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ENERGY SAVING MODES OF EXCAVATORS TYPE POWER SHOVEL

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Abstract

Taking into account the high actual energy intensity of excavation of the excavator type mechanical shovel, the idea of its reduction due to the information component is considered in the work - that is, optimization of the operating mode of the excavator according to the criterion of minimum energy intensity is used.

The purpose of the work is analytically and experimentally established dependence of the energy intensity of the excavation works on the performance of the excavator, which is of extreme nature, which allows to establish its local optimal value, which corresponds to the minimum energy intensity of digging for different categories of rocks.

In system optimization, considering a quarry as a system of two or more working excavators, the mathematical model of their joint work is formulated as an Eulerian problem on conditional extremum, which includes a goal function and constraints using the method of indefinitely multiplying the solution Lagrange.

It has been found that the optimal local digging performance values for each excavation block do not coincide with the optimal values for system optimization for the career as a whole (the principle of emergence).

Thus, the system optimum mode of excavation allows to obtain the lowest energy intensity of the process of excavation in comparison with the local optimum mode, and even more so with the actual daily one.

Key words: Excavator, performance, power consumption, optimization, operating modes, local, system, minimum.

Introduction

For comparative evaluation of the performance of quarries for the extraction of building materials use the indicator of total cumulative cost, or other indicator, which includes the cash costs of production.

But the work of such enterprises over the last two decades has shown that in an unstable economy, the estimation of production efficiency by cost indicators leads to negative consequences. Under these conditions, a much better result is the use of natural indicators [1].

In this regard, the energy used in excavation works is used as an indicator of efficiency [1;2]. On the other hand, the introduction of such an indicator is due to the significant increase in the recent tariff for all types of energy, including electricity.

The most profound and systematic relationship of the energy intensity of the rock excavation process with the parameters of the excavation process was investigated by I.O. Tangayev [2]. The results of his research, carried out during the operation of the excavator on blocks with different mining and technological conditions, physical and technical properties of the rock mass and the parameters of the collapses, made it possible to recommend the energy scale of excavation of rocks for practical use.

Using the given classification of rocks by the energy intensity of the excavation, it is easy to set the table for each rock category as the average performance of the excavator and the associated average energy of the excavation [2].

Comparing the energy intensity of the excavation process in domestic and foreign quarries is clearly not in our favor (2 to 2.5 times higher), which requires searching for operating modes that can reduce energy costs.

Thus, the purpose of the study is to determine the dependence of the energy intensity of excavation work on the performance of the excavator, which allows you to set its local value, which corresponds to the minimum energy intensity of digging for different categories of rocks.

To achieve this goal, the following scientific problems are formulated and solved:

Considering that the process of excavation is a random dynamic non-stationary dissipative process, for its mathematical modeling it is necessary to apply the principle of duality when moving mass in space [3], which allowed to consider the process of digging as a probable non-stationary motion of a body of variable mass in a solid medium in a solid medium from the mass and filling the volume of the bucket with the products of destruction, in the form of the Hamilton-Jacobi and Fokker-Planck-Kolmogorov (FPC) equations;

the analytical solution of these equations made it possible to determine the dependence of the exploitation energy of the excavation works on the productivity of the excavation, which is of extreme nature;

the study of the established dependence on the extremum has allowed to establish both the optimum values of the excavator productivity for the given conditions, and the minimum values of the energy of digging;

the developed approach allowed to consider the work of excavators of three main modes: actual average mode; local optimal mode; system optimal mode and perform a detailed analysis of these modes for different categories of rocks.

Excavator operating modes while optimizing the quarry process.

The scientifically grounded method of calculating the operational productivity of direct-excavator type excavators has made it possible to consider three basic modes of operation of the excavator:

- average actual mode of operation;
- local optimal;
- system optimal.

