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Establishing the influence of the excavator standard sizes on the kaolin pit mining system parameters

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Abstract. The article is devoted to the issue of the overburden excavators effective standard sizes substantiation in the conditions of the development of kaolin pits. The influence of the excavator standard dimensions on the total weight of the extraction and loading equipment in the pit at a given annual productivity of the pit was investigated. It has been proven that when the shovel capacity of a hydraulic excavator increases by 7 times from one to 7 m^3, the total number of excavators in the conditions of the Rozivskyi kaolin pit decreases by 6.7 times from 20 to 3, and their total metal capacity decreases by 2.3 times from 760 to 348 t. The established dependences of the daily productivity of the equipment and the excavation work cost on the excavator shovel volume allow claiming that scheme where using 5 Volvo EC 750D excavators and 10 Volvo A45 dump trucks is the most effective. The worst performance for all types of costs is the technological scheme using 20 Volvo 350D excavators and 17 Volvo A45 dump trucks. When using 5 Volvo EC 750D excavators and 10 Volvo A45 dump trucks in the proposed scheme, the cost of excavation works up to 34.5 UAH/m^3 and is minimal due to the lowest costs for depreciation and repair of equipment, as well as for fuel and lubricants.

1 Introduction

More than 10% of the world's kaolin reserves are concentrated in Ukraine, in this connection country accounts for more than 5% of the world's production of this material [1]. In terms of kaolin production, the country ranks 6th in the world and the largest exporters are European countries – Italy, Spain, Germany, Poland and France [2].

The study of geological reserves of kaolin reveals that the majority are concentrated in the Vinnytsia region, accounting for approximately 50% of all kaolin reserves listed in the state balance of mineral reserves of Ukraine, and about 60% of primary kaolin reserves.

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Implementing principles of Industry 4.0 in kaolin pit mining can optimize system parameters, enhancing efficiency and productivity [3]. The advanced capabilities of Industry 4.0, such as automation and data analytics, streamline excavation processes while accommodating standard excavator dimensions, ensuring ease of implementation [4]. This empowers kaolin mining operations to achieve higher throughput, precision, and cost-effectiveness, ultimately fostering greater profitability and sustainability [5]. Also, mining activity have been provided according to the principles of sustainable development and environmental management [6].

Also, significant mineral reserves are in the Donetsk region, where minerals differ in the complexity of their development due to their depth, hydrogeological conditions, physical and mechanical properties [7]. One of such areas in Ukraine is Rozivska, which is especially close to the Kucherovoiarskyi deposit of refractory clays.

Due to the complex hydrogeological structure [8] of the Rozivskyi area, the upper and middle layers of refractory clays [9], as well as overburden must be developed selectively with separate loading into vehicles [10].

The efficiency of the mining technology of the Rozivskyi pit will depend on the correct choice of the excavator standard sizes [11, 12], therefore, in this work, the main attention is paid to the justification of the overburden bench parameters [13], which will allow the use of modern hydraulic excavators with high productivity [14].

2 The choice of object to study

The Kucherovoiarske deposit is located in the Dobropillia district of the Donetsk region in Ukraine, with the nearest Mertsalovo railway station 11.6 km west of the deposit area. The village of Nove Shakhove is located in the immediate vicinity (2.0 km to the west) of the mining site. The village of Kucheriv Yar is located 2.5 km to the north of the site, and the village of Zhovtneve is 5 km to the east.

The object of research in the work is the development technology of the Rozivskyi pit, located between the Kucherovoiarsk and Yuzhno-Zhovtneve deposits on board the approved reserves of the Zhovtneve deposit of refractory clay (Fig. 1).

