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SUBSTANTIATION OF THE OPTIMAL PARAMETERS OF THE BENCH ELEMENTS AND SLOPES OF IRON ORE PITS

Purpose. To establish the optimal parameters of the bench elements and slopes of the pit at the mining of Horishne-Plavnynske and Lavrykovske deposits of ferruginous quartzites for further use of these parameters at the design.

Methodology. Methods for determining the influence of the bench height on the productive pit capacity involves taking into account the quality of the ore, the rate of the mining front advancement, the rate of pit depth at the mining operations, the total length of the mining front, as well as the angles of the working and non-working pit slopes.

Findings. The most effective parameters for mining benches and slopes of an iron ore pit are considered, using the example of the Ferrexpo Poltava Mining. Parameters of the bench elements with a height of 24–30 m have been established, which are worked out in layers with a height of 12, 10 and 15 m. The studies carried out made it possible to establish that layers with a height of 10 m, followed by the final and temporary pit contour with a bench height of 30 m, can improve safety due to the flattened slope of the pit up to 45°, while, with a bench height of 15 m, the angle of inclination of the slope will be 47°.

Originality. The established dependence of the pit ore productivity in percentage on the bench height suggests that with an increase in the bench (layer) height, the ore productivity of the pit decreases. Determination of the influence of the working bench (layer) height on the total volume of ore losses in the design contour of the pit makes it possible to assert that at constant angles of the bench slope and the ore deposit fall, the values of operating losses and clogging change in direct proportion to the height.

Practical value. A technological scheme has been developed for the development of a bench with a height of 30 m with a layer thickness of 10 m, which makes it possible to improve safety in the pit by pit slope flattening to 45°, to reduce the cost of ore mining by optimizing drilling operations (shorter drilling time per well, reduction of overdrilling and etc.) and thereby improve the economic performance of the enterprise.

Keywords: *pit, bench elements, pit slope, bench layers, iron ore, overall pit slopes*

Introduction. The development of iron ore deposits is one of the promising directions of sustainable economic development of Ukraine. However, the constant increase in the current depth of iron ore pits makes it necessary to improve the technology of surface mining [1].

The main feature of the development of the global mining industry today and for the near future is a sustainable orientation towards a surface mining method, which provides the best economic indicators. The specific weight of the surface mining method of development is 72–73 % in the world, in the USA – 83 %, in the CIS countries – about 70 %. In Ukraine more than 90 % of iron ores are mined by the surface mining method [2].

The expansion of the surface mining method of mineral deposits is characterized by an increase in the concentration of production, accompanied by an increase in the depth and spatial dimensions of pits, haulage distances, and the difficulty of delivering rock mass to the pit surface. Currently, the largest pits in Ukraine (including the Ferrexpo Poltava Mining) have exceeded a depth of 400 m.

Analysis of project solutions shows that the majority of currently operating iron ore pits will be operated after 2035 (within the next 15–20 years). It is planned to extract 70–75 % of ore and 75–80 % of rock mass by 2035 in pits with a depth of 300 m or more [3]. Thus, the main volume of mining and extraction of rock mass in the iron ore subsector in the next two decades will continue to be carried out mainly by developing deep horizons [4].

The issues of developing deep pits were theoretically raised in the 50–60s [5]. The first classifications of pits by depth, which were based on the difference between the

markings of the pit bottom and surface, belong to the same time [6].

Pits with working horizons located at a depth of 100–150 m were classified as deep [7]. Under the influence of technical progress in the mining industry, the concept of a “deep pit” has undergone changes. In the 1980s, deep pits were classified as pits with a depth of more than 200 m. In the same period, the characteristic features of deep pits were formulated by leading scientists, which are as follows [8]:

- large ore production capacity (10–25 million t/year and more), volumes of rock mass (50–60 million t/year and more);
- a long pit life cycle (usually at least 30 years);
- a sharp reduction in parameters of the working zone with increasing depth [9];
- combined pit opening, using underground workings;
- simultaneous application of various mining technologies, as well as types of mining and haulage equipment.