The theoretical calculations given in and experimental studies [2] have shown that energy costs for rock excavation are described by the Hamilton-Jacobi equation

$$\frac{\partial D(t)}{\partial t} - \frac{e_K K_B \varPi_K}{E_x} D(t) = 0 \qquad (1)$$

and FPK(Fokker-Planck-Kolmogorov) equation

$$\frac{\partial \omega(t)}{\partial t} = \frac{D}{2m} \nabla^2 \omega(t) + \frac{\nabla D}{m} \nabla \omega(t) + \frac{U}{D} \omega(t) \qquad (2)$$

where $D(t)$ is the mechanical action expended on the excavation of the specified number of meters of cubic mountain mass, $J{\cdot}s$; E_x is the energy of idle motion of the excavator, J.; e_K , - energy intensity of the digging process, J/m^3; K_B - the utilization coefficient of the excavator per shift; $\varPi_K$ - excavation digging capacity, m/s; $\omega(t)$ is the non-stationary probability density of the bucket trajectory coordinates in the array; m is the mass of the ladle with the rock; U is the potential energy of the bucket with the breed, J.

The first-order solution of the initial equation can be written in the form

$$D(t) = E_x \cdot t_k \, exp\left[\int_0^{t_k} \frac{e_K K_B \varPi_K}{E_x} dt \right], J{\cdot}s. \qquad (3)$$

The power consumed by the drive to dig is described by the expression

$$N_E(t) = \frac{D(t)}{t_k^2} = N_x \, exp\left[\int_0^{t_k} \frac{e_K K_B \varPi_K}{N_x t_k} dt \right] = N_x \, exp\left[\frac{e_K K_B \varPi_K}{N_x} \right] (4)$$

By decomposing this expression into a power series and confining ourselves to a quadratic polynomial, we obtain

$$N_E = N_x + e_K K_B \Pi_K + \frac{e_K^2 K_B^2}{2N_x} \Pi_K^2 + \ldots$$

The solution of the FPK equation gives an analytical expression for the probability density $\omega(\Pi_K,t)$. Then the mathematical expectation for the power of digging is found by expression

$$\bar{N}_E = \int_0^{t_k} N_E \omega(\Pi_K,t)\, d\Pi_K = \int_0^{t_k} N_x \omega(\Pi_K,t) d\Pi_K +$$

$$+\int_0^{t_k} e_K K_B \Pi_K \omega(\Pi_K,t)\, d\Pi_K + \int_0^{t_k} \frac{e_K^2 K_B^2}{2N_x} \Pi_K^2 \omega(\Pi_K,t)\, d\Pi_K.$$

Integrating this equation, we obtain

$$\bar{N}_E = \bar{N}_x + \bar{e}_K \bar{\Pi}_E + \frac{\bar{e}_K^2}{2N_x}\left[\left(1 - \frac{\Pi_0}{\bar{\Pi}_E}\right)^2 + \left(1 + \frac{\sigma_{\Pi E}^2}{\bar{\Pi}_E^2}\right)\right]\bar{\Pi}_E^2 \qquad (5)$$

where $\bar{N}_E$ - the average power of the excavator drives during operational productivity; $\bar{e}_K$ - average energy of the digging process; $\bar{\Pi}_E$ - mathematical expectation of the excavator's operational productivity; $\left(\bar{\Pi}_E = \bar{K}_B \cdot \bar{\Pi}_K\right)$; $\bar{N}_x$ - drive power at mode of idle moution; $\sigma_{\Pi E}^2$ - dispersion of excavator operating productivity; $\Pi_0 = \frac{\sqrt{2} N_x}{\bar{e}_K}$ - the optimum value of operational productivity.

The operational energy intensity of the excavation works is calculated by the expression

$$e_E = \frac{\bar{N}_E}{\bar{\Pi}_E} = \frac{A}{\bar{\Pi}_E} + B\bar{\Pi}_E + C \text{, J/m}^3, \qquad (6)$$

where $A = N_x$; $B = \frac{e_K^2}{2N_x}\left[\left(1 - \frac{\Pi_K^0}{\bar{\Pi}_E}\right)^2 + \left(1 + \frac{\sigma_{\Pi E}^2}{\bar{\Pi}_E^2}\right)\right]$; $C = \bar{e}_K$.

