OPTIMIZATION OF THE PRODUCTIVITY OF EXCAVATION, LOADING, AND HAULAGE SYSTEMS IN OPEN-PIT MINING

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Abstract: An analysis of the operation of excavator–truck complexes in open pits is presented, and possible ways to improve the efficiency of their use are considered. It has been established that one of the ways to increase productivity is to reduce the loading time of dump trucks by decreasing the number of excavator loading cycles. This can be achieved through the use of high-capacity excavators (with large bucket volumes) in combination with dump trucks of relatively low payload capacity.

Keywords: dump truck, excavator, productivity, payload capacity, cycle time, bucket capacity, body volume, outriggers, open-pit mining.

Annotatsiya. ekskavator–yuk mashinalari komplekslarining ochiq chuqurlarda ishlashi tahlili keltirilgan va ulardan foydalanish samaradorligini oshirishning mumkin bo'lgan usullari ko'rib chiqilgan.ulosa: ekskavator–yuk mashinalari komplekslarining ochiq chuqurlarda ishlashi tahlili keltirilgan va ulardan foydalanish samaradorligini oshirishning mumkinulosa: ekskavator–yuk mashinalari komplekslarining ochiq chuqurlarda ishlashi tahlili keltirilgan va ulardan foydalanish samaradorligini oshirishning mumkin bo'lgan usullari ko'rib chiqilgan. Hosildorlikni oshirish usullaridan biri ekskavatorlarni yuklash davrlarini kamaytirish orqali samosvallarni yuklash vaqtini qisqartirish ekanligi aniqlandi. Bunga nisbatan past yuk ko'tarish qobiliyatiga ega samosvallar bilan birgalikda yuqori quvvatli ekskavatorlardan (katta chelak hajmli) foydalanish orqali erishish mumkin.

Kalit so'zlar: samosval, ekskavator, mahsuldorlik, foydali yuk hajmi, aylanish vaqti, chelak hajmi, Kuzov hajmi, tirgaklar, ochiq usulda qazib olish.

Аннотация: Представлен анализ работы экскаваторно–самосвальных комплексов на карьерах и рассмотрены возможные пути повышения эффективности их использования. Установлено, что одним из способов повышения производительности является сокращение времени загрузки самосвалов за счет уменьшения количества циклов загрузки экскаватора. Этого можно достичь за счет использования высокопроизводительных экскаваторов (с большим объемом ковша) в сочетании с самосвалами относительно небольшой грузоподъемности.

Ключевые слова: самосвал, экскаватор, производительность, грузоподъемность, время цикла, емкость ковша, объем кузова, выносные опоры, открытые горные работы.

Introduction

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At many open-pit mines, the technical and economic indicators of surface mining are determined primarily by the process of moving overburden rocks and mineral resources. At present, transportation costs in open-pit mining operations reach 50–70% of the total costs of mineral extraction [1].

Since under modern market conditions the activity of any enterprise is aimed at achieving maximum profit, which is determined by the ratio of revenues obtained from performing the required volumes of rock mass haulage to the costs of its transportation, one of the main tasks is to increase the efficiency of the transport process. This makes it possible to reduce enterprise expenses and, as a result, increase profitability.

The main type of technological transport in open-pit mining is road transport. In the USA, Canada, and South America, more than 85% of the rock mass is hauled by dump trucks, while in Australia this figure is practically 100%. In Russia and the CIS countries, the share of road transport exceeds 75% and tends to increase [2].

At the same time, the main approach to increasing the productivity of excavation and haulage complexes currently lies in the introduction of new models of excavators (with increased power and bucket capacity) and mining dump trucks with high and ultra-high payload capacities.

In 2010, the first BelAZ-75600 dump trucks with a payload capacity of 320 t were commissioned at enterprises in the Kuzbass region. In autumn 2013, the first unit of the world's largest dump truck, the BelAZ-75710 with a payload capacity of 450 tonnes, was manufactured and put into operation at the Chernigovets coal open-pit mine (Bere-zovsky, Kemerovo Region) (Fig. 1).

At present, the largest excavator in the world is the RH400 excavator manufactured by the American company Terex. With a weight exceeding 1,000 tonnes (an absolute record), the excavator is equipped with a 45 m³ bucket and has a payload capacity of 95 tonnes. This giant is capable of excavating and loading about 10,000 tonnes of rock per hour (Fig. 2).