Two general directions for solving the problem of developing deep pits are highlighted:

- reducing the negative consequences of increasing the pits depth;
- compensation of negative consequences due to changes in the parameters of the mining system, introduction of new technologies and equipment.

Setting the factors impact on pit productivity when increasing the depth of development. Since the most general, unifying parameter, which largely determines the technical and economic indicators of surface mining, is the production capacity of the pit, the implementation of these areas is necessary, first of all, to maintain the deep pits capacity [10].

All the factors affecting pit productivity when increasing the mining depth can be divided into three main groups:

- mining and geological (natural);
- technical;

- mining and technical (technological).

The change in mining and geological conditions for the development of deep pits is objective in nature and has specific features for each deposit or group of deposits.

The diagram of the interrelationship of factors affecting pit production capacity at the increasing depth of mining operations is presented in Fig. 1.

The research conducted on the example of halls and ore pits has established that with an increasing depth of development, mining and geological factors are characterized by [11]:

- increasing the specific weight of rocks in the total volume of the rock mass;
- increasing the average rocks strength;
- as a rule, a decrease in the content of iron in raw ore;
- a decrease in the strength of ore bodies, a change in the angle of deposit fall;
- development by changes in hydrogeological conditions (increased water inflow);
- changes in rock stability in pit sides.

The forecast of the share of rocks in the rock mass of the Ferrexpo Poltava Mining pit in the subsequent periods of mining is presented in Fig. 2

At mining enterprises that develop iron ore deposits, there is a decrease in the content of useful components, especially the content of common and magnetic iron. In most pits, there is a close correlation between the iron content in raw ore and the depth of development.

Statistical relationship between the iron content in raw ore by the depth of iron ore pits is presented in Table 1.

The patterns of iron content reduction in raw ore, which are of an ambiguous nature, should be considered in two aspects:

1. Technological reduction of the content due to the involvement at the development of poor ores in parallel with

the improvement of beneficiation technology, the change in technical conditions and the increase in clogging in connection with the growth due to operating parameters of the extraction and loading equipment. These factors do not have a physical relationship with the depth of development, and their influence on the average iron content in crude ore is manifested in time.

2. Geological decrease in content is due to the genesis of iron ore deposits and has a close relationship with the depth of mining.

In most deposits, the parameters of iron ore body, thickness along the extension, dip angles and structure change with the depth. At the same time, the nature of changes is individual for each deposit.

The deposit capacity, which determines the operational (active) ore area, has the greatest influence on the productivity of the pit from the listed factors. In a number of iron ore pits in the period 1990–2010, a decrease in ore productivity was observed due to the reduction of the operational areas of ore deposits.

Mining and geological factors can be divided into two main groups according to the nature of their impact on pit productivity:

- factors that directly affect pit productivity;
- factors whose impact on pit productivity is manifested through a change in technical and technological factors.

The first group includes the content of the useful component in raw ore, the strength and conditions of occurrence of the ore body.

The second group includes physical and mechanical properties of pit rocks, hydrogeological conditions of development and stability of slopes, that is, factors affecting the productivity of the pit through the technical and operational performance of the equipment.