Thus, depending (6), not only the deviation of the average productivity over cycles for change from the optimal value is taken into account $\left(\Delta\Pi_0\right)^2=\bar{\Pi}_E^2\left(\dfrac{\bar{\Pi}_E-\Pi_0}{\bar{\Pi}_E}\right)^2$, but also the variance of productivity, both within the digging cycle and cycles per shift

$$\left(\Delta\Pi_0\right)^2=\bar{\Pi}_E^2\left(\frac{\bar{\Pi}_E^2+\sigma_{\Pi Ц}^2+\sigma_{\bar{\Pi}}^2}{\bar{\Pi}_E^2}\right)=\bar{\Pi}_E^2\left(1+R_{VЦ}^2+R_{\bar{V}}^2\right)$$

Expression (6) has an extreme appearance, that is, the minimum value of the energy intensity corresponds to the optimal value of the excavator $P_E = P_0$ meets the minimum value of energy $e_{\min}$ (fig. 1).

The study of the dependence (6) on the extremum $\dfrac{\partial e_E}{\partial\bar{\Pi}_E}=-\dfrac{A}{\bar{\Pi}_E^2}+B=0$ allows to determine the optimum value of the excavator's operational productivity, taking into account the random nature of oscillations of both the digging productivity on the cycle and the oscillations of the average digging productivity on the cycles per shift

$$\Pi_0^{\phi}=\sqrt{\frac{A}{B}}=\frac{N_x}{e_K}\cdot\frac{\sqrt{2}}{\sqrt{\left[\left(\dfrac{\bar{\Pi}_E-\Pi_0}{\bar{\Pi}_E}\right)^2+\left(1+\dfrac{\sigma_{\Pi E}^2}{\bar{\Pi}_E^2}\right)\right]}}, \tag{7}$$

where $\Pi_0=N_x\sqrt{2}/\bar{e}_K-$ is the absolute optimum of productivity at $\sigma_{\Pi E}\rightarrow 0$, and $\bar{\Pi}_E\rightarrow\Pi_0$.

The minimum value of energy is the optimum value of the excavator's operating productivity

$$e_E^{min}=2\sqrt{A\cdot B}+C=2\sqrt{\frac{e_K^2N_x}{N_x\cdot 2}\left[\left(\frac{\bar{\Pi}_E-\Pi_0}{\bar{\Pi}_E}\right)^2+\left(1+\frac{\sigma_{\Pi E}^2}{\bar{\Pi}_E^2}\right)\right]}+\bar{e}_K=$$
$$=\bar{e}_K\left\{\sqrt{2\left[\left(\frac{\bar{\Pi}_E-\Pi_0}{\bar{\Pi}_E}\right)^2+\left(1+\frac{\sigma_{\Pi E}^2}{\bar{\Pi}_E^2}\right)\right]}+1\right\}. \tag{8}$$

When digging automated process control possible mode in which $\bar{\Pi}_E=\Pi_0^{\phi}\rightarrow\Pi_0,\quad \sigma_{\Pi E}\rightarrow 0,\ e_E^{min}\rightarrow e_0^{min}$ (fig. 1).

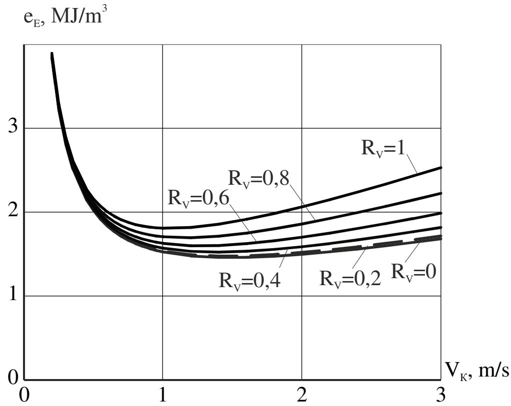

Fig. 1. Effect of random oscillations (R_V variations) of the digging velocity of the V_K of the excavator on the operational energy intensity of the e_E of the excavation process

When manually controlling the excavation process for optimum operation, the driver must: maintain at each cycle as close $\bar{V}_{KЦ}$ as possible to V_K^0; reduce digging fluctuations in each cycle to $\sigma_{ПЕ} \to \sigma_{ПЕ}^{min}$.