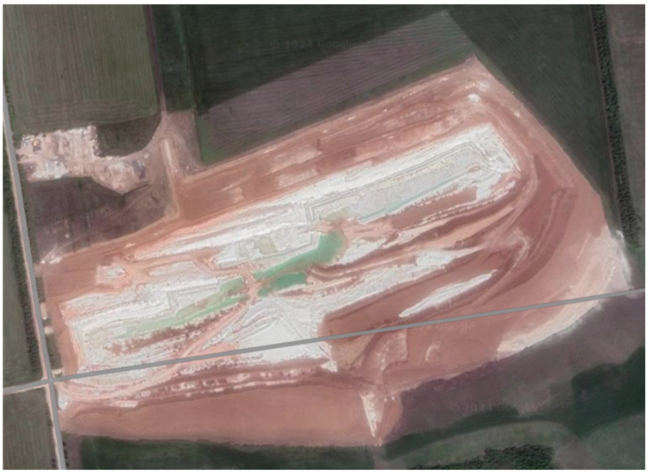

Fig. 1. Situational plan of the Rozivskyi pit.

This refractory clay pit is located within the mineral reserves record, within the right-of-way and within the license area. Its area within technical limits is 271.43 hectares.

The pit has been operating since 2011. According to the reported balance of minerals for 2017, the production volume of refractory clays for 2017 amounted to 307.3 thousand tons, including category B – 307.3 thousand tons, with losses during mining – 26 thousand tons.

The mineral layer on the site is divided into two layers of clay. At the same time, the lower layer is spread over the entire area of the site. Its thickness ranges from 0.0 – 0.3 m to 4.1 m. The average thickness of the conditioned clays of the lower layer is 1.58 m. The clays are mostly of high quality. Clay fine-grained sands with a thickness of 0.0 m to 3.6 m, on average – 0.2 m, lie above the lower layer.

The upper layer of kaolin is separated from the lower one by a layer of sand, and lies with erosion on the underlying rocks over the entire area of the site [15]. The thickness of the clays of the upper layer varies from 0.0 m to 3.6 m. Conditional clays are present only in the northern part of the site, where they are usually of high content. The average thickness of conditioned clays is 1.15 m.

Overburden consists of interclay sands and unconditioned clays [16], which lie inside the productive layer of conditioned clays. The thickness of overburden rocks varies from 0.0 m to 6.4 m, the average thickness is 0.4 m.

The Rozivskyi site is opened in the southern part of the pit field by an entrance trench of internal laying to the full capacity of the mineral [17]. The development of mining operations [18] is carried out in the northern direction. Excavation and mining operations are carried out in parallel process [19]. The development of the site is carried out by surface mining [20] with the storage of the overburden in residual space of the pit [21].

The main parameters of the mining system of the Rozivskyi pit for the performance of kaolin mineral deposit extraction according to the current project are given in the Table 1.

Table 1. Main parameters of the mining system according to the current project.

Mining system elements	Bench project value			Bench actual value		
	Kaolin	Overburden		Kaolin	Overburden	
		loam	sand		loam	sand
The height of the bench, m	6	4	4	0.5-3.5	3	3
The number of benches	2	4	8	1	4	5
Slope angles of benches:						
– working bench, degree	80	60	50	80	60	45
– stable bench, degree	60	40	30	60	40	30
Width of the bench mining area, m	28.5	34	37	34	35	40
The width of the excavator pit, m	9.5	10.5	10.5	9.5	10	10
The width of the collapse prism, m	2.4	2.5	3.6	0.2-0.8	2.5	3.6

Excavation work [22] in the pit begins with the removal of the soil-vegetation layer with a Caterpillar D6R-II or Komatsu D65 bulldozer, the soil-vegetation layer is pushed into the side with the same bulldozer, and the Volvo EC 480D excavator is loaded into Volvo A45 trucks and taken to the temporary storage of the soil-vegetation layer on the internal dumps surface [23].

The mining of overburden benches [24] is carried out by Caterpillar 365C and Caterpillar 345CL excavators with a shovel volume of 4.8 and 3.2 m^3, respectively. Rocks from external overburden are haulage to the internal dumps [25] of the pit by Caterpillar 735 dump trucks with a carrying capacity of 32.7 tons, where they are dumped separately from each other in the same order as before development.

Since for the safe operation of the pit it is necessary to divide the layer of overburden into a large number of low height benches [26], the problem of choosing rational standard sizes of the extraction and loading equipment arises [27]. In accordance with the established problem, the goal of the research was formulated, which consists in establishing the influence of the standard dimensions of excavators on the parameters of the Rozivskyi pit mining system, with further development of recommendations regarding the effective number and productivity of overburden excavators [28].