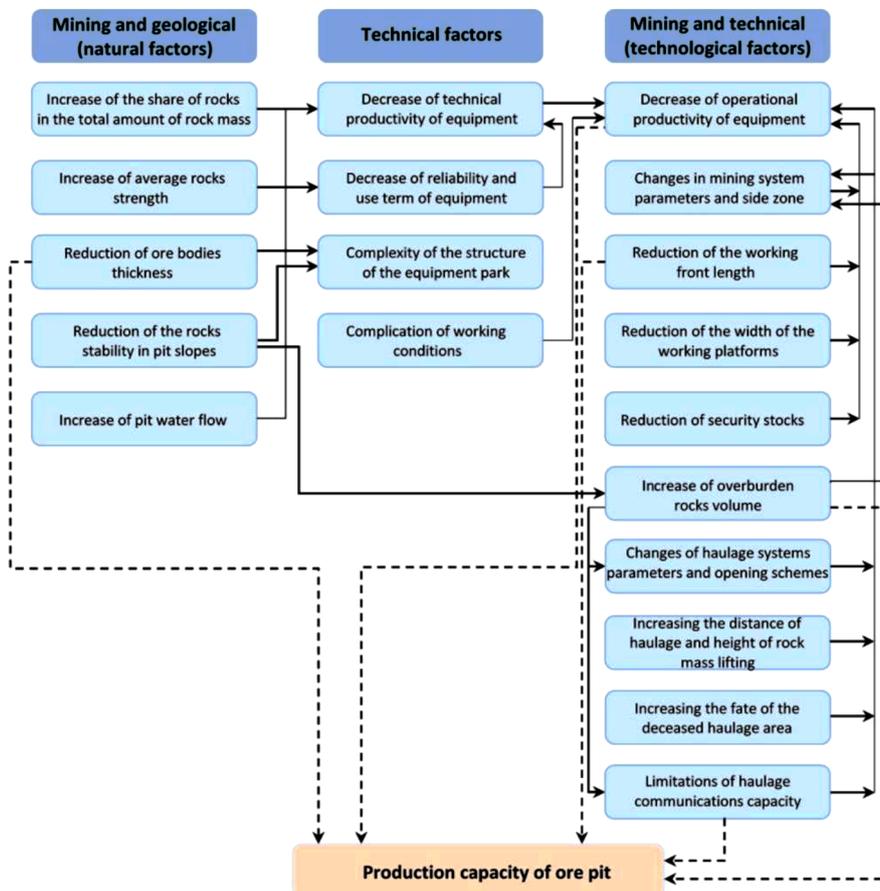


Fig. 1. The diagram of the relationship of factors affecting pit productivity with increasing mining operations depth

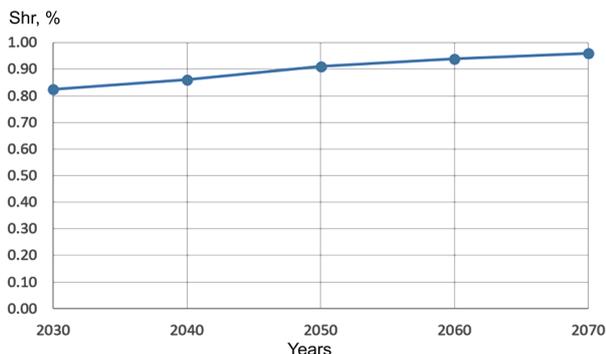


Fig. 2. Forecast of the hard rocks share (Shr) in the rock mass of Ferrexpo Poltava Mining pit in the exploitation periods

Table 1

Statistical relationship of iron content in raw ore by the depth of iron ore pits

Enterprise	Equation	Correlation coefficient
PJSC "Pivd GZK"	$a = 36.15 - 0.0051 H_K$	-0.8469
PJSC "InGZ K"	$a = 33.37 - 0.0021 H_K$	-0.5782
Ferrexpo Poltava Mining	$a = 34.54 - 0.021 H_K$	-0.7692

The largest group is represented by mining technical (technological) factors, which include changes in the parameters of mining systems and the working area, haulage system parameters and pit opening schemes, an increase in the volume of overburden and a decrease in the operational productivity of mining haulage equipment (Fig. 1).

Technological factors are characterized by a close relationship and have a general tendency to change with increasing mining depth in different pits.

An important feature of mining factors is that, unlike natural factors, they are controllable within a certain range of changes. Controlling influences, including the use of high-performance mining and haulage equipment, improvement of mining system parameters, opening schemes and haulage systems of pits, allow compensating for the negative impact of development depth and maintaining the productivity of pits at a given level for long periods.

Based on statistical analysis, it was established that the current state of the working area of most deep iron ore pits is characterized by:

- reduction of the average width of road and ramp width;
- a decrease in availability of ready-to-extract reserves up to 0.7–1.0 months;
- reducing the working front length.

At a number of pits (pit No. 1 of PJSC "Tsentralny GZK", Hannivskiy and Pervomaiskiy pits of PJSC "Pivnich GZK", the pit of Ferrexpo Poltava Mining), when reaching a depth of 300–350 m, the width of the road and ramp width decreased down to 30–40 m, and the number of sites with a standard width in some cases decreased to 30–40 %.

