ABSTRACT. When designing the strip mining methods at the deep open pits at the stage of preliminary studies, it is necessary to determine the optimum number and succession of relocation of crushing and transfer stations while developing the open pit. This cuts the transport costs and reduces the number of dump trucks required. An analytical dependence has been established to determine the optimum number of transfer points with their uniform location along the length and height of the open pit working area. The features of changes in the basic technological parameters of truck operation, depending on the number of crushing and transfer stations, the open pit size and output are studied. The conditions for simultaneous use of several crushing and transfer stations, their optimum number and performance have been determined; the economic benefits of using the flowcharts with multiple transfer points have been estimated. Optimisation of the number of transfer points reduces the required capacity of each crushing and transfer plant of up to 10-20 million tons/year. Reducing the required capacity of transfer points makes it possible to equip them with primary jaw crushers.

Key words: truck and conveyor transport, haulage level, crushing and transfer station

Formulation of the problem

One of the key focuses of engineering and technology development of open pit mining operations is the improvement of in-pit crushing and conveying systems (IPCC). In recent decades, the global mining industry has implemented projects for which new designs of crushing and transfer points have been developed and high angle conveyors have been introduced. The overseas experience of open pit mining confirms the validity of key approaches to optimising the methods of deep open pit development, which are substantiated in the mining theory (Drizhenko, 2009; Novozhilov, 1972; Yakovlev, 1989). One of the theoretical concepts of deep open pit mining is the principle of preference, all other conditions being equal, in which the proportion of electric energy in rock transportation is maximum. The global economic trends encourage the engineers to seek the combined traffic patterns that minimise the diesel truck operation in the open pit mines. Provision of a rationale for principles of optimising the haulage level location when using the in-pit crushing and conveying methodology in the deep open pit mine is an important scientific and practical problem.

A particular feature of deep iron ore open pits in Ukraine is the use of combined traffic patterns based on truck-rail and truck-conveyor transport. The location and design of transfer points have a significant impact on the truck operation and performance indicators of the open pit in general. As the open pit deepens, the haulage distance and the transport costs increase. In order to reduce the truck haulage distance and maintain it economically feasible, it is necessary to timely relocate the transfer points to deeper levels.

The traffic patterns of the Ukrainian iron ore open pits are characterised by a large proportion of IPCC process flows with the use of underground openings and immobile crushing and transfer points equipped with the KKD gyratory crushers. The use of mobile truck-to-conveyor transfer points and conveyor systems being capable of fast adaptation to the mining area development can increase the efficiency of mining operations in the deep open pit mines.

Analysis of researches and publications

The works of many researchers (Drizhenko, 2009; Surface Mining, 1990) analyse and generalise the technical solutions adopted in projects of foreign deep open pits with complex mining and geological environment. There is a long and intentional elaboration of mine opening systems throughout the entire period of field development.

There are many examples of effective cost reduction for open pit transport through the use of a system of underground conveyor ways (Fig. 1), located outside the promising pit shell.
Articulation of objectives

The purpose of the work is to provide a rationale for the design of the transfer point and the opening method with the use of truncated adits, to develop a methodology for optimisation of number and location of IPCC transfer points, at which the costs of truck and conveyor transport are minimised. In order to minimise the costs of open pit transport, the case of location of crushing and transfer points on the highwall is considered. In this case, the conveying system consists of two main subsystems:

- delivery of crushed rock from crushing and transfer points to the transfer chamber onto the elevating belt;
- lifting and delivery of rock to the unloading point on the day surface (it is assumed that the entire rock flow from multiple crushing and transfer points is conveyed to the surface by a single elevating belt).

While performing the work, the challenges were dealt with as follows:

- development of a methodology for determining the total costs of truck and conveyor transport;
- study of peculiarities of changes in total costs depending on the parameters of the mining area of the open pit and the number of crushing and transfer points in situ;
- tracing an analytic dependence in order to optimise the number of transfer points provided that they are uniformly located within the limits of the mining area of the open pit.

Presentation of the main study material

Taking into account the peculiarities of opening systems at a number of Ukrainian iron ore open pits (Drizhenko, 2009), it seems possible to consider the option of reconstruction of the transport system of the open pit based on existing permanent underground openings and transfer points on the day surface. Let us consider the common case. The deep levels of the open pit are mined by a system of underground workings (inclined and vertical shafts, an adit) equipped with conveyors and located under the mining pitwall. By the time the decision is made, the immobile crushing and transfer point prevents the advance of mining operations and preserves mineral reserves underneath. The construction of a new immobile crushing and transfer point is irrational, since there is no possibility to make a site of the required size with a lifetime reimbursing the costs of the crushing and transfer point construction. The emergence of this situation is often associated with the mining and geological properties of the deposit, lack of favourable topological features in the deposit structure, which, under the long-term plan, can be used to make sites suitable for placing transfer points with a long service life.

