, as well as on the walls of cutting and transport elements M_k; $\overline{M}_r$ moment of impulse forces, neglecting the work of Coriolis and variation forces. The action of external forces for the bucketless inertial rotor is shown in Figure 2, b, and for the bucket rotor - in Figure 2, c (Kozbagarov et al., 2023b; Kozbagarov et al., 2026).

Average energy consumption for transportation of excavated material by inertial bucketless rotor can be determined by taking an infinite number of cutting and transport elements, and the transport volume itself in the working process unchanged and having a constant value within the angles from β_1 to β_1 (Figure 2, a) (Kozbagarov et al., 2023b; Kozbagarov et al., 2026).

Then the elementary volume of the removed chip in the natural state dV_c can be compared with the elementary volume in the stress-free state dV_o through the loosening factor k_p

$$dV_o = dV_c k_p \tag{4}$$

or

$$B_{cp} R_{cp} d\beta \cdot C(\beta) = k_p v_b dt S_o \sin \beta d\beta, \tag{5}$$

where $d\beta = \omega_p dt$: angle β - position of the cutting edge of the blade relative to the rotor axis; B_{cp} - the average distance between the cutting elements; v_b - rotor side feed; S_o – maximum chip thickness to be removed; $_p$ - rotor angular velocity; $C(\beta)$ - rotor radius.

There fore, the accepted regularity of distribution of thickness of the excavated material along the plurality of cutting and transporting elements $C(\beta)$ can be written as follows.

$$C(\beta) = \frac{k_p v_b S_o}{R_p B_{cp} \omega_p} sin\beta \cdot d\beta = \frac{k_p v_b S_o}{R_c B_c \omega_p}(cos\beta_1 - cos\beta) \tag{6}$$

Such distribution of the excavated mass between cutting and transporting elements of the bucketless inertial rotor can be considered as a constant transport mass, on which the forces of gravity G and friction of the transported material on the surface of the developed layer and trough F_{mp} act.

Applying the theorem of change of quantity of motion and dividing the transport mass into two parts from β_1 to π and from π to β_H, respectively, with centers of gravity C_1 and C_2, the elementary transport area from β_1 to π can be written as (Kozbagarov et al., 2023b; Kozbagarov et al., 2026)

$$dF_1 = C(\beta)R_p \cdot d\beta \tag{7}$$

or

$$F_1 = R_p \frac{v_b S_o}{B_{cp}\omega_p R_p}\left[\sin\beta_1 + (\pi - \beta_1)\cos\beta_1\right] \tag{8}$$

The coordinates of the center of gravity of this transport section are defined by angle β_{C1}:

$$\rho_1 = \frac{\int_{\beta_1}^{\pi} \rho_k C(\beta)R_p \cdot d\beta}{F_1}, \tag{9}$$

$$\beta_{C1} = \frac{\int_{\beta_1}^{\pi}\left(\beta + \frac{d\beta}{2}\right)C(\beta)R_p \cdot d\beta}{F_1} \tag{10}$$

where ρ_k and $\beta + \frac{d\beta}{2}$ -coordinates of the center of gravity of the elementary site ($\rho_k = R_p - \frac{C(\beta)}{2}$).

Substituting in formulas (9) and (10) the obtained values included in them, and integrating, we obtain:

$$\rho_1 = R_p\left[1 - \frac{v_b S_o}{2B_{cr}\omega_p R_p}\cdot\frac{0.75\sin 2\beta_1 + (\pi - \beta_1)(0.5 + \cos^2\beta_1)}{\sin\beta_1 + (\pi - \beta_1)\cos\beta_1}\right], \tag{11}$$

$$\beta_{C1} = \left(1 + \beta\sin\beta_1 + \left[1 + 0.5(\pi^2 - \beta_1^2)\right]\cos\beta_1\right)\times\left[\sin\beta + (\pi - \beta_1)\cos\beta_1\right]^{-1}. \tag{12}$$

In the second part of the transport site from π to β_H, the excavated material with center of gravity C_2 is carried on a lotox of constant height $C(\pi)$, therefore

. (13)