It follows from expressions (7) and (8) that both the optimum excavation $П_0^{ф}$, productivity and the minimum amount of operational energy e_E^{min} depend on the magnitude of the random fluctuations in the digging rate, which is estimated by the coefficient of variation R_V. The decrease in the coefficient of variation leads to a decrease in the energy intensity of the digging process and to an increase in the value of optimal productivity $П_0^{ф}$ (fig. 1).

Dependences of type (6) are calculated and constructed (fig. 2) for each rock category, taking into account the dynamic coefficient of digging resistance K_F^{∂}.

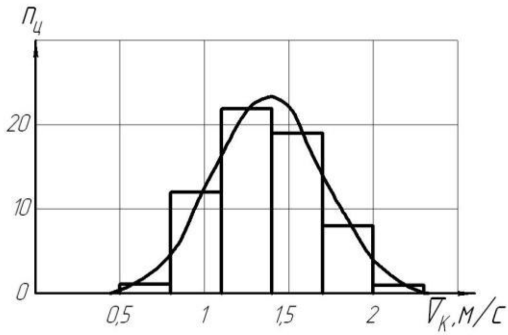

Fig. 2. Histogram of excavation speed distribution of excavator per cycle per shift ($n_ц$ = 60)

Considering these dependencies as an extreme task, the optimal productivity and corresponding minimum energy intensity e_E^{min} for each category (at $R_{VK}\to 0$) of the breeds are calculated.

Local optimal mode excavator

The analysis showed that to maintain the energy intensity of the excavation at a level close to the minimum for the rocks of the first and second categories, even a low qualification of the driver (fig. 1). The same can be said about working on rocks of the sixth category, when productivity close to optimal actually supports the drive itself.

A more difficult task arises when working on rocks (3 - 5) categories. Direct excavator type excavators are not equipped with a digging speed indicator, so only a highly skilled driver is able to maintain optimal digging. But in this mode he controls not the very speed of digging, which is close to the optimum V_0^{ϕ}, but the digging time t_0^{ϕ}, which corresponds to the optimal speed of digging, at approximately constant height of the ledge *H, s*

$$t_0^{\phi} = H_Y / V_0^{\phi} \qquad (9)$$

Thus, a high-skill operator to operate the excavator in near-optimal mode must withstand as little as possible the deviation of the actual digging time from the optimum, s

$$\Delta t = \left(t_{\phi} - t_0^{\phi}\right) \rightarrow min \tag{10}$$

which is equivalent to the condition $\Delta\Pi = \left(\bar{\Pi}_{\phi} - \bar{\Pi}_E^0\right) \rightarrow min$.

The second condition is to reduce the variation of the digging speed to a minimum level, which depends on the dynamics of the excavator and the oscillation of the soil resistance to digging

$$\Delta\sigma_{VK} = \left(\sigma_{VK}^{\phi} - \sigma_{VK}^{min}\right) \rightarrow 0 . \tag{11}$$

These two conditions are the prerequisites that ensure the digging mode is near the optimum. Unfortunately, the absolute optimum mode (at $\sigma_{VK} \rightarrow 0$) is almost impossible due to technical and geotechnological reasons.

To confirm these conditions, studies were conducted on the work of excavators with different qualifications (Table 1).