Currently, the mining equipment market already shows demand for excavators with even larger bucket capacities (up to 60 m³). At IZ-KARTEX named after P.G. Korobkov LLC, the design of the EKGV-50 excavator with a 60 m³ bucket has now been completed.

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Fig. 1. BelAZ 75710

Further increases in the payload capacity of mining dump trucks are constrained by the lack of high-load-capacity tires. Thus, at present, the maximum achievable productivity of the world's most powerful excavation and haulage complex—consisting of a Terex RH400 excavator with a 45 m³ bucket and a BelAZ 75710 dump truck with a payload capacity of 450 t—is about 10,000 t/h. Further increases in productivity are not expected in the near future, since there is no possibility to increase the payload capacity of the dump truck.



Fig. 1. Terex RH400

Efficiency Criteria

The development of dump truck parameters and excavator equipment is interrelated. As a rule, the selection of the optimal ratio between excavator bucket capacity and dump truck payload capacity is achieved by satisfying the condition of loading the truck body in 5–12 excavation cycles.

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It is obvious that reducing the number of loading cycles required for an excavator to load a dump truck will accordingly increase the productivity of the entire excavation and haulage complex. This occurs due to an increase in excavator capacity while maintaining an unchanged payload capacity of the dump truck.

The productivity of an excavator and a transport machine is determined by the amount (volume, mass) of material moved per unit time (second, hour, shift, year). Technical and operational productivity are distinguished. Technical productivity (Q) is determined by the technical parameters of the machine and the properties of the material being transported. Operational productivity (Q_e) depends not only on the technical parameters of the machine and the properties of the material, but also on the actual operating conditions [3].

Technical and operational productivity are related by the following relationship.

$$Q_э/Q = K_э ,$$

where K_e is the overall operational utilization coefficient of the machine, representing the product of the coefficients of load non-uniformity K_n, time utilization K_v, and machine availability K_g. Under continuous operation with normal loading, $K_e=1$; with partial loading and downtime, $K_e<1$.

Based on the value of technical productivity, the main design parameters of machines that ensure this productivity are calculated.

The productivity of road transport is defined as the total productivity of all transport units (dump trucks):

$$Q = \Sigma Q_a$$

The individual productivity of a single unit (dump truck) per unit time is determined as:

$$Q_a = r\, q_i ,$$

where $r = \frac{1}{T}$ is the number of trips per unit time; qiq_iqi is the weight of the load (in the dump truck body); and T_r is the trip time.

T_r — trip time. The trip time of a dump truck consists of the loading time t_z, unloading time t_r, as well as the travel time in the loaded and empty directions t_{dv}:

$$T_p = t_з + t_{дв.гр} + t_{дв.пор} + t_p .$$

If we consider these three components of trip time, the majority is, of course, taken up by travel time. For long transportation distances, loading and unloading times can be neglected. However, if the transportation distance does not exceed 2 km, these times cannot be ignored. Moreover, the unloading time, which consists of raising and lowering the truck body, is practically independent of the dump truck's payload capacity (averaging around 40 seconds). The loading time, on the other hand, depends on the excavator cycle time and, according to the loading specifications, the number of cycles (i.e., the number of bucket loads). The number

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of cycles ranges from 5 to 12. Therefore, with an average cycle time of 30 seconds, the loading time can reach up to 6 minutes. These durations are already comparable to the total travel time of the dump truck.

One possible way to intensify the transportation process is to use low-payload dump trucks in combination with powerful, high-productivity excavators.

Comparative Analysis of Two Configurations of Excavator–Truck Complexes

Consider the following example. An excavation and haulage complex consists of an EKG-20 excavator and BelAZ-7530 dump trucks with a payload capacity of 200 t and a geometric body volume of 100 m³, transporting rock with a density of 2 t/m³. For simplicity of calculations, we assume a transportation distance of 1,890 m, a loaded travel speed of 12 km/h (4.2 m/s), and an empty travel speed of 26 km/h (7.2 m/s). The waiting time during loading is 150 s (5 cycles of 30 s each), and during unloading is 40 s (20 s for raising and lowering the body). Maneuvering time is not considered.