Thus, a vital task is the development of rational process flowchart to open the mining levels using truncated underground workings equipped with conveyors, the development of rational and efficient designs of mobile and semi-mobile transfer points, optimisation of the number, location and capacity of transfer points.

One of the solutions to this problem may be the joint use of a system of conveyors located in adits, mobile conveyors and mobile (semi-mobile) crushers (Novozhilov, 1972; Surface Mining, 1990; Vilkul, 2004).

A reasonable option is the use of mobile crushers and a system of mobile conveyors, which transport the rock from the transfer point to the conveyor in the truncated adit. This solution allows continuing the operation of existing equipment and facilities of IPCC and cutting the distance of truck haulage due to the placement of the crusher in the mining area of the open pit.

The process flowchart is proposed as follows: a reloading station for shovels is arranged on a new haulage level (Fig. 2). As the equipment of the transfer point, we accept a shovel with a 15-25 m³ capacity bucket, a LT-160 (LT-200) Lokotrack mobile crusher and three or four mobile conveyors, which ensure the mobility of the mobile crusher relative to the mining front. As the face for shovels moves, we move the mobile crusher and the mobile conveyor system. When the haulage level moves to deeper levels, an inclined conveyor should be added to the process chain in order to connect the mobile group and the conveyor in the underground working. The distinctive features of this technology are: joint use of a system of mobile and semi-mobile conveyors; the use of a transfer point with a mobile crushing plant in the mining area of the deep open pit; shortening the conveyor adit as mining operations advance.

This design of the transfer point ensures the independent operation of truck and conveyor transport, simplifies the arrangement of work to truncate the conveyor adit. The disadvantage of the system is an extra shovel at the transfer point. However, replacing the shovel with a mobile apron feeder will make correlation between truck and conveyor operation rigid.

Fig. 2 Scheme of mining arrangement at the reloading site for shovels: 1- mobile crusher; 2- mobile conveyors; 3 - semi-mobile conveyor located on the haulage berm

A common disadvantage of most transfer point designs is the need of truck overtravel by one step above the level of the conveyor location. A similar problem is also typical for truck and rail transport (Slobodyanyuk, 2018). A critical analysis of the crushing and transfer point design with the use of a receiving bin to unload the trucks is given in work (Slepian, 1996). It is noted that this design causes a large height of the crushing and transfer point and requires the construction of high retaining walls to hold the loads of trucks. This complicates and raises the costs of the transfer point construction. In addition, the high reloading height leads to
excess mileage of trucks. Slepian V.Y. proposed a design of the transfer device, which is characterised by operational reliability and reduces excess mileage of trucks. The receiving tank of the crushing and transfer device is made in the form of a bucket. The rear wall of the bucket is separated from it and has the shape of a cylindrical shell. A crusher is located inside the cylindrical shell, and a hole is made in the shell above the inlet of the crusher. The bucket is able to rise by turning around the shell. The transfer device may be equipped with several buckets. Several designs of the crushing and transfer device have been proposed, which differ in the method of unloading the truck into the bucket of the transfer device: without the truck driving into the bucket and with the truck driving into the bucket. The crushing and transfer device operates as follows: the blasted rock is loaded by trucks into the buckets of the crushing and transfer device, which, using hydraulic or rope lifting mechanisms, moves the rock into the crusher inlet. The crushed rock is loaded from the crusher outlet onto a belt conveyor. Specialists from FLSMIDTH and MAPLESOFT ENGINEERING (Maplesoft, 2015) also came to a similar decision (Fig. 3).

Let us consider the possible options for opening systems with truncated underground workings (Vilkul, 2004). The proposed method of opening involves sinking the inclined shafts and adits equipped with conveyors. The adits are located under the mining pitwall. A mobile or semi-mobile transfer point (haulage level) is located near the adit portal. The adits are shortened, the transfer point is relocated as the mining operations advance.

Parallel to the permanent adit is an adit, which is periodically shortened. The permanent adit is equipped with an immobile conveyor, the truncated adit is equipped with a mobile conveyor. The rock in the transfer chamber is reloaded from the mobile conveyor onto the immobile conveyor.