At the same time, the reduction of the width of the road and ramp width excludes the possibility of multi-row location of wells on blasting blocks (the number of rows of wells decreases to 3–4 versus 6–7), the output of oversize increases, the latter in some bottoms reached 20–25 %.

In these conditions, mining haulage equipment, limited by a small slaughter space, loses the necessary mobility and cannot be used at full parameters and with possible productivity.

An important technological feature of deep pits is the wide use of temporary conservation of individual parts of the slopes.

The temporary preservation of benches and individual sections of working sides helps to regulate the regime of mining operations with an increase in their depth and the transfer of the overburden volume part to more distant periods, that is, it plays a positive role from the point of view of the time factor.

The presence of temporarily non-working road and ramp in the area is a natural phenomenon in deep pits with a large overburden coefficient, especially at the time when the working edges approach the pit boundary contour, when the volume of overburden works reaches its maximum value. At the same time, excessive conservation of bench and reduction of the width of the working sites leads to a decrease in the number of explosives of well rows, an increase in the frequency and number of explosions, the complication of the work organization on the bench, a decrease in the productivity of mining haulage equipment and, most importantly, a reduction in the working front, which can cause premature disposal of capacities.

On the basis of statistical analysis, it was established that with a decrease in mining operations by 100 m, the average actual decrease in the productivity of drilling machines in iron ore pits is 10–15 %; excavators working in combination with road haulage 9–15 %; dump trucks – 25–39 %.

In addition, the value of equipment productivity is affected not only by the deterioration of mining-geological and mining technical conditions of development with an increase in the depth of pits, but also the factor of technical progress [12].

The depth of development has the greatest impact on productivity, technical and economic indicators of pit haulage. Until now, in the majority of domestic pits, full compensation for the decrease in the technical and economic indicators of haulage with an increase in the depth of development cannot be provided by technical progress [13]. In this regard, the haulage problem was and remains one of the most important problems in the development of deep pits.

One of the directions of maintaining the production capacity of the pit and improving the quality indicators of ore extraction in the conditions of increasing the depth of development, increasing the quality indicators of raw ore extraction, increasing the operational productivity of the mining equipment complex, increasing the speed of movement of the mining front is optimization of the mining system parameters [14].

Determining the influence of the bench height on the iron ore pit productivity. The height of the bench directly affects the pit productivity, the quality of the mined ore, the speed of the advance of the front and the rate of deepening of the mining works, the total length of the front of the mining works, the overall bench slope angle of the working and non-working slopes.

As is known, the productivity of an ore pit according to mining technical capabilities is determined by the formula

$$Ap = hr \cdot Sp \cdot \gamma \frac{1-r}{1-v},$$

where hr is the rate of reduction of mining operations, m/year; Sp is the area of the ore body, within which the reduction of work takes place, m^2 ; r is operational losses, unit share; v is operational clogging, unit share; γ is volumetric weight of ore, m^3/ton .

The rate of deepening mining operations is determined from the expression

$$hr = \frac{hy \cdot Vpr}{hy(ctg\alpha + ctg\beta) + Bp},$$

where hy is the height of the bench, m; Vpr is the maximum speed of work front advance on the limiting horizon, m/year; Bp is the road and ramp width, m; α is the slope angle of the

mining bench, degree; β is the angle of the deepening direction, degrees.

The maximum possible speed of mining front advancement V_{pr} on the limiting horizon is determined by the formula

$$V_{pr} = \frac{Qe \cdot n}{hy \cdot Lf},$$

where Qe is productivity of the excavator, $m^3/year$; n is the number of excavators on the horizon, units; Lf is the length of the work front on the horizon, m.

In order to determine the dependence of the productivity of the pit on ore from the height of the bench (layer), a calculation was made for a conventional section of the pit edge, which has similar parameters (size, ore body thickness, equipment productivity) with the average mining "wave" of the Ferrexpo Poltava Mining pit.

The dependence of the ore productivity of the pit on the height of the bench in the percentage of the base height of the bench (layer) equal to 10 m is shown in Fig. 3.