Table 1

Experimental data for the study of the parameters of the excavation cycle

№	Digging time t_K, s	Bucket turning time and unloading time t_{Π}, s	The time of dipping the bucket into the slaughter t_0, s	Cycle duration, t_C, s	Cycle utilization rate of the excavator, $K_{BЦ}$	Speed digging, V_K, m/s
1	7,0	6,5	4,5	28,0	0,25	1,42
2	7,0	10,0	12,0	29,0	0,24	1,42
3	8,6	9,0	13,0	30,5	0,28	1,16
4	9,0	9,0	14,0	32,0	0,28	1,11
5	6,5	7,5	10,5	24,5	0,26	1,66
…	…	…	…	…	…	…
53	6,0	10,0	13,0	29,0	0,20	1,66
54	7,0	8,0	12,0	27,0	0,25	1,42
55	6,0	9,0	14,0	29,0	0,20	1,66
56	5,0	10,0	14,0	29,0	0,17	2,00
57	5,0	9,0	14,0	28,0	0,17	2,00
58	6,0	13,0	12,0	29,0	0,20	1,66
59	5,0	12,0	12,0	29,0	0,17	2,00
60	7,0	9,0	12,0	27,0	0,25	1,42

The actual distribution of the digging velocity in the cycle $V_{KЦ}$ is analytically described by Gauss law. Then the distribution of the average speed of digging in cycles $\bar{V}_{KЦ}$ (fig. 2) with the mathematical expectation of the speed of digging per shift is $\bar{V}_{K3}$ calculated by the expression,m/s

$$\bar{V}_{K3} = \frac{1}{n}\sum_{1}^{n}\bar{V}_{КЦi} \qquad (12)$$

and variance

$$\sigma_{\bar{V}3} = \frac{1}{n-1}\sum_{1}^{n}\left(\bar{V}_{КЦi} - \bar{V}_{K3}\right)^{2}. \qquad (13)$$

In our case, the values $\bar{V}_{КЦi}$ are given in table. 1 and in fig. 2 at n=60 cycles per shift. The value of $\bar{V}_{K3} = 1{,}40$ m/s, and the variance and the coefficient of variation $\sigma_{\bar{V}3} = 0{,}30$ m/s, $R_{\bar{V}3} = 0{,}21$ m/s, respectively. The optimal value for the rock of the third category $V_K^{\phi} = 1{,}45$ - m/s, ie the average speed of digging is close to the optimum. Fluctuations in digging speed both on cycle and on cycles per shift lead to an increase in energy intensity from 1.4 MJ/m^3 to 1.7 MJ/m^3. But this value is less than the operation of the excavator in the actual suboptimal mode e^{ϕ}=1.85 MJ/m^3 (according to Tangayev I.O).

Therefore, the operation of the excavator in the mode close to the optimum, is possible on rocks of all categories, if the driver of the excavator is sufficiently qualified.

The absolute optimum, that is $П_0^{\phi} \to П_0 = \frac{\sqrt{2}N_x}{\bar{e}_K}$ at $R_{ПЕ} \to 0$, can only be achieved with the use of automated digging mode control.

Comparison of the actual value of operational energy consumption (e_E^{ϕ}) with the minimum at local optimization (e_E^{min}) established: the energy intensity is affected not only by the average digging speed ($\bar{V}_K$), but also by its deviation from the optimal value (V_0^{ϕ}); the variation of the digging velocity (V_K) is influenced by both the change in the rock resistance of the digging cycle on the ledge height ($R_{VЦ}$) and the driver's qualification ($R_{\bar{V}}$).

The saving of electric energy in the process of digging due to the optimization of process parameters for six categories of rocks with the average qualification of the driver is shown in fig. 3 and fig. 4. Maximum savings on the fifth category. The smallest - on the rocks of the first category.

Reducing the magnitude of the digging velocities of the first and second types leads to a decrease in the energy intensity of the excavation process (fig. 1). On average, the energy intensity of the excavation process in the transition from the average actual excavation mode to the local optimum decreases from 10% to 25%.