A truncated underground working is equipped with a single transfer unit, and the mobile conveyor is equipped with an intermediate transfer device to reload the rock onto an immobile conveyor. In order to reduce the volume of sinking and capital mining operations, a truncated underground working is sunk as an extension of the adit with an immobile conveyor. Fig. 4 shows a fragment of the plan of the mining pitwall with a truncated working, equipped with a single transfer unit.

The opening method is applied as follows (Fig. 4). An inclined shaft (2), connected with an adit (3), equipped with an immobile conveyor (4) is sunk while mining a steeply dipping ore body (1). The shaft (2) and the adit (3) are located outside the final open pit (11). A truncated adit (5), located parallel to the adit (3) and equipped with a mobile conveyor (6) is sunk from the side of the mining area of the open pit. A mobile crushing plant (7) is installed on the haulage level near the truncated adit portal (5). The transfer unit (8) is equipped with a feeder (9) (chute, vibratory feeder, belt reloader, etc.), which is installed at an angle that ensures reloading the rock from the mobile conveyor (6) onto the immobile conveyor (4). The transfer unit (8) may be equipped with an intermediate transfer device, made, for example, in the form of a diagonal plow (12) or a double-drum unloading carriage.

The pit opening is carried out as follows. The rock is delivered from the mining faces to the mobile transfer point. After crushing, the rock is fed onto a mobile belt conveyor (6). The conveyor (6) transports the rock to the transfer unit (8) and reloads the material by the feeder (9) onto the immobile conveyor (4). When mining operations take place at the truncated adit portal, the mobile conveyor (6) is moved into the depth of the truncated adit (to the dead end (10)) to make blasting operations and rock excavation. After cleaning and strengthening the truncated adit portal (5), the conveyor (6) is returned to its original position. Each time after a new face cut of the shovel, the mobile belt conveyor (6) is moved into the depth of the adit (5) by a step of truncation (shown by the dotted line). However, at the same time, the place of reloading the rock from the mobile conveyor (6) onto the immobile conveyor (4) remains unchanged. Whenever blasts are made in dangerous proximity to the conveyor (6), it is moved to the adit (5).

As compared to in-pit crushing and conveying systems being conventional for iron ore open pits in Ukraine based on immobile crushing and transfer points, the traffic patterns using truncated conveyor adits and mobile transfer points have significant technological advantages: the possibility of reducing the truck haulage distance and, as a result, cutting the costs of rock development and the need for dump trucks; high flexibility and mobility of the process flowchart; compactness of equipment; availability to be used on the narrow sites; insignificant restrictions on blasting operations (presplit and low impact blasting at the truncated adit).
At the majority of iron ore open pits in Ukraine, the rock mass is transported using in-pit crushing and conveying systems (Drizhenko, 2009). As a rule, the process flowcharts that are quite simple in terms of topology with a single immobile crushing and transfer point are used. At the same time, the costs of lifting the rock to the surface are reduced, but the costs of rock delivery by truck to the transfer point remain significant. These costs increase with deeper mining progression and expansion of the mining area. In the mining theory, the issues of substantiating a step of relocating the transfer point in depth while mining operations deepen have been explored, but the issues of the simultaneous use of multiple crushing and transfer points have been insufficiently studied.

Earlier, the authors (Vilkul, 2009) solved the problem of optimising the number of haulage levels in depth of the open pit. With an open pit capacity of 8-20 million tons/year, the use of two haulage levels cuts the total costs by 6-22%. With an open pit capacity of 20-30 million tons/year, the use of three haulage levels reduces the total costs by 22-31%. With a capacity of above 40 million tons/year, the optimum number of haulage levels is 4-5, but the major economic benefit is formed when transferring from one to three haulage levels. The utilisation efficiency of multiple transfer points on a single level was studied in work (Vilkul, 2011). It is shown that using up to three transfer points for a wide range of open pit capacity (10-40 million tons/year) on a single level is reasonable.

This work investigates the features of the simultaneous use of multiple crushing and transfer points, both horizontally and vertically (Fig. 5). Let us consider the problem of optimising the number of transfer points (horizontally and vertically), evenly located in the area of mining operations. We divide the area into n zones horizontally and m zones vertically. With an increase in the parameters n and m, the size of separate mining zones and truck transport costs decrease, whereas the operating and capital costs for the rock delivery to the main conveyor using additional (collecting) conveyors increase. The optimum values of the parameters n and m are determined from the condition of minimising the total costs of rock delivery from the mining faces to the main conveyor.