The results of the calculations confirm the effect of the height of the bench on the speed of preparation and working out of the horizon, namely, a longer preparation time corresponds to a higher height of the bench, a lower speed of lowering of mining and, accordingly, mining operations. Accordingly, the productivity of the ore pit directly depends on the height of the benches; the greater the height of the benches (layers) is, the less the possible productivity of the ore pit is.

Based on this, to ensure the stability of mining operations, it is advisable to work out the pit with benches (layers) of lower height.

Establishing the dependence of loss and clogging indicators on the bench height. In addition to the production capacity, the bench (layers) height is one of the main factors affecting the indicators of qualitative and quantitative losses of ore extraction. Ore losses are defined as the difference between mineral reserves in the subsoil and its extracted volume in the pit.

The ratio of the amount of ore losses to its reserves in the subsoil, expressed in fractions of a unit or in percentages, is the coefficient of operational losses of ore (P). At the contacts of overburden and ore deposit, in the process of working out the bench and as a result of different angles of bench slopes and the falling direction of the ore deposit, operational losses and ore clogging occur.

The amount of losses and clogging depends on the relative position of the slope of the mining ore bench and the contact plane of the ore body. Regardless of the direction of mining operations development, relative to the fall of the ore body, there is an inverse relationship between ore loss and clogging.

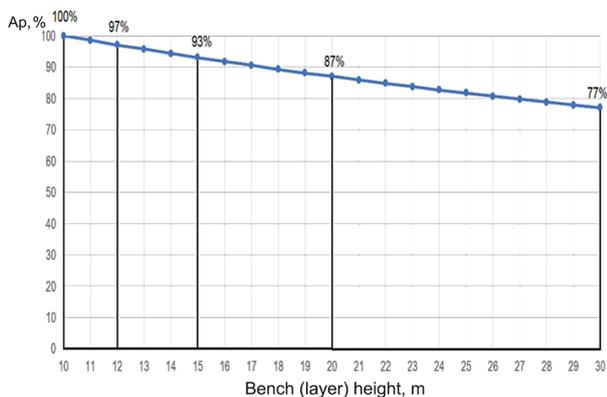


Fig. 3. Dependence of the ore productivity of the pit on the height of the bench in the percentage of the base height of the bench (layer) equal to 10 m

Calculation of ore losses and clogging is carried out according to the following formulas

$$P = \frac{K^2 \cdot h^2 \cdot l \cdot \gamma_p \cdot (\text{ctg} \alpha \pm \text{ctg} \beta)}{2},$$

$$B = \frac{K^2 \cdot h^2 \cdot l \cdot \gamma_v \cdot (\text{ctg} \alpha \pm \text{ctg} \beta)}{2},$$

where P is loss; B is clogging; K is the ratio of the ore and the total height of the bench; h is the height of the mining bench, m; l is the length of the contact zone, m; γ_p, γ_v are density in the massif, respectively, of ore and overburden, t/m^3 ; α is the slope angle of the bench; β is the angle of the line between the ore and rock contact.

To determine the effect of the height of the benches (layers) on the indicators of losses and clogging, calculations of these indicators were performed for the conditions of the Ferrexpo Poltava Mining pit. The values of loss and clogging indicators largely depend on the angle of ore deposit fall and the angle of the ore bench slope. For this calculation, the angle of ore deposit fall $\beta = 80^\circ$, and the slope angle of the bench $\alpha = 55^\circ$ were taken.

The dependence of loss and clogging indicators on the height of the bench (layer) is presented in Fig. 4.

Based on the obtained values of the loss coefficient, it is possible to calculate the total volumes of ore losses $K_2^2 + K_3^2$ in the design contour for different heights of working benches (layers).

The total volumes of ore losses in the design contour at different heights of the working bench (layer) are presented in Fig. 5.