In this case, the object of research will be the technological schemes of overburden excavation works in the conditions of the Rozivskyi pit of PJSC "Clays of Donbas". The subject of the study is the parameters of the mining system elements [29] when using modern hydraulic excavators in the development of the Rozivskyi pit.

To achieve the set goal, the following tasks are expected to be performed at the researches to: perform an analysis of modern technological solutions for increasing the efficiency of excavation work at kaolin extraction pits with a low bearing capacity of the mining massif; establish the influence of the standard sizes of excavators on the parameters of the mining system in the conditions of the Rozivskyi pit; calculate the technical and economic indicators of the proposed solutions and determine the most effective technological scheme for the kaolins development in the conditions of the Rozivskyi pit.

3 Research methods

The parameters of the mining system [30] at the pit are determined by the selected mining transport equipment provided for in the Design task, the engineering-geological and mining technical conditions of the deposit and the experience of operating pits for the refractory clays production [31].

At the Rozivskyi pit, a haulage system developed according to the following schemes is used: "overburden excavator – dump truck – overburden dump"; "mining excavator – dump truck – rail-side storage of clay at Mertsalove railway station". According to the project, external and internal dumping of overburden rocks is provided.

When developing technical solutions regarding the further exploitation of the Rozivskyi site of the Kucherovoiarske deposit, it is recommended to provide for the use of the following loading and unloading machines and vehicles:

– Volvo 350D excavators with a shovel volume of 1.9 m^3; Caterpillar 336D (2 m^3), Volvo EC 480D (3.0 m^3), Volvo EC 750D (5.4 m^3) and CAT 6015 (7 m^3);

– Caterpillar D6R-II and Komatsu D65 bulldozers;

– Volvo-180 and Volvo-220 loaders;

– Volvo A40 (A45) dump trucks with a carrying capacity of 41 and 39 tons, Volvo with a carrying capacity of 21 and 32 tons.

The elements of the mining system are defined taking into account the applied mining technology and the technical characteristics of the used mining haulage equipment, as well as the experience of the Rozivskyi site pit of refractory clays.

Mining operations are carried out in longitudinal pits with the mining front moving from the south to the northwest. The height of the overburden benches on loams and sands is assumed to be equal to 6.0 m. According to the technical characteristics and experience of using Volvo EC 480D and Volvo EC 750D excavators in the pit of the refractory clays Rozivskyi pit, it is allowed to work on the benches of two approaches with a height of 3.0 m.

The haulage connection between the benches is carried out by a temporary ramp. The height of the mining bench when using the technological selective method of mineral development in the project is taken up to 4.9 m in accordance with the technical characteristics and experience of using excavators in Caterpillar 336D and Volvo 350D (Fig. 2).

Haulage connection between the benches, as well as during excavation works, is carried out by a temporary ramp. Steady angles of the bench slopes should be accepted into the corresponding project on the geological study of the subsoil "Geological and economic assessment of the Rozivskyi site of the Kucherovoiarske deposit of refractory clays".