The interval between dump trucks cannot be less than the loading time (2.5 min). At a loaded travel speed of 12 km/h (4.2 m/s), the distance between trucks will be 630 m. Figure 3 shows the loading point (Ex), the unloading point (Rp), and dump trucks 1, 2, 3, 4, 5, 6. The diagram indicates the moment when dump truck 1 is fully loaded and ready to depart, trucks 2 and 3 are en route to the unloading point, truck 4 has arrived at the unloading point and is preparing to unload, and trucks 5 and 6 are traveling empty toward the loading point. In 30 seconds (the excavator cycle time), truck 6 will be positioned for loading. This ensures continuous operation of the entire excavator–truck complex.

For the adopted rock density of 2 t/m³, excavator bucket volume of 20 m³, and cycle time of 30 s, the maximum productivity of the excavator is…

$$Q_э = 20 \cdot 2/30 = 1{,}33 \text{ т/с} = 4800 \text{ т/ч}.$$

With the adopted parameters for the dump truck—loaded travel speed of 12 km/h (4.2 m/s), empty travel speed of 26 km/h (7.2 m/s), number of loading cycles 5 (5 × 30 = 150 s), and unloading time of 40 s—the trip time Tr is:

$$T_р = t_з + t_{дв.гр} + t_{дв.пор} + t_р = 2{,}5 + 7{,}9 + 5{,}99 + 0{,}67 = 17 \text{ мин} = 0{,}28 \text{ ч},$$

The maximum productivity of a dump truck can be calculated using the formula:

$$Q_a = r \cdot q_i = q_i/T_р = 200/0{,}28 = 714 \text{ т/ч}.$$

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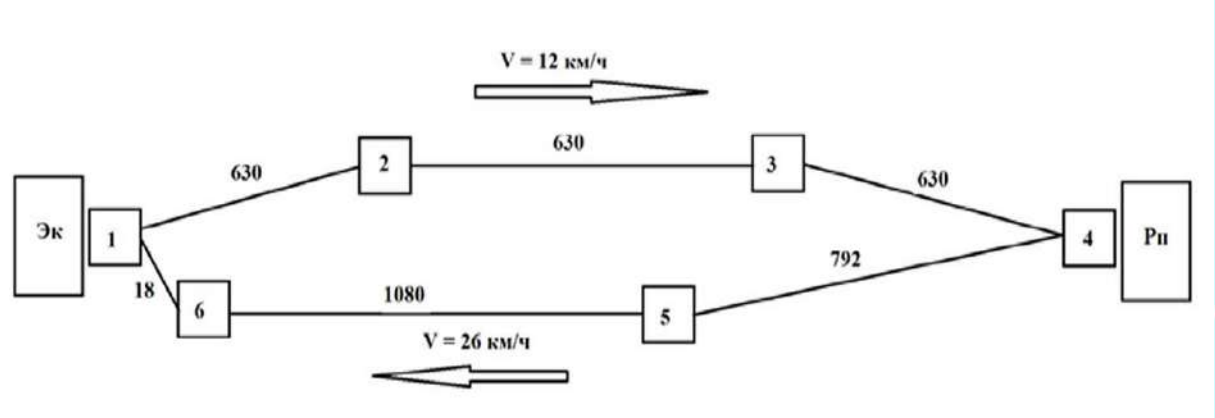


Fig. 3. Operation diagram of the excavation and haulage complex consisting of an EKG-20 excavator and BelAZ-7530 dump trucks

To ensure the required productivity of the excavator, the following number of dump trucks is needed:

$$N_a = 4800/714 = 6,7 \text{ авт.}$$

Based on the given diagram (Fig. 3), the complex can use only 6 dump trucks. With 6 dump trucks in operation, the productivity of the complex will be:

$$Q = \Sigma Q_a = 714 \cdot 6 = R\ R\ 4284 \text{ т/ч.}$$

Consider another example. An excavation and haulage complex consists of an EKG-20 excavator and BelAZ-7547 dump trucks with a payload capacity of 45 t and a geometric body volume of 21.5 m³. The loading downtime is 30 s (1 cycle). All other operational parameters of the complex remain unchanged. At a loaded travel speed of 12 km/h (4.2 m/s), the distance between the dump trucks will be 126 m (Fig. 4).