Analyzing the obtained graphs, we can come to the following conclusions:

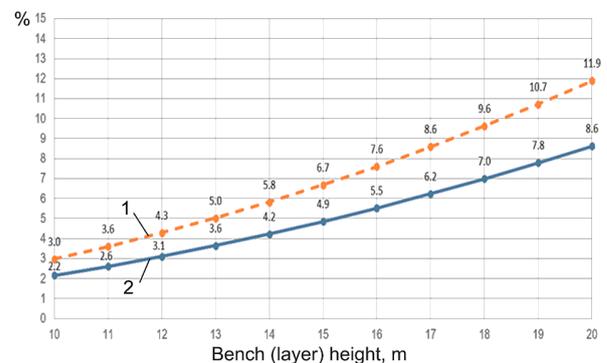


Fig. 4. Dependence of loss and clogging indicators on the bench (layer) height:

1 – clogging; 2 – losses

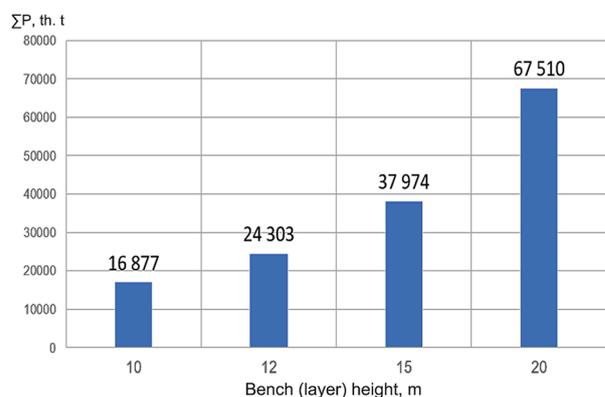


Fig. 5. Total volumes of ore losses (thousands tons) in the design contour at different of the bench (layer) height

- at the constant angles of bench slope and ore deposit fall, the values of operational losses and clogging are directly proportional to the height of the bench;

- to improve the qualitative and quantitative indicators of ore extraction, it is advisable to use layer-by-layer working of benches, since for the conditions of the Ferrexpo Poltava Mining pit, working out mining benches to the full height causes an increase in the coefficient of losses and clogging by 2.5–4 times;

- at a layer height of 10 m, the coefficients of losses and clogging are 2–2.5 times less than at a height of 15 m.

Results. The obtained results show that the planning of the deep pit parameters should be based on the study of the engineering and geological conditions of the pit fields, whose consequence is the zoning of the pit according to the stability of the benches and sides as a whole. The integrity of the pit slope benches depends primarily on the state of the rock mass, which is influenced by a number of factors.

The stability of the pit slopes is directly related to natural and following mining technical factors such as:

- climatic conditions of the deposit;
- geological features;
- structural and tectonic factor;
- hydrogeological conditions of the deposit.

In addition, mining technical conditions are affected by the geometric parameters of the pit, blasting operations, as well as mining haulage equipment. The performance of the specified production processes was considered during the performance of scientific and research works.

Since the bench is one of the main elements of the mining development system, its rational height should be the one ensuring the safety of mining operations, the planned annual volumes of mining and excavation works, high productivity of equipment, minimum volumes of auxiliary works, minimum costs for mining and excavating works.

The height of the bench directly affects the following technical and production indicators:

- the quality of mined ore;
- the speed of advancement of the mining work front;
- speed of deepening mining operations;
- production capacity of the pit;
- volume of mining and capital works;
- the total length of the work front;
- angle of inclination of working and non-working slopes.

According to the norms of technological design of mining enterprises, the height of the benches is set by the project taking into account the physical and mechanical properties of the rocks, the type of the used mining haulage equipment, the amount of loss and clogging of minerals, the necessary production capacity of the pit and rock mass, the rational distri-

bution of the volume of rock mass in times and is limited in accordance with the requirements of safety regulations.

The rational height of the benches cannot be determined by one of the listed factors, it must be chosen based on the determination of the combined influence of these factors, which play an important role in the process of organizing the pit as a whole.

When developing inclined and steeply sloping ore deposits the possible production capacity according to mining technical conditions is determined by the maximum speed of deepening of mining operations, which is determined based on the height of the bench, its angle of inclination, as well as the maximum possible speed of advancement of the front of mining operations on the bench, which indicates a proportional dependence of ore pit productivity on the bench height.