Then the total torque, spent on the transport of excavated material by inertial bucketless rotor, from the action of gravity and friction forces of the material transported by it on the profile of the developed layer and trough, after transformations is reduced to the form

$$M = M_{kp} = -\gamma R_p^3 B_{cp} \langle [\sin\beta_1 + (\pi-\beta_1)\cos\beta_1] \left\{ \left[1 - \frac{v_b S_o}{2B_{cp}\omega_p R_p} \times \frac{0.75\sin 2\beta_1 + (\pi-\beta_1)(0.5+\cos^2\beta_1)}{\sin\beta_1 + (\pi-\beta_1)\cos\beta_1} \right] \times \right.$$
$$\left. \times \sin\beta_{c1} + \left(\cos\beta_{c1} - \frac{R_p\omega_p^2}{g} \right)\mu \right\} + (\beta_H - \pi)\cdot(1+\cos\beta_1) \times \left\{ \left[1 - \frac{v_b S_o}{2B_{cp}\omega_p R_p}(1+\cos\beta_1) \right] \cos\frac{\beta_H}{2} - \right. \quad (14)$$
$$\left. - \left(\sin\frac{\beta_H}{2} + \frac{R_p\omega_p^2}{g} \right)\mu_1 \right\} + \frac{R_p\omega_p^2}{g} \left[1 - \frac{v_b S_o}{2B_{cp}\omega_p R_p}(1+\cos\beta_1) \right]^3 (1+\cos\beta_1) \rangle.$$

The obtained formula is more preferable than expression (1), but for determination of energy consumption spent by inertial rotor on transportation of excavated material more simplified methods of calculation are needed.

For what, having expressed a part of parameters (3) and (14) through dimensionless coefficients, it is possible to write:

$$e = \frac{v_b S_o}{B_{cp}\omega_p R_p} = \frac{v_b S_0}{B_{cp} v_p} = \frac{S_o}{B_{cp}} tg\tau_o \quad \text{and} \quad C_v = \frac{v_p^2}{gR_p} = \frac{R_p\omega_p^2}{g}, \quad (15)$$

where g - free fall acceleration.

Setting $\beta_1 = 60^o$, $\beta_H = 125^o$ and making pre-transformations of formulas (3) and (14) can be reduced to these forms:

- for the first method (3), considering the transport volume as a continuous flow of variable mass:

$$M_{kp}^I = \gamma B_{cp} R_p^3 e[-0.86 + 0.72e - 1.137e^2 + C_v\mu(2.82 - 3.52e + 1.22e^2) + \mu(2.13 - 1.5e) -$$
$$- C_v(1.5 - 3.8e + 2.54e^2 - 0.63e^3)] \quad (16)$$

-for the second method (14), considering the transport flow as a constant mass on the shear and chute surfaces:

$$M_{kp}^{II} = -\gamma B_c R_p^3 e[1.07 - 0.97e - 2.83\mu C_v + 2.23\mu + C_v(1.5 - 3.38e + 2.53e^2 + 0.63e^3)] \quad (17)$$

Results and Discussions. Experimental studies of a number of models of inertial rotors in field and production conditions have established that at $Z = 8 \div 12$ pair of knives with angles of installation $\tau_H = 15^o$ and cutting $\tau_H = 7^o$, as well as the coefficient of their height $k_\varepsilon = 1.35 \div 4.0$ determining the ratio of the rotor radius to the height of cutting elements, almost all the cut material is carried out by cutting and transporting elements on the receiving conveyor. At that, 90%

filling of the volume between the paired knives was observed, characterized by the coefficient of geometric capacity of a pair of knives $k_q = 0.8 \div 0.9$ (lower value for cohesive rocks, higher value for uncohesive rocks). From here we can proceed to determination of rotor parameters. To calculate the size and distance between the pair of knives, it is necessary to proceed from the correspondence of the volume between the knives to the volume of cut chips with the coefficient of loosening of excavated materials $k_p = 1.35 \div 1.5$:

$$B_{cp} \cdot h_\varepsilon l_H k_q = S_o b h_c k_p, \tag{18}$$

where h_ε, l_H and B_{cp} - respectively height, length and average distance between a pair of knives diverging at angle $2\tau_H$; S_o, b, h_c - respectively the thickness, width and height of the chip to be cut.