Conducted experiments on the optimal control of the excavation process showed that in the mode closest to the optimum, a driver of even intermediate qualification on soils from the first to the sixth categories can work. The results of the experiment on soils of the third category for 60 cycles per change are shown in fig. 1 and in table. 2.

Table 2

The results of the experiment

category	K_F^{∂} MPa	$n_ц$	$\bar{\bar{V}}_K$ м/s	$\sigma_{\bar{V}}$ м/s	$R_{\bar{V}З}$	$R_{VЦ}$	V_0 м/s	e_K MJ/m³	e_E^{ϕ} MJ/m³	e_E^{min} MJ/m³	Δe MJ/m³
3	0,27	60	1,40	0,3	0,2	0,2	1,50	0,60	1,70	1,45	0,25

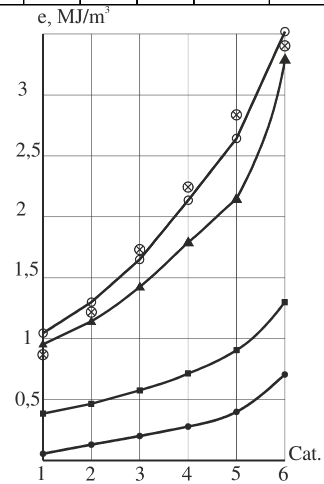

Fig. 3. Comparison of actual and calculated energy indices of the excavation process for different categories of rocks: ⊗ - actual operational energy of the excavation process (e_E^{ϕ}); ○ - estimated operational energy of the excavation; ▲ - energy consumption at optimum excavation mode; ■ - energy intensity of the digging process (e_K); • - coefficient of dynamic resistance of the breed of digging (K_F^{∂}).

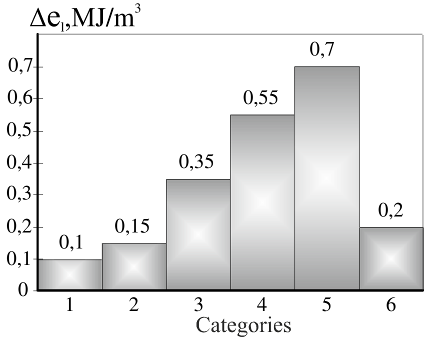

Fig. 4. Reduction of energy intensity of rock excavation at local optimization mode

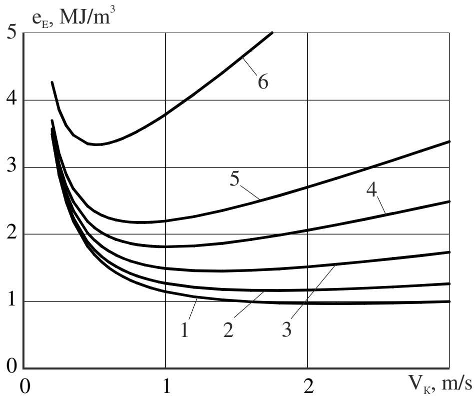

Fig. 5. Operational energy intensity (e_E) of the excavation process, depending on the speed of digging (V_K) for six categories of rocks: △ - actual mode; ○ - local optimal mode; □ - system optimal mode

System optimum operation of excavators

If two or more excavators work on the same quarry and are interconnected by a common transportation system, power supply system, common conditional costs and other connections, then the task is to establish the optimal productivity of each excavator, in which the total energy intensity of excavation works on the group of two excavators will be the smallest. In this case, the total career productivity should be equal to the sum of the two productivity of independently operated excavators [3].

In this approach, we obtain the classical Euler problem of conditional extremum. We find this solution by the method of undetermined Lagrange multipliers [3].