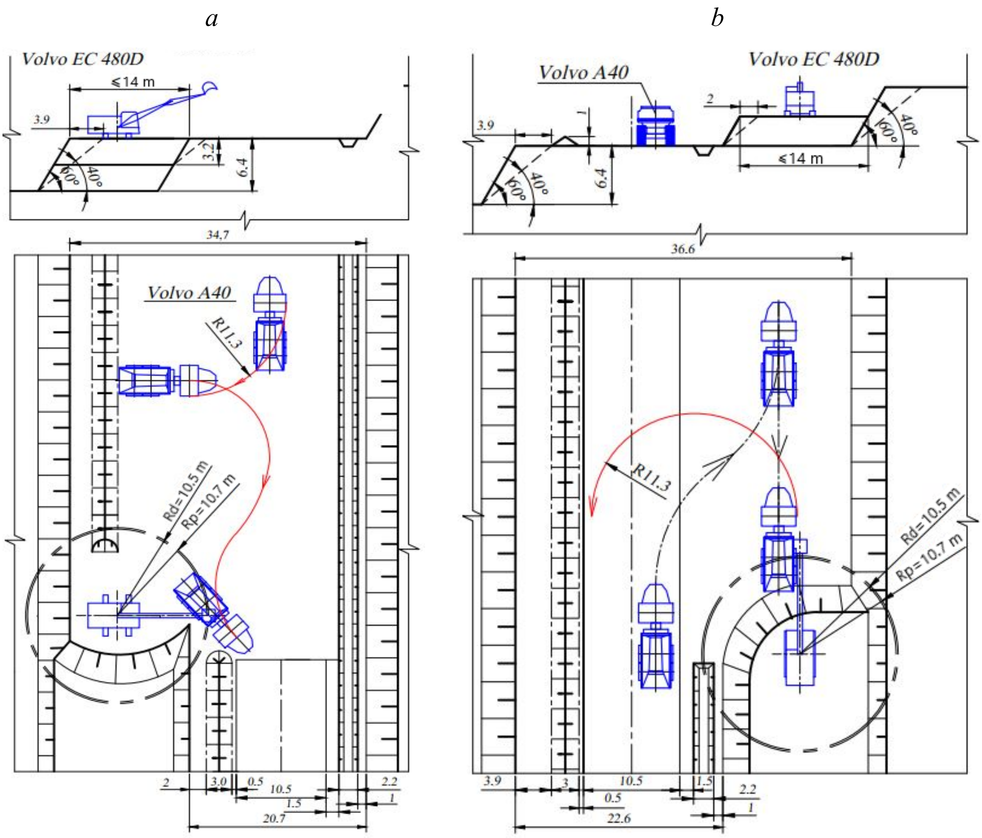

Fig. 2. Scheme of development of (a) upper and (b) lower sub-benches.

According to the physical and mechanical properties [32] of the rocks being developed, the angles of working bench have next inclination:

– overburden (sand) – 45º;
– overburden (loam) – 60º;
– kaolins – up to 80º.

Angles of stable pit slope:

– overburden benches (loam) – 40º;
– sand rocks slope – 30º;
– the resulting angle of kaolin – 60º.

Acceptance of the slope angle values and the bench stable slopes are meeting the requirements of section 1.2 and 1.3 of part B of the NPAOP 0.00-1.24-10 "Rules of labor protection in the development of mineral deposits by open method".

The width of the safety berms in accordance with the requirements of section 1.8 of part B of the NPAOP 0.00-1.24-10 is accepted under the conditions of their mechanized extraction by Caterpillar D6R-II and Komatsu D65 bulldozers with a width of 3.3 m equal to for:

– protective berms on loams, clays, sandy loams – 6.0 m;
– safety berms on sand – 10.0 m.

Upon reaching the design border of the pit slope, overburden and mineral benches are developed. The height of the non-working eastern bench of overburden loam should be equal to 12.0 m, on sand – 6.0 m, depending on specific rocks geology.

The height of the non-working (repaid) bench on the mineral is up to 7 m. Angles of inclination of the non-working bench:

– overburden (sand) – 30º;

– overburden rocks (loam, sandy loam) – 40º;

– kaolin – 60º.

In the conditions of the Rozivskyi pit, it is proposed to compare five excavators with different shovel volume: Volvo 350D (1.9 m^3); Caterpillar 336D (2 m^3); Volvo EC 480D (3.0 m^3), Volvo EC 750D (5.4 m^3) and CAT 6015 (7 m^3), in order to determine the best option in condition of Rozivskyi kaolin pit.

4 Research results

4.1 Determination of the excavator required number

According to the physical and mechanical types of overburden rocks in the Rozivsky site of the refractory clays Kucherovoiarskyi deposit, they are represented by mining mass, which includes a soil – vegetable layer, loam, and sand. The capacity of overburden rocks reaches 52.4 m, on average it is 38.5 m. According to its technical characteristics, overburden rocks are in accordance with DSTU B.D.2.2-2:2012 “Resource elemental estimate standards for construction works. Mining and overburden works (Collection 2)”, include:

– the soil-vegetation layer with an average density of 1400 kg/m^3 – up to 1 group of soils according to the difficulty of working with a scraper and an excavator;