It was proven by scientists in the field of iron ore mineral deposits that the productivity of an ore pit directly depends on the height of the bench: the greater the height of the bench is, the lower the possible ore productivity is.

Working out the benches by layers creates an opportunity to ensure the uniformity and stable productivity of the ore pit by increasing the productivity of the drilling equipment, increasing the length of the active front, as well as accelerating the advancement of the mining front. In addition, working out the benches in layers allows reducing the time for preparing new horizons for working out.

When determining the optimal parameters of the bench elements, safety requirements should also be observed [15], according to the rules of labour protection when developing the deposits by the surface mining method.

Taking into account the long-term experience of operating the pit of Ferrexpo Poltava Mining (more than 50 years), a generalization of the existing side designs is carried out and the optimal one is determined.

During the research, three options for performing mining operations in layers in height were considered:

- 12 m, with further access to the final and temporary circuit with a bench height of 24 m;
- 15 m with further access to the final and temporary circuit with a bench height of 30 m;
- 10 m, with further access to the final and temporary circuit with a bench height of 30 m.

A detailed analysis of each of the options allows us to state that the third option is the most effective for the conditions of development of the Ferrexpo Poltava Mining pit, with the resulting angle of inclination of the pit slope being 45°, and the angle of the bench slope – 55°.

The established parameters of the development system increase the safety of mining operations in the pit by setting the angle of inclination of the side of the pit to 45° against 47° when

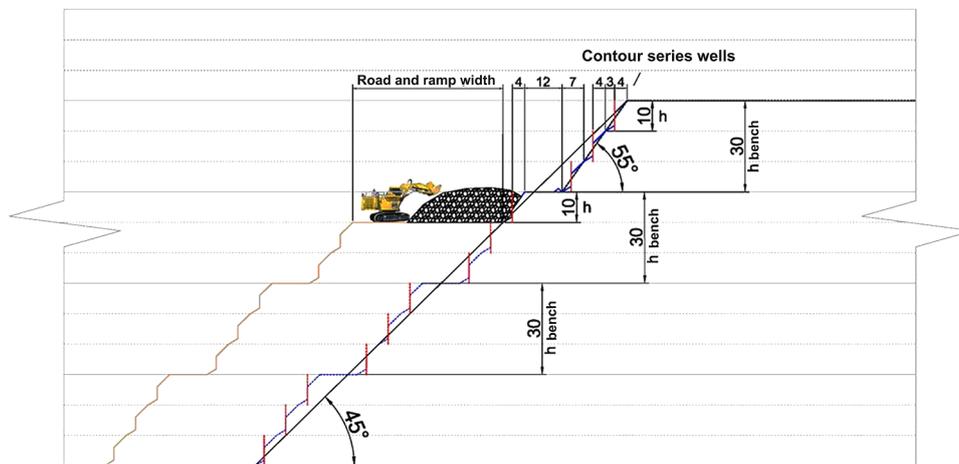


Fig. 6. Scheme of working out the first layer of the bench with a height of 30 m with a layer thickness of 10 m

working in layers of 15 m, and also ensure more complete extraction of the mineral from the subsoil compared to the development of the system with working benches in layers of 12 m.

In addition, the development system with working out benches in layers of 10 m (Fig. 6) fully meets the requirements of Clause 1.1, Part 1 of Section V. NPAOP 0.00-1.24-10, in which "It is allowed to work out benches up to 30 m high in layers, subject to temporary repayment of benches on the intermediate contour and derivation of benches on the design contour. When applying the proposed option, the pit face height should not exceed one and a half of the maximum scooping height of the excavator during the development of the first (upper) layer and the scooping height during the development of the following (lower) layers", and should respond to operating parameters of the mining equipment available at the enterprise.

The conducted research made it possible to establish that the proposed development system allows reducing the cost of ore extraction due to the optimization of drilling operations (shorter drilling time for wells, reducing the length of drilling, reducing the resistance line on the sole, and others) and thus improving the economic indicators of the enterprise [16], as well as to exclude costs for re-equipment of the enterprise in order to work out the benches of the pit in layers of 15 m.