Figure 2, e also shows such parameters of the inertial rotor as l_z - distance between the knives; $l^/$ - length of the working part of the knife; v_p - rotational speed of the rotor.

Taking $h_c = 1.5R_p$, $S_o = 0.8h_\varepsilon$, $b = 2\pi R_p v_b \left(z \cdot v_p\right)^{-1}$ and making transformations, we can write according to Figure 2, e:

$$B_{cp} = 2.4\pi k_p R_p^2 tg\tau_0 \left(z l_H k_q\right)^{-1} \tag{19}$$

and

$$l_H = 2\pi R_p tg\tau_0 \left[z\left(tg\tau_H + tg\tau_o\right)\right]^{-1} \tag{20}$$

The last value should be increased by 2.5 times, because it is determined by the width of the removed chips, which in case of oscillating processes of the boom can practically exceed its calculated value by 1.8÷2.5 times. Using the experimental values obtained k_p, k_q, τ_o and τ_H, the dimensions of the blades for dense rock of category IV can be determined using the following expressions:

$$B_C = (210 \div 310)D_p;\ l_H = (210 \div 320)D_p \text{ and } B_{\max} = (220 \div 340)D_p \tag{21}$$

where the smaller value is for z = 12 and $k_\varepsilon = 4.0$, and the larger value is for $z = 8$ and $k_\varepsilon = 2.0$. Then the values of the dimensionless coefficient will be $e = 0.06$ at $k_\varepsilon = 4.0$ and $e = 0.08$ at $k_\varepsilon = 0.2$, respectively, which, in turn, makes it possible to write formulas (16) and (17), taking $\mu = 0.7$ as:

-at $\kappa_e = 4.0$ and $e = 0.06$:

$$M_{kp}^I = \gamma B_{cp} R_p^3 e\left(0.61 + 0.504C_v\right) \text{ and } M_{kp}^{II} = \gamma B_{cp} R_p^3 e\left(0.568 + 0.68C_v\right) \tag{22}$$

- at $\kappa_\varepsilon = 2.0$ and $e = 0.08$:

$$M_{kp}^{I} = \gamma B_{cp} R_p^3 e(0.603 + 0.533 C_v) \text{ and } M_{kp}^{II} = \gamma B_{cp} R_p^3 e(0.568 + 0.59 C_v) \tag{23}$$

Calculated values of these equations for Ekibastuz coals with volumetric bulk weight of $\gamma = 1.3$ t/m³ are summarized in Table 1 in the form of power consumption of the bucketless inertial rotor for the transport of excavated material along the profiles of the removed layer and chute, considering it as a constant transport mass and a continuous variable mass flow.

For more complete identification of advantages of the inertial rotor it is advisable to analyze its performance in comparison with existing rotors.

One of the main advantages of inertial rotor should be attributed to its high transport capacity, which is determined by the ability to work at high digging speeds and to apply increased height of cutting and transport elements.

The design capacity of the bottom discharge bucketless inertial rotor is determined by the formula

$$Q_p = 110 \frac{D_p^2 v_p}{\kappa_\varepsilon}, \tag{24}$$

where D_p - rotor diameter, mm; v_p - rotor linear velocity along cutting edges, m/s; k_ε - height coefficient of cutting elements.

Let us analyze the formula for the value of coefficient k_ε, which corresponds to the average values of the working bodies with centrifugal and gravity bucket unloading, the productivity of which is determined respectively by the formulas

$$Q_p = 110 \frac{D_p^2}{0.0004} \tag{25}$$

$$Q_p = kD^{2.5} \tag{26}$$

where $k=12\div30$ – performance coefficient (the first value is used for cohesive rock formations, the second for non-cohesive rock formations).

Table 1. Power consumption of inertial rotors for transportation of excavated material along the profiles of the removed layer and chute.