– sandy loam with an average density of 1650 kg/m^3 – up to 1 group of soils according to the difficulty of working with an excavator, up to 2 groups of soils according to the difficulty of working with a scraper;

– sands with an average density of 1500 kg/m^3 – up to 1 group of soils according to the difficulty of working with an excavator, up to 2 groups of soils according to the difficulty of working with a scraper;

– loam with an average density of 1750 kg/m^3 – up to 2 groups of soils according to the difficulty of working with a scraper and excavator;

– clay with an average density of 1800 kg/m^3 – up to 3 groups of soils according to the difficulty of working with an excavator.

For the development of overburden rocks, five technological scheme were adopted in the research, according to which the same volume of overburden work will be performed by the following excavators: Volvo 350D, Caterpillar 336D, Volvo EC 480D, Volvo EC 750D and CAT 6015. Overburden is transported by Volvo A45 and Volvo A40 dump trucks with a capacity of 41 and 39 tons to the internal dump. The distance of overburden transportation to the dump is 1.0 km.

The overburden bench with a height of 6.4 m is divided into two sub-benches with a height of 3.2 m each. Excavation of overburden bench rocks is carried out with a face cut width of up to 14.0 m. When working out the upper sub-bench Volvo A40 (A45) dump trucks are used to load the upper platform of the bench.

Initial data for conducting research on determining the productivity of overburden excavators and their number in the conditions of development of the Rozivsky pit consist in (Table 2).

In addition to the given initial data (Table 2), the following parameters are also used for calculations: shovel filling factor is 0.7; the face cut ratio is 0.9; coefficient of excavation technology is 0.83; utilization factor is 0.7; coefficient of rock loosening is 1.2; shift duration is 11 hours; number of shifts is 2; the number of working days per year is 356.

Table 2. The main parameters of the development system according to the current project.

Excavator	Shovel capacity, m^3	Work cycle time, s	Excavator mass, t
Volvo 350D	1	25	38
CAT 336D	2	25	35
Volvo EC480D	3	30	53
Volvo EC 750D	5.4	30	74
CAT 6015	7	23	116

The results of the obtained calculations for determining the elements parameters of the Rozivskyi pit development system are shown in Table 3. At the same time, a significant part of the parameters will be the same for all specified types of excavators: the width of the collapse prism is 2.7 m; the height of the bench is 3.2 m; the stable slope angle of the working bench is 40 degrees; the slope angle of the working bench is 60 degrees; the width of the protective shaft is 3 m; safe distance is 0.5 m; the width of the truck way for the Volvo A40 is 10.5 m; curb width is 1.5 m; the width of the floor ditch is 2.2 m; the distance from the truck way road to the lower edge of the bench is 1 m.

Table 3. Technological parameters of the mining system elements when using various excavators at the development of the Rozivskyi pit.

Excavator	Digging radius, m	Face cut width, m	Width of bench working area, m
Volvo 350D	11.1	14.4	35.8
CAT 336D	11	14.3	35.7
Volvo EC480D	10.5	13.7	35.1
Volvo EC 750D	10.5	13.7	35.1
CAT 6015	10	13.0	34.4

According to the existing methods of calculating the theoretical and technical output of shovel excavators and the initial data indicated in (Tables 2 and 3), it was established that in the mining conditions of the Rozivskyi site, when the shovel capacity is increased from 1 to 7 m^3, the mass of the necessary excavators in pit changes disproportionately. In order to establish the effect of the excavator standard dimensions on the total weight of the extraction and loading equipment in the pit, calculations were made to determine their productivity and the required number of excavators with an annual volume of overburden of 7.22 million m^3. The calculation results are given in Table 4.

Table 4. Operating parameters of shovel excavators at the Rozivskyi pit.

Excavator	Types of productivity					Number of excavators
	Theoretical, m^3/h	Technical, m^3/h	Operational, m^3/shift	Daily, m^3/day	Annual, M m^3/year	
Volvo 350D	144	63	483	966	0.35	20
CAT 336D	288	125	966	1933	0.70	10
Volvo EC480D	360	157	1208	2416	0.88	8
Volvo EC 750D	648	282	2174	4348	1.58	5
CAT 6015	1096	477	3676	7352	2.68	3

The parameters set in the Tables 2 and 4 made it possible to establish the influence of the excavator standard size on their number and total mass at a given annual volume of overburden excavation work under the technological conditions of the Rozivskyi pit development (Fig. 3).