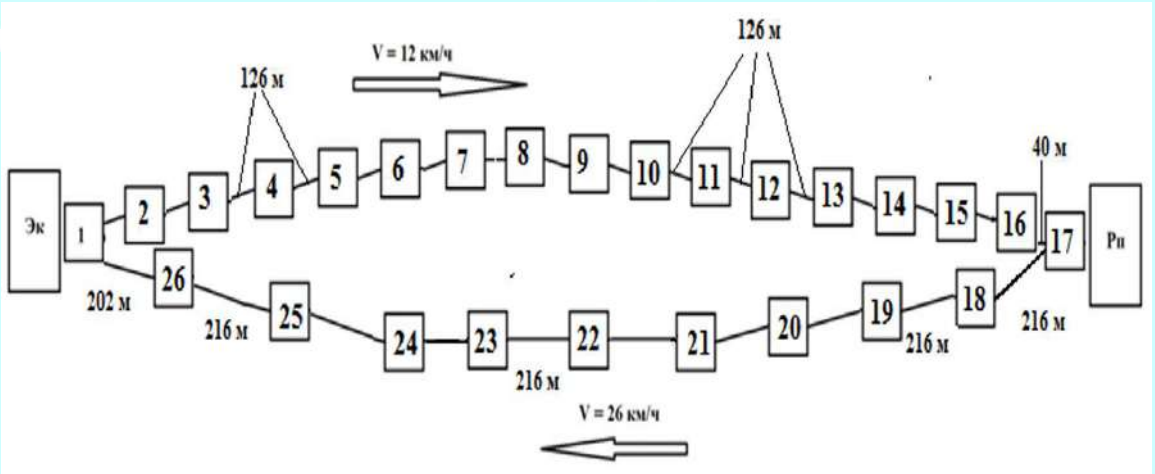


Fig. 4. Operation diagram of the excavation and haulage complex consisting of an EKG-20 excavator and BelAZ-7547 dump trucks

The trip time Tr will be:

$$T_p = t_з + t_{дв.гр} + t_{дв.пор} + t_p = 0,5 + 7,9 + 5,99 + 0,67 = 15,06 \text{ мин} = 0,25 \text{ ч.}$$

Maximum productivity of one BelAZ-7547 dump truck under these conditions is approximately 207 t/h.

$$Qa = r \cdot qi = qi/Tp = 45/0,25 = 180 \text{ т/ч.}$$

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To ensure the required productivity of the excavator, the number of dump trucks needed can be calculated as:

$$Na = 4800/180 = 26,7 \text{ авт.}$$

The productivity of the excavator–truck complex with 26 BelAZ-7547 dump trucks is approximately 5,382 t/h.

$$Q = \Sigma Qa = 180 \cdot 26 = 4680 \text{ т/ч.}$$

Conclusion

Compared to the complex considered in the first example (with BelAZ-7530 dump trucks), the productivity of the second complex (with BelAZ-7547 dump trucks) increases by 9%.

Regarding the cost of 6 BelAZ-7530 dump trucks versus 26 BelAZ-7547 dump trucks, the following can be noted. According to open sources [4], the 450-ton BelAZ-75710 costs 7.5 million USD, which is twice the price of the 220-ton BelAZ-7530. Thus, the cost of a BelAZ-7530 is approximately 3.75 million USD. Based on these proportions, the cost of a 45-ton BelAZ-7547 dump truck would be 4.5 times lower than that of a BelAZ-7530. Therefore, the total cost of 26 BelAZ-7547 trucks is less than the cost of 6 BelAZ-7530 trucks.

Additionally, there is a significant reduction in capital expenditures for building transport infrastructure, since the road width required for BelAZ-7530 trucks is more than twice that needed for BelAZ-7547 trucks.

Another important point is reliability: if one BelAZ-7530 truck fails, the productivity of the excavator–truck complex decreases by 27%. In contrast, if one BelAZ-7547 truck fails, the complex's productivity decreases by only 4%.

Most importantly, this approach allows further increases in the productivity of excavator–truck complexes by increasing the excavator bucket volume up to 157.5 m³ (corresponding to the geometric body volume of the BelAZ-75710 dump truck).

However, existing dump truck designs are designed for 5–12 loading cycles. This number of cycles is necessary to reduce dynamic loads on the truck frame caused by the falling rock mass from the excavator bucket [5].

To ensure single-cycle loading of a dump truck, two approaches are possible:

1. **Significant reinforcement of the truck frame**, which would increase the overall dimensions and weight of the vehicle, raise the load on tires, and consequently reduce payload capacity.
2. **Use of outriggers**, which absorb the dynamic loads occurring during loading of the truck body [6].

The principle of outriggers is simple: after positioning the dump truck under the excavator, the outriggers extend and rest on the ground, taking on the load from the

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falling rock mass. After loading, the outriggers retract, gradually transferring the load back to the truck frame.

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