№, n/a	v_p, m/s	D_p, mm	C_v	B_{cp}, mm, at		Q_C, m³/hour, at		N^*_{kp}, kW, at		$\xi^*_{y\partial}$, kWh m³, at	
				k_ε =4	k_ε =2	k_ε =4	k_ε =2	k_ε =4	k_ε =2	k_ε =4	k_ε =2
1	2	2000	0.410	400000	600000	220	440	5/5.2	10.2/9.7	0.023/0.024	0.023/0.022
2		4000	0.204	800000	1200000	880	1760	35/36.1	69.7/66.4	0.04/0.041	0.039/0.038
3		6000	0.136	1200000	1800000	1960	3960	112.1/109.3	222/215	0.057/0.056	0.056/0.054
4		8000	0.102	1600000	2400000	3520	7040	253.2/250.0	476/491	0.072/0.071	0.068/0.07
5	4	2000	1.161	400000	600000	440	880	18.8/20.0	37/37.6	0.043/0.0455	0.042/0.043
6		4000	0.816	800000	1200000	1760	3520	100/104	203/207	0.057/0.059	0.058/0.059
7		6000	0.544	1200000	1800000	3960	7920	292/302	588/593	0.074/0.076	0.074/0.075
8		8000	0.408	1600000	2400000	7040	14080	644/661	1288/1278	0.092/0.094	0.091/0.092
9	6	2000	3.670	400000	600000	660	1320	49.3/54.0	94/98.9	0.075/0.080	0.071/0.076
10		4000	1.835	800000	1200000	2640	5280	246/266	465/484	0.093/0.10	0.088/0.092
11		6000	1.223	1200000	1800000	5420	11980	647/693	1241/1277	0.109/0.118	0.104/0.107
12		8000	0.917	1600000	2400000	10500	21120	1369/1388	2566/2601	0.129/0.131	0.121/0.123

*- in the numerator - estimated power and specific energy consumption of the rotor drive, spent on transportation of excavated material along the face and chute, considering the flow as a constant transport mass;

- in the denominator the same as variable flow

For a centrifugal rotor the formula of productivity is written for $k_\varepsilon = 3.85$ and its application is expedient at rotor diameter 3500 mm and above, because for providing full unloading of rotors of smaller sizes speeds considerably exceeding 6 m/s are required.

Comparing the calculated data made by these formulas, it is easy to notice that the productivity of inertial rotors of the same diameter significantly exceeds the productivity of working bodies with gravitational and centrifugal unloading (Figure 3 and Table 2).

For example, the productivity of a $D_p = 4000$ mm inertial bucketless rotor at a digging speed of 6 m/s exceeds that of a centrifugal rotor of the same diameter and with a bucket height coefficient of $k_\varepsilon = 4.0$ by 2. 4 times at $k_\varepsilon = 1.25$, a gravitational - respectively 3.6 and 10 times when developing unconsolidated rocks and 7.3 and 14 times or more when excavating consolidated rocks.

Table 2. Comparison of calculated values of inertial, gravity and centrifugal rotor capacities.

D_p	k_ε	Maximum capacity of rotors in dense body Q_p, max, m³/ hour									Note
		inertial bottom unloading at v_p, m/s					gravitational at v_p, m/s		centrifugal at v_p, m/s		
		2	3	4	5	6	$v_p=0.3v_{кр}$	$v_p=0.7v_{кр}$	v_p, оп	Q_p max	
1.6	4.00	145	186	250	320	400	35	85	8.76	320	$\kappa_\varepsilon=3.65$
	2.00	260	400	530	670	800	-	-	-	-	-
	1.25	485	600	800	1000	1320	-	-	-	-	-
2.0	4.00	225	330	450	570	670	70	170	7.62	625	$\kappa_\varepsilon=3.72$
	2.00	450	670	900	1120	1350	-	-	-	-	-
	1.25	760	1120	1340	1950	2150	-	-	-	-	-
3.0	4.00	510	760	1000	1270	1520	140	450	6.84	1400	$\kappa_\varepsilon=3.80$
	2.00	1000	1520	2000	2520	3050	-	-	-	-	-
	1.25	1860	2740	3460	4250	5120	-	-	-	-	-
4.0	4.00	900	1330	1880	2250	2700	370	920	5.86	2300	$\kappa_\varepsilon=3.82$
	2.00	1880	2660	3600	4500	5400	-	-	-	-	-
	1.25	3000	4440	5920	7560	9600	-	-	-	-	-

Increase in the performance indicators of inertial bucketless rotor in comparison with centrifugal and gravity working bodies is due to its greater transport capacity due to the ability to produce excavation works with a greater height of cutting and transport elements and at higher digging speeds.