The costs of the connecting conveyor system that provide the rock delivery from the crusher to the main elevating conveyor depend on their specific location on the pitwall, as well as on the design features of underground workings in which the elevating conveyor is placed. In this work, the most common, simplified approach is considered, when the haulage distance from each crushing plant to the main conveyor is taken equal to d, m. The required length of the connecting conveyor is determined taking into account the safety of mining operations and the speed of horizontal pushback of the pitwall. Analysis of possible opening methods applied in the open pit mines shows that parameter d varies within 500-1000m. This is a simplified model, but at the same time it allows us to determine the main dependences of total costs on the development parameters and optimise the number of transfer points.

The mining area with the size $L \times H$ (m) and the annual capacity $Q$ (t/year) is divided into n zones horizontally and m zones vertically (total $n \times m$ zones). The total annual costs of delivering the rock to the main conveyor is

$$Z = 0.001\frac{C_o + \frac{A}{q} \cdot T_a}{T_k} \left( \frac{L}{4n} + \frac{H}{4m} \right) + 0.001C_kQd + \frac{C_o \cdot mnd + C_d \cdot mn}{T_d}, \text{ usd,}$$

where $C_o$ is the cost of truck haulage, usd/km; $A$ is a price of one dump truck, usd; $q$ is the annual truck tonnage, tkm/year; $T_a$ is the rated lifespan of the truck, years; $i$ is a gradient of haul roads, unit fractions; $C_o$ is the capital costs per one running meter of additional conveyor workings (taking into account the costs of sinking the adit and of the conveyors), usd/m; $T_k$ is the period of operation of auxiliary conveyor workings, years; $C_d$ is the cost of transporting the rock by the conveyor, usd/km; $T_d$ is the period of operation of the crushing and transfer point, years; $C_d$ is the capital costs per one crushing and transfer point, usd.

The optimum values of the parameters $n$ and $m$ are found from the equality to zero of the partial derivatives

$$n^2 m \left( \frac{C_o}{T_k} \cdot d + \frac{C_d}{T_d} \right) = 0.001 \frac{L}{4} \left( \frac{C_o + \frac{A}{q} \cdot T_a}{T_k} \right)$$

$$m^2 n \left( \frac{C_o}{T_k} \cdot d + \frac{C_d}{T_d} \right) = 0.001 \frac{H}{4} \left( \frac{C_o + \frac{A}{q} \cdot T_a}{T_k} \right)$$

In order to separate the price and mining-geometrical parameters, we introduce an auxiliary coefficient $K_t$. Coefficient $K_t$ is equal to the ratio of unit costs of truck and conveyor transport.

$$K_t = 0.001 \left( \frac{C_o + \frac{A}{q} \cdot T_a}{T_k} \right) / \left( \frac{C_o}{T_k} \cdot d + \frac{C_d}{T_d} \right)$$

$$n^2 m = K_t Q L \cdot$$

$$m^2 n = K_t Q \frac{H}{i} \cdot$$

We divide the second equation by the first one and obtain the ratio between the parameters $n$ and $m$, which is determined by height to length ratio of the mining area, as well as a gradient angle of the haul road

$$m = \frac{n}{L \cdot H}$$

For the existing mining conditions, we obtain the values of $m$ two to three times as much as $n.$
From the first equation of the system (4) we find

$$n_0 = L \times \left( \frac{K_t Q}{HL} \right)^{\frac{1}{3}}$$  \hspace{1cm} (6)

By substituting, we find

$$m_0 = \frac{H}{i} \times \left( \frac{K_t Q}{HL} \right)^{\frac{1}{3}}$$  \hspace{1cm} (7)

The factors under cube roots in formulas (6) and (7) are identical and determine a certain proportionality coefficient for values $m_0$ and $n_0$. The optimum number of transfer points horizontally ($n_0$) is proportional to the length of the mining area, and in height ($m_0$), it is proportional to the height of the mining area and inversely proportional to the gradient of haul roads.

Since the performance and mining-geometric parameters in formulas (6) and (7) are under the cube root, even significant changes in one of them lead to a slight change in the optimum number of transfer points. If any of the parameters under the cube root changes by 30%, then $n_0$ and $m_0$ change only by 9%. Even if one of the initial parameters, for example, capacity, is changed twice, the optimum values of $n_0$ and $m_0$ will change by 26%.