Conclusions. The results of studies on the substantiation of the optimal parameters of the benches and slope elements, when developing the Horishne-Plavnynske and Lavrykivske iron quartzite deposits, allow concluding about unfavourable mining technical conditions on the southern and south-western slopes, which require the development of special measures in the formation of the final contour, and also require laying out the sections of the pit side.

In order to optimize the parameters of the benches and slope elements of the pit, three variants of the slope construction were considered when setting them in their final or temporarily non-working position. In the research work, the possibilities of developing benches with a height of 24 m (2 layers of 12 m), 30 m (2 layers of 15 m) and 30 m (3 layers of 10 m) are considered.

As a result of the conducted research, it was established that the existing system of development, which provides for conducting mining operations in layers 10 m high, with subsequent access to the final and temporary contour with a bench height of 30 m, complies with the specified regulatory documents and allows improving safety in the pit due to setting the angle of inclination of the side of the pit up to 45 versus 47° when working in layers of 15 m.

The proposed parameters of the benches and slopes elements of the pit provide for the development of benches with a height of no more than 30 m in three layers of 10 m, in compliance with the requirements regarding the height of scooping during the development of the next (lower) layers and the equipment available at the enterprise. The proposed system also makes it possible to reduce the cost of ore extraction due to optimization of drilling operations (shorter drilling time for wells and reduction of over-drilling, etc.) and thereby improve the enterprise's economic performance.

This work was conducted at the Department of Surface Mining at Dnipro University of Technology within the projects "Substantiation of optimal parameters of bench elements and slopes of the pit developed by Horishne-Plavnynske and Lavrykivske deposits of ferrous quartzites" (Agreement No. 010269-20, Dnipro University of Technology).

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Обґрунтування оптимальних параметрів елементів уступів і бортів залізородних кар'єрів

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Мета. Встановити оптимальні параметри елементів уступів і бортів кар'єру, що розробляє Горішне-Плавнинське й Лавриківське родовища залізистих кварцитів для подальшого використання даних параметрів при проектуванні.

Методика. Методика визначення впливу висоти уступу на продуктивну потужність кар'єру передбачає врахування якості видобутої руди, швидкість посування фронту гірничих робіт, темп поглиблення гірничих робіт, загальну протяжність фронту гірничих робіт, а також кути укосів робочих і неробочих бортів кар'єру.

Результати. Розглянуті найбільш ефективні варіанти відпрацювання уступів і бортів залізорудного кар'єру на прикладі Полтавського ГЗК. Встановлені параметри елементів уступів висотою 24 і 30 м, що відпрацьовуються шарами висотою 12, 10 і 15 м. Виконані дослідження дозволили встановити, що застосування шарів висотою 10 м, із подальшим виходом на кінцевий і тимчасовий контур з висотою уступу 30 м, дозволяє покращити безпеку в кар'єрі за рахунок вилучення куту нахилу борту кар'єру до 45° , у той час як, за висоти шару 15 м, кут нахилу борту складе 47° .

Наукова новизна. Встановлена залежність продуктивності кар'єру по руді від висоти уступу у відсотках дозволяє стверджувати, що зі збільшенням висота уступу (шару) продуктивність кар'єру по руді знижується. Визначення впливу висоти робочого уступу (шару) на сумарний об'єм втрат руди у проектному контурі кар'єру дозволяє стверджувати, що при постійних кутах укосу уступу і падіння рудного покладу значення експлуатаційних втрат, і засмічення змінюється прямопропорційно від висоти.

Практична значимість. Розроблена технологічна схема відпрацювання уступу висотою 30 м при потужності шарів 10 м, яка дозволяє покращити безпеку в кар'єрі за рахунок вилучення куту нахилу борту кар'єру до 45° , зменшити собівартість видобутку руди за рахунок оптимізації бурових робіт (менший час буріння на свердловини, зменшення перебуру тощо) та покращити тим самим економічні показники підприємства.

Ключові слова: кар'єр, елементи уступу, борт кар'єру, шари уступу, залізна руда, укоси бортів

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