Efficiency of rotors with inertial, centrifugal and gravitational unloading can be compared k_{TP} by determining their transport capacity, defined as the ratio of the volume of excavated material fed for one turn of the rotor to the transport annular cavity enclosed between the outer and inner diameter of the rotor and its width, called the geometric transport volume of the rotor. The calculation results are presented in Table 3, which also contains experimental data from testing rotor models in field and laboratory conditions. For gravitational and centrifugal types of working bodies, the passport parameters of boom rotary excavators manufactured by foreign industries were used.

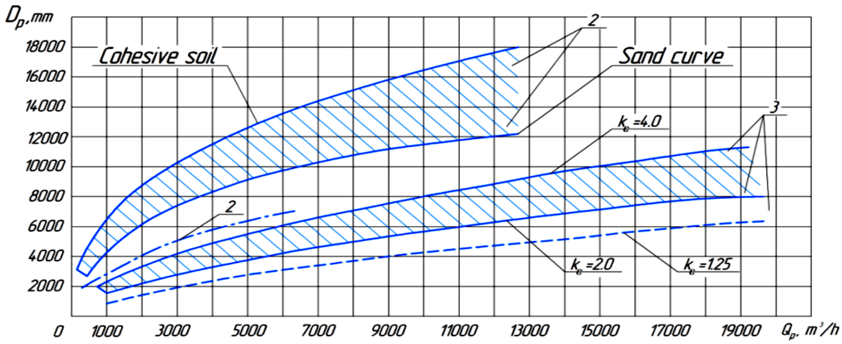

Figure 3. Dependence of productivity on the diameter of rotors, their transport capacity and properties of excavated rocks,
1 – gravitational; 2 - centrifugal; 3 – inertial.

The calculated and experimental values of the transport capacity coefficient k_{TP} of the inertial bucketless rotor given in Table 3 are much higher than those of traditional machines. Increase in the output of the investigated working body only due to its greater transport capacity can be up to 1.2÷3.0 times. The value of the coefficient k_{TP} increases significantly with the increase in the height of the cutting elements and the diameter of the rotor, but decreases slightly with the increase in digging speed, although productivity increases. The latter can be explained by the fact that increasing the height of the cutting elements leads to a decrease in the number of cutting elements due to their design and attachment to a smaller diameter shell.

The experimental results presented in Table 3 were obtained during field tests of the full-scale inertial rotor prototype under identical operating conditions. For each operating mode, the energy consumption, rotor torque, rotational speed and excavation productivity were recorded. These experimental data served as the basis for validating the proposed calculation method and assessing its agreement with the analytical predictions.

Dependence of inertial bucketless rotor output on its diameter, operating speed and coefficient value is graphically shown in Figure 4, which significantly increases with the increase of one of these parameters.

The results of experimental and calculated data for the bearingless inertial rotor show high transport capacity, allowing for a significant increase in its performance.

It should be noted that the proposed model is intended for engineering estimation of the transport process and therefore employs a number of simplifying assumptions regarding the behaviour of fragmented rock. Further improvement of the model should include the influence of particle size distribution, moisture, cohesion, internal friction, self-compaction and possible particle interlocking between the rotor blades, which may affect transport resistance and excavation productivity under specific mining conditions.

It should be noted that the analytical model developed in this study is intended to evaluate the transport energy consumption and excavation productivity of the inertial rotor under steady operating conditions. The model is focused on the kinematic and energy characteristics of the excavation process and therefore does not account for dynamic and impact loads acting on the cutting tools, rotor shell or excavator boom at increased peripheral rotor speeds. Consequently, the effects of these loads on structural strength, wear resistance and operational reliability were beyond the scope of the present investigation. Consideration of these phenomena requires coupled dynamic and structural analyses and will be the subject of future research.

Table 3. Comparison of main parameters and transport capacity of gravity, centrifugal and inertial rotor.

