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# TECHNICAL AND TECHNOLOGICAL SOLUTIONS REGARDING THE DEVELOPMENT OF PILLARS DURING FINAL MINING OF DEEP OPEN PITS

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**Abstract.** When mining operations achieve the total depth of open pits within their boundaries, a significant share of balance ore reserves remains in pillars under transport communications as well as under reloading points. Liquidation of the available transport communications should follow by the development of the new ones. Hence, mining stages of a steep-grade field and periodicity of a pillar initiation within both working open pit flank and temporarily nonworking one have been studied.

Hannivskyi open pit has been taken as an example to substantiate the expediency to extract balance reserves occurring under crushing and reloading point within ±0 m level. The substantiation of technical and technological solutions concerning the development of a protective pillar involved cuts of geological ore formation which supported the idea of availability of the preserved reserves and topicality of the selected problem.

Operation schedules to mine the pillars have been developed for general conditions; the required equipment set has been analyzed. New technological solutions have been obtained using current excavating and transportation machinery. Engineering solutions as for possibility to open the pillars and liquidate them in terms of the limited technical and technological potential have been substantiated. The technological schemes of pillar mining have been systematized depending upon the technological processes, taking place in the open pit, and the applied equipment set.

Scientific significance of the paper is the developed systematization of facilities in terms of operation schedules of pillar mining.

Practical significance is the developed operation schedules to mine and liquidate the pillars.

Technical and technological expediency to use skip hoist while reactivating temporarily nonworking open-pit walls for rock mass transportation from the pillars up to the surface has been substantiated. It has been proved that during final mining operations in an open pit, complicated by difficulties in electricity delivering to the preservation pillar, it is expedient to apply loaders in one operation schedule. Use of loaders and skip hoist to mine the preservation pillar is the optimum strategy. It has been substantiated that the proposed procedure is more advantageous to compare with the conveyor transport.

**Keywords:** open pit mining, preservation pillars, transport communications, reloading points, final mining, balance reserves, technological complexes.

## 1. Introduction

Open pit extraction of steep-grade fields is supported by complex transport communications in the mined-out area. The transport communications are constructed to enable operation of each transportation facility; for the purpose, pillars are left along walls of the open pit.

When mining operations achieve the final depth of the open pits, a significant share of balance ore reserves (i.e. the mineral) remains in their boundaries. The ore is concentrated in pillars under transport communications (i.e. railway and motor vehicles), within the pillars under reloading platforms of motor and railway transport as well as motor and conveyor facilities of cyclic-flow technology (CFT), and under other communication systems. On the one hand, the balance ore reserves should be extracted according to the law on the mineral resources; on the other hand, it is quite economical since there is no necessity to extract overburden rocks. Nevertheless, liquidation of the available transport communications makes it necessary to use other ones which would correspond to the final open pit mining at great depth; the problem is rather topical and needs its solving. Moreover, the specific drilling and blasting procedure is required for explosive rock fracture in the pillars, substantiation of excavating facilities, and possibilities to apply both inclined and steeply inclined conveyor transport or a skip hoist [1, 2].

Much attention is paid to this problem by the prominent experts from different institutions whether research or design ones. Authors of paper [3] identify economic efficiency of an enterprise as well as its activity time depending upon complete mining of mineral resources. In addition, the paper substantiates the total operating costs subjecting to the selected mining depth, worked-out area, and mining allotment boundaries. The authors have assessed raw material base and proposed to identify a border opening coefficient if the price of the goods, manufactured by the projected enterprise, is not higher than the price of similar commodity products in the world market. Mostly, the paper is of economic nature since it did not develop any technical and technological solutions of the problem.

Authors of paper [4] have considered a problem on the determination of the final open pit boundaries. The matter is that in the majority of cases, surface working boundaries of open pits have achieved their final position. Development of technical and technological solutions as for mining scheduling needs reassessment of a raw material base potential concerning future activities of mining enterprises. The abovementioned paper has applied the known idea how to identify the boundaries of open pit operations being determination of the boundaries based upon the comparison of allowable costs for ore extraction with the expected ones in the context of the designed open pit.