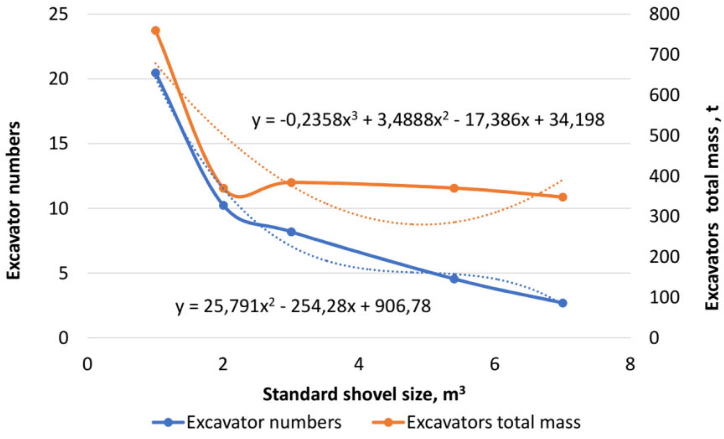

Fig. 3. Dependence of the excavator numbers and their total mass on the standard shovel size machines with an annual volume of overburden works of 7.22 million m^3.

As can be seen from the obtained dependencies (Fig. 3), the increase of excavator shovel volume allows reducing the amount of extraction and loading equipment to excavate the given volume of mining work, but the total metal capacity of the equipment decreases non-linearly. Thus, when the capacity of the shovel increases by 7 times from one to 7 m^3, the total number of excavators for the development of overburden with a volume of 7.22 million m^3 decreases by 6.7 times from 20 to 3, and their total metal capacity decreases in 2.3 times from 760 to 348 tons.

In this connection, there is a need to determine the influence of the excavator standard sizes on the cost of overburden. This task can be solved by evaluating the technical and economic indicators of the overburden development.

4.2 Determination of technological schemes economic indicators

The following raw data are used when calculating the salary fund for the number of employees who service equipment for the development of overburden rocks. In the first scheme 20 Volvo 350D excavators and 17 Volvo A45 dump trucks are used. A total number of working people on overburden site are 76. Analysis of the second scheme indicators allows to determine that 10 CAT 336D excavators and 12 Volvo A45 dump trucks are used on the overburden site. A total number of workers on the overburden site are 46. In the third scheme 8 Volvo EC480D excavators and 11 Volvo A45 dump trucks are used on the overburden site. A total number of workers on the overburden site are 40. In order to ensure the annual productivity from the overburden according to the fourth scheme it is necessary to attract 5 Volvo EC 750D excavators and 10 Volvo A45 dump trucks. A total number of people work on the overburden site are 32. The practical implementation of the fifth scheme of overburden development requires the use of 3 CAT 6015 excavators and 9 Volvo A45 dump trucks. 26 employees must be hired to service them.

A comparison of the technical and economic indicators of the considered schemes for performing excavation work in the conditions of the Rozivskyi pit allows us to establish that the scheme with the smallest standard dimensions Volvo 350D, which uses 20 excavators and 17 Volvo A45 dump trucks, is the most expensive. Scheme 4 using 5 Volvo EC 750D excavators and 10 Volvo A45 dump trucks are the most effective. Schemes using CAT 336D, Volvo EC480D and CAT 6015 excavators have approximately the same indicators of the overburden works cost (Table 5).

Table 5. The cost of development of overburden rocks in the conditions of the Rozivskyi pit.