The total number of transfer points is

$$m_0 n_0 = \left( \frac{K_t^2 Q^2 L^2 H}{i} \right)^{\frac{1}{3}}$$  \hspace{1cm} (8)

We find the optimum distances between transfer points vertically and horizontally

$$\frac{H}{m_0} = \left( \frac{H \cdot L \cdot i}{K_t Q} \right)^{\frac{1}{3}}$$  \hspace{1cm} (9)

$$\frac{L}{n_0} = \left( \frac{H \cdot L}{K_t \cdot i} \right)^{\frac{1}{3}}$$  \hspace{1cm} (10)

We find a vertically projected area of the mining zone per one transfer point

$$\frac{H \times L}{m_0 n_0} = \left( \frac{H^2 \cdot L^2 \cdot i}{K_t^2 Q^2} \right)^{\frac{1}{3}}$$  \hspace{1cm} (11)

We find height to length ratio for a particular area

$$\frac{H}{m_0 n_0} = i$$  \hspace{1cm} (12)

An economic and mathematical model was built on the basis of above formulas and the obtained dependencies. Due to this model, the optimum number of transfer points horizontally and vertically, their total number, the size and area of separate zones, and the capacity of one crushing plant were determined. As the main criterion, the economic benefit was determined ($\Delta Z = Z_1 - Z_{min}$), being equal to the difference in total costs of delivering the rock to the main conveyor using a single crushing plant ($Z_1$) and their optimum number ($Z_{min}$). In addition, the number of trucks for a single and multiple transfer points was determined.

The models were used to study the change in the above parameters when increasing the productivity of mining operations. In this case, the following values of the initial mining-geometric and price indicators were taken into account: height ($H=200$ m) and length of the mining area ($L=2000$ m); a gradient of the haul road ($i=0.08$); average distance from the crushing plant to the main conveyor ($d=800$ m); truck haulage cost $C_d=0.2$ $/tkm$; price of a dump truck $A=USD1.25$ million; the annual truck tonnage $q=2.5$ million $tkm/year$; cost of additional production and installation of auxiliary conveyors $C_p=USD6.25$ thousand$/r.m$; cost of the crushing plant $C_C=USD2.50$ million, the lifespan of auxiliary conveyors and mobile crushing plants $T=10$ years. The simulation results are shown in the graphs (Fig. 6-9).

As can be seen from Fig. 6, the optimum number of transfer points horizontally ($n_0$) and vertically ($m_0$), as well as their total number ($m_0 n_0$), increases with increasing the productivity of mining operations. With a capacity from 13 to 25 million tons/year, it makes sense to use two transfer points placed at different heights, with a capacity from 25 to 55 million tons/year, it is feasible to use four transfer points located on two haulage levels. With a further increase in mining rate, the rational number of haulage levels rises to three (two transfer points at each). The studies show that with an increase in mining rate, the number of haulage levels rises first of all, and then the number of transfer points on the level. The economic benefit (Fig. 7) becomes positive with a relatively low productivity of mining operations, and when increasing, both the absolute and the relative value of the economic benefit rises (100%×$\Delta Z/Z_1$).

The use of multiple transfer points makes it possible to reduce the volume of truck operation and the number of trucks twofold to threefold (Fig. 8). This explains the significant economic benefits that can be achieved when using multiple transfer points. Cutting the costs of truck transport covers in access the costs of an additional conveyor transport. Apart from a significant economic benefit, this allows simplifying the truck operation in the open pit mine, the haulage length is shortened, the truck traffic is localised in certain areas, and the traffic safety is improved.
The simulation results (Fig. 9) show that while using the opening systems with multiple crushing and transfer points, the capacity of the mobile crushing plant varies within 8-12 million tons/year and becomes higher only when the output of the open pit in terms of rock mass is higher than 75 million tons. This conclusion suggests that in most cases, when using the opening systems with multiple transfer points, it will be efficient to use jaw crushers, characterised by a capacity lower than that of gyratory crushers, but requiring significantly lower capital costs. Besides, the crushing and transfer points based on jaw crushers are simpler in terms of design, the mobile and semi-mobile options are acceptable.

Conclusions and trends for further research

The research has shown the ability to significantly reduce the costs of truck and conveyor transport using the optimum number of multiple movable crushing and transfer stations. The research results may be used in reconstruction of truck and conveyor transport at the deep open pits. The further research requires substantiating the construction of a movable crushing and transfer station and the methods of mining operations to be used simultaneously in the mining area.

References