Mathematically, the model of this problem is written as

$$\begin{gathered} \bar{e}=\frac{e_{E1}\cdot\bar{\Pi}_{E1}+e_{E2}\bar{\Pi}_{E2}}{\bar{\Pi}_{E1}+\bar{\Pi}_{E2}}\rightarrow min, \text{ – target function;} \\ \bar{\Pi}_{E1}+\bar{\Pi}_{E2}=\sqrt{\frac{A_1}{B_1}}+\sqrt{\frac{A_2}{B_2}} \text{ – limitation.} \end{gathered} \tag{14}$$

The energy intensity for each excavator is calculated by the expressions

$$e_{E1}=\frac{A_1}{\bar{\Pi}_{E1}}+B_1\bar{\Pi}_{E1}+C_1, \text{ J/m}^3; \tag{15}$$

$$e_{E2}=\frac{A_2}{\bar{\Pi}_{E2}}+B_2\bar{\Pi}_{E2}+C_2, \text{ J/m}^3. \tag{16}$$

Optimal productivity for each excavator when working independently (local optima)

$$\Pi^0_{E1}=\sqrt{\frac{A_1}{B_1}};\quad \Pi^0_{E2}=\sqrt{\frac{A_2}{B_2}}, \text{ m}^3\text{/s}. \tag{17}$$

Minimum values of excavation energy consumption at local optima

$$e^{min}_{E1}=2\sqrt{A_1B_1}+C_1, \text{ J/m}^3. \tag{18}$$

$$e^{min}_{E2}=2\sqrt{A_2B_2}+C_2, \text{ J/m}^3. \tag{19}$$

To solve this problem, we construct a standard first-order Lagrangian function with the goal and constraint function

$$\begin{gathered} \bar{L}\left(\bar{\Pi}_{E1},\bar{\Pi}_{E2},\lambda\right)=\frac{\left(\frac{A_1}{\bar{\Pi}_{E1}}+B_1\bar{\Pi}_{E1}+C_1\right)\bar{\Pi}_{E1}+\left(\frac{A_2}{\bar{\Pi}_{E2}}+B_2\bar{\Pi}_{E2}+C_2\right)\bar{\Pi}_{E2}}{\sqrt{\frac{A_1}{B_1}}+\sqrt{\frac{A_2}{B_2}}}+ \\ +\lambda\left[\left(\bar{\Pi}_{E1}+\bar{\Pi}_{E2}\right)-\left(\sqrt{\frac{A_1}{B_1}}+\sqrt{\frac{A_2}{B_2}}\right)\right], \end{gathered} \tag{20}$$

where λ is an indefinite Lagrange multiplier.

The study on the extremum of the function of three variables gives the following system of equations

$$\left.\begin{aligned}
&\frac{\partial L}{\partial \bar{\varPi}_{E1}}=\frac{\left(2B_1\bar{\varPi}_{E1}+C_1\right)}{\sqrt{\frac{A_1}{B_1}}+\sqrt{\frac{A_2}{B_2}}}+\lambda=0;\\
&\frac{\partial L}{\partial \bar{\varPi}_{E2}}=\frac{\left(2B_2\bar{\varPi}_{E2}+C_2\right)}{\sqrt{\frac{A_1}{B_1}}+\sqrt{\frac{A_2}{B_2}}}+\lambda=0;\\
&\frac{\partial L}{\partial \lambda}=\left(x_1+x_2\right)-\left(\sqrt{\frac{A_1}{B_1}}+\sqrt{\frac{A_2}{B_2}}\right)=0.
\end{aligned}\right\} \qquad (21)$$

The solution of these equations gives optimum productivity values for each excavator, but even with system optimization

$$\bar{\varPi}_{E1}^{C}=\frac{2B_2\left(\sqrt{\frac{A_1}{B_1}}+\sqrt{\frac{A_2}{B_2}}\right)-C_1+C_2}{2\left(B_1+B_2\right)} \qquad (24)$$

$$\bar{\varPi}_{E2}^{C}=\frac{2B_1\left(\sqrt{\frac{A_1}{B_1}}+\sqrt{\frac{A_2}{B_2}}\right)-C_1+C_2}{2\left(B_1+B_2\right)} \qquad (25)$$

From the last two expressions we can conclude that the optimum values of excavator productivity during system optimization do not coincide with the optimum values of local optima (the principle of emergence).