Type of expenses	Excavators for overburden works				
	Volvo 350D	CAT 336D	Volvo EC480D	Volvo EC 750D	CAT 6015
Wage fund, UAH/m^3	13.65	8.4	7.4	5.9	4.8
Depreciation expenses, UAH/m^3	2.58	1.9	2.1	1.7	2.5
Repair costs, UAH/m^3	1.23	0.9	1.0	0.8	1,2
Costs for PMM, UAH/m^3	55.08	35.3	32.4	26.0	31.7
Total, UAH/m^3	72.54	46.4	42.9	34.5	40.2

The summary calculations results of the excavator shovel volume dependence on the excavator daily productivity and carrying out excavation work cost in the conditions of the Rozivskyi pit development for the five considered schemes are shown in the graphs (Fig. 4).

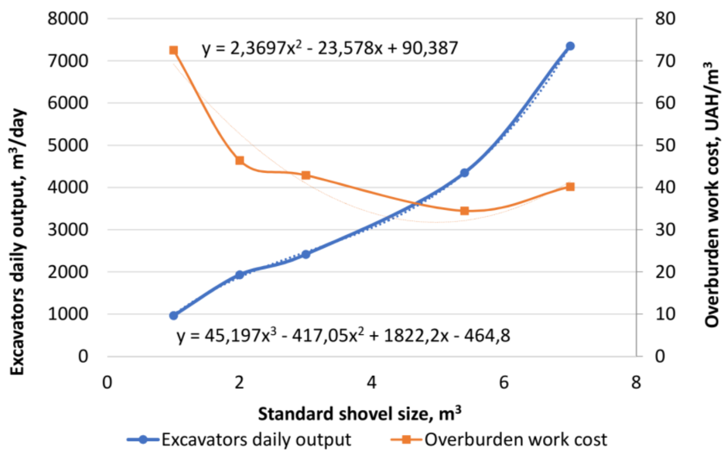

Fig. 4. The influence of the shovel volume on the excavators daily output and the overburden work cost in the conditions of the Rozivskyi pit development.

The performed analysis of dependencies (Fig. 4) shows that the cost of excavation works in the scheme using the Volvo EC 750D excavators is minimal due to the lowest costs for depreciation and equipment repair, as well as for fuel and lubricants and amounts to 34.5 UAH/m^3. This scheme is inferior only to the scheme using CAT 6015 in terms of the payroll, as it requires a larger number of employees to achieve pit annual output.

5 Conclusions

An analysis of modern technological solutions to increase the efficiency of excavation work at kaolin pits mining was performed, which allowed to formulate research tasks and compare the effectiveness of the use of 5 standard sizes of excavators in the kaolin pit development conditions: Volvo 350D (1.9 m^3); CAT 336D (2 m^3), Volvo EC 480D (3.0 m^3), Volvo EC 750D (5.4 m^3) and CAT 6015 (7 m^3).

According to the research results obtained during the development of the Rozivskyi pit it was established that when the shovel capacity increases from 1 to 7 m^3, the number of loading equipment in the pit decreases. In order to establish the effect of the excavator standard dimensions on the total weight of the extraction and loading equipment in the pit. These calculations were made to determine the productivity and number of excavators with a fixed annual overburden volume of 7.22 million m^3.

It was established that increasing the excavator shovel volume allows to reduce the number of loading and unloading equipment to perform a given volume of mining work, but the total metal capacity of the equipment decreases in a non-linear way. Thus, when the capacity of the shovel increases by 7 times from one to 7 m^3, the total number of excavators for the overburden work with a volume of 7.22 million m^3 decreases by 6.7 times from 20 to three, and their total metal capacity decreases in 2.3 times from 760 to 348 tons.

The dependences of the equipment daily productivity and the excavation work cost on the excavator shovel volume were established, which allow to claim that scheme 4 using 5 Volvo EC 750D excavators and 10 Volvo A45 dump trucks is the most effective. The first technological scheme with the use of 20 Volvo 350D excavators and 17 Volvo A45 dump trucks has the worst indicators for all types of costs.

When using 5 Volvo EC 750D excavators and 10 Volvo A45 dump trucks in the fourth scheme, the cost of excavation works up to 34.5 UAH/m^3 and is minimal due to the lowest costs for depreciation and repair of equipment, as well as fuel and lubricants. This scheme is inferior only to the fifth scheme using CAT 6015 in terms of the wage fund, as it requires a larger number of employees to achieve annual pit output.

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