№	Parameters	Unit of measurement	Methods of discharging excavated material from rotor wheel buckets									
			gravity		centrifugal		inertial					
							experimental				calculated at 2...5 m/s	
			RE-1250	RE-2500	RE-1250-OC	RE-1600-OC	MPS	RTC	RTM	ERE-200		
1	Rotor diameter, D_p	mm	6500	8000	4000	4000	1540	650	1600	2400	2000	4000
2	Rotor speed:											
	– rotations n_p	tur/m	8.5	7.2	28	30	58.4	70	80	26	19.2–87.3	9.6-28.65
	– linear v	m/s	2.89	3.62	5.86	6.28	4.6	2.32	6.4	3.26	3–6	2–8
3	RTE height factor, k_ε	–	4.45	4.4	3.64	3.66	4.3	2.35	1.34	4.2	4.0–1.25	4.0–1.25
4	Feeding of excavated material per revolution of the rotor wheel	m³/tur	3.83	5.78	1.25	1.75	0.1	0.022	0.748	0.204	0.2–0.64	1.56–525
5	Coefficient k_{TP} :	–	0.21	0.2	0.16	0.22	0.23	0.43	0.66	0.25	–	–
	– at $k_\varepsilon = 4.0$	–	–	–	–	–	–	–	–	–	0.28–0.24	0.36–0.28
	– at $k_\varepsilon = 2.0$	–	–	–	–	–	–	–	–	–	0.33–0.27	0.44–0.32
	– at $k_\varepsilon = 1.25$	–	–	–	–	–	–	–	–	–	0.42-0.36	0.54–0.38
6	Performance	m³/h	1700	2500	2100	3150	360	86	3560	390	–	–
	– at $k_\varepsilon = 4.0$	–	–	–	–	–	–	–	–	–	227–670	900–2700
	– at $k_\varepsilon = 2.0$	–	–	–	–	–	–	–	–	–	450–1350	1860–5300
	– at $k_\varepsilon = 1.25$	–	–	–	–	–	–	–	–	–	760–3150	300–8100

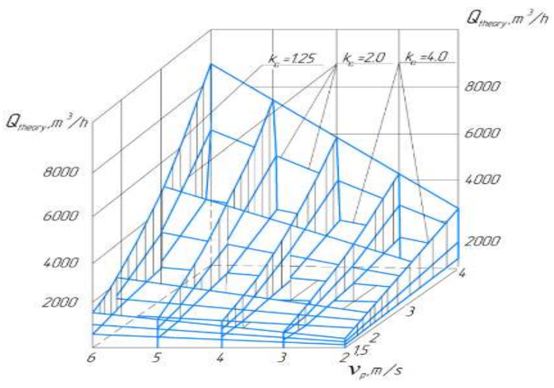

Figure 4. Dependence of inertial rotor productivity on its diameter D_p, digging speed v_p and height of cutting elements k_ε

The proposed analytical model should be interpreted within the limits of the adopted assumptions. In practical excavation conditions, additional transport resistance may arise due to friction of the fragmented material against the lower part of the excavation face and the accumulation of a rock cushion at the bottom of the excavation. These effects were not explicitly considered in the present model and may influence the quantitative agreement between calculated and experimental results under specific operating conditions. Their incorporation into the mathematical model requires further investigation and represents a direction for future research.

Conclusion. Comparison of the obtained values of the two calculation methods shows that the energy inputs increase significantly with increasing speed and rotor diameter and have insignificant differences between them. So the minimum percentage of discrepancies of these energy inputs (2÷5)% is observed at rotor diameter of $D_p = (4000 \div 6000)$ mm, $\nu_p = (4 \div 5)$ m/s and $k_\varepsilon = 2.0$, and the maximum - at the same parameters respectively (6÷2.9)%. Such small percentage of discrepancies and compliance of calculated values with experimental data indicates that both calculation methods are acceptable for practical use and contribute to the determination of the main parameters of the cutting and transporting elements of the inertial rotor according to the simplified formulas proposed by the authors.

The increase in the performance indicators of the inertial bucketless rotor compared to centrifugal and gravitational working bodies is due to its greater transport capacity, thanks to the ability to perform excavation work with greater height of cutting and transport elements and at increased digging speeds.

The new design of the slewing ringless inertial rotor and the unconventional rock excavation process proposed in the article make it possible to significantly increase the productivity of rotary excavators and reduce energy consumption by increasing the height of the cutting and transport elements.

Overall, the results of the analysis of experimental and calculated data for the bottom discharge inertial rotor confirm its potential for creating a new type of high-performance excavation equipment.

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