Local and system optimums will only coincide if two identical excavators will operate with drivers of approximately the same qualification under the same conditions, ie $A_1=A_2=A$, $B_1=B_2=B$, $C_1=C_2=C$.

Тоді $\varPi_{01}^{\phi}=\varPi_{02}^{\phi}=\varPi_{0}^{\phi}=\sqrt{\frac{A}{B}}$.

For Demidov quarry conditions, consider the operation of two EKG-5A excavators in the third category and the fifth category. Under these conditions, the average digging energy is $\bar{e}_{K1}=0{,}60$ MJ/m^3, $\bar{e}_{K2}=$ 0,80 MJ/m^3, and the actual average operating energy for two excavators is 2.23 MJ/m^3. The local optimum parameters for each of the excavators were calculated using expression (7) for optimal productivity and expression (8) for minimum excavation energy consumption. The results of the calculation are given in table. 3 and fig. 5.

In system optimization, the optimum productivity for each excavator is calculated by expressions (24) and (25), and the substitution of these values into expressions (15) and (16) allows to obtain minimum values of energy capacities that do not really coincide with local optima (the principle of emergence). If, with local optimization, the weighted average energy consumption is 2.04 MJ/m^3, then in system optimization it will be lower by 0.34 MJ/m^3 and is 1.7 MJ/m^3, table. 3

Table 3

Excavator modes

Modes	$П_{E3}$ m^3/s	$П_{E5}$ m^3/s	e_{E3} MJ/m^3	e_{E5} MJ/m^3	$\overline{e}_E$ MJ/m^3	Δe_E MJ/m^3	ΔC UAH/m^3
Factual	0,11 (0,59)	0,09 (0,5)	1,72	2,85	2,23	–	–
local optimal	0,24 (1,5)	0,17 (0,92)	1,45	2,17	2,04	0,19	0,093
optimal system	0,27 (1,62)	0,14 (0,80)	1,46	2,2	1,70	0,53	0,300

Comparison of the parameters of the excavators in the three modes (fig. 5) shows the feasibility of reducing electricity costs by optimizing the parameters of the excavation process.

Thus, if you convert MJ to kW. hours, then when operating the excavator in the mode close to the optimum saving for the article "electricity" is from 0.10 to 0.30 UAH. / m3 on each cube of rock mass.

The implementation of the proposed optimal modes of operation of the excavator during the experiments on the Tovkachivsky quarry has resulted in savings of electricity costs in the amount of 70 thousand UAH. during the experiment. Expected savings are about 150 thousand UAH. / year for each excavator.

Conclusions

1. In work instead of cost criteria of production efficiency in the conditions of unstable economy the criterion of minimum energy intensity of excavation works was used.

2. The dependence of the energy intensity of the excavation works on the productivity of the excavator has an extreme nature, which allowed to establish the optimal productivity, which corresponds to the minimum energy intensity for all categories of rocks.

3. The work of the excavator is considered in three modes: actual average mode; local optimal mode; system optimal mode.

4. When operating the excavator in the local optimal mode, depending on the category of rocks, reducing the energy intensity of excavation compared with the average actual is from 0.15 to 0.40 MJ/m3, or from 8 to 20%.

5. Considering a quarry as a system of two or more excavation sites, it was found that the optimal productivity values of each site when working in the system did not coincide with the optimal value at local optimization, which allowed to reduce the average energy consumption by 20-40% compared to the average actual value, based on the fact that the total productivity does not change and ensure a minimum energy intensity of excavation work on the quarry.

6. Studies have shown that the driver of the secondary qualification excavator after proper training can work in a mode close to optimal not only on soils of the first and second categories, but also on soils from the third to sixth categories.

7. The energy saving during the operation of the excavator in the optimal mode is from 0.19 to 0.53 MJ/m^3, or from 0.10 to 0.30 UAH./m^3.

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