Papers [5, 6] have performed studies as for expansion of protective pillars within the open pits. Open pits of Inguletskyi mining and processing plant (MPP) PJSC, Poltavskyi MPP PJSC, and Lebedynskyi MPP PJSC have been taken as an example to identify balance reserves preserved in the pillars under transport communications. Findings have helped identify priority tendencies of mining operations for operations to the final depth for the reduced losses of the mineral. Paper [6] proposes decrease in the preserved balance iron ore reserves, occurring under transport communications, concentration levels of a cyclic-flow technology, and reloading points to drop high prime cost of the concentrate.

Paper [7] proposes an interesting solution concerning balance reserve mining from pillars. Authors of the mentioned paper have suggested extracting temporarily preserved minerals, occurring under internal dumps within the mined-out area of an open pit, using the combined surface and underground technique. They have proved that the heightened energy consumption, reduced parameters of a site, increased slope angles of an open pit, and lagged opening result in unprofitability of surface mineral extraction. The listed new technological solutions will help improve technoeconomic indices through transformation of the internal dump into the constant one. In this vein, Hannivskyi deposit has been taken into example to calculate that prime cost of ore extraction will be decreased by USD 1.33 per ton.

In paper [8], team of scientists and researchers develops and substantiates the idea [8]. They have analyzed the impact by a surface dump on the geomechanical state of underground mine workings in terms of Pivdenno-Bilozersk field of high-grade iron ores while applying numerical modelling based on the SolidWorks software system.

That has helped them to study influence by the dump location and mine working depth on the bulk stress state of the rock mass. It has been identified that the maximum impact degree by the rock dump is observed within the upper levels. It has been proved that on the periphery of a sidewall the stresses increase up to 10 % if compared with the situation when a dump is not available at the earth's surface. Accuracy of the calculations depends upon the consolidated database, sample size, and geometry of points corresponding to location of the research objects both at the earth's surface and within the rock mass as paper [9] proves.

Before balance reserve starts to be mined, one should be aware of the fact that the operations are safe. Consequently, there are papers concerning geomechanical stability as well as degradation of protective pillars in open pits and in mines. Authors of paper [10] have substantiated that the traditional 3D Electrical Resistivity Imaging (ERI) techniques are unsuitable for assessment of pillar stability in open pits. The matter is that the complete three-dimensional ERI needs accurate three-dimensional geometry. Thus, the paper proposes to apply economically efficient Surface Resistivity Probe Methods (SFM) procedures for the development of 3D medium. An innovative evaluation method is suggested based upon combination of SFM procedures and the specific electric resistance. The methods are used for the real pillar in a limestone quarry. Inversion results demonstrate the key role of a 3D model.

Losses of minerals may not be accumulated only in pillars. Authors of papers [11–15] have performed research and substantiation of both balance and non-balance reserves collected in technogenic objects.

Hence, it becomes possible to conclude that the problem, studied in the paper, is topical; it is solved partially as for substantiation of the reserves, accumulated in pillars, and for geomechanical stability. Technical and technological solutions, concerning mining of protective pillars in open pits, are not substantiated.

Purpose is to generate operation schedules and substantiate technological complexes for mining of protective pillars while developing steep-grade deposits.

## 2. Methods

Stage one of the activities involved the work inspection by experts from research institutes which helped highlight topicality of the tendency, formulate and solve a problem, and form the purpose. The abovementioned has made it possible to make a decision of the comprehensive approach use including modelling and substantiation of the technological system.

Stage two involved study of the steep-grade field mining as well as conditions and necessities to form protective pillars.

Stage three involved analysis of mining alternatives. Six operation schedules have been developed depending upon a type of drilling and blasting operations, and excavating and transportation facilities. The operation schedules have been applied to analyze use of the technological complex. The analysis results have helped systematize equipment of the operation schedules. An optimum operation schedule for mining of pillars have been developed which involved operations by loaders and skip hoist.

## 3. Results and discussion

Almost each open pit in Kryvyi Rih iron ore basin approached a boundary of its efficiency being 450–500 m on the average. Mining of a steep-grade field takes several stages. Stage one starts (Fig. 1) from overburden operations and preparation of transport communications. Most of all, the stage uses motor vehicles; sometimes, railway transport is applied. Stage two is intensive mining; the first line balance reserves are extracted. During the period, permanent mine workings as well as numerous reloading points are built to achieve maximum production capacity. Stage three is preparation of the second line balance reserves to be extracted. For the purpose, transport system options are analyzed. Either available transport communications are being improved or new ones are being built. Stage four is the final open pit mining with the complete excavation of all possible balance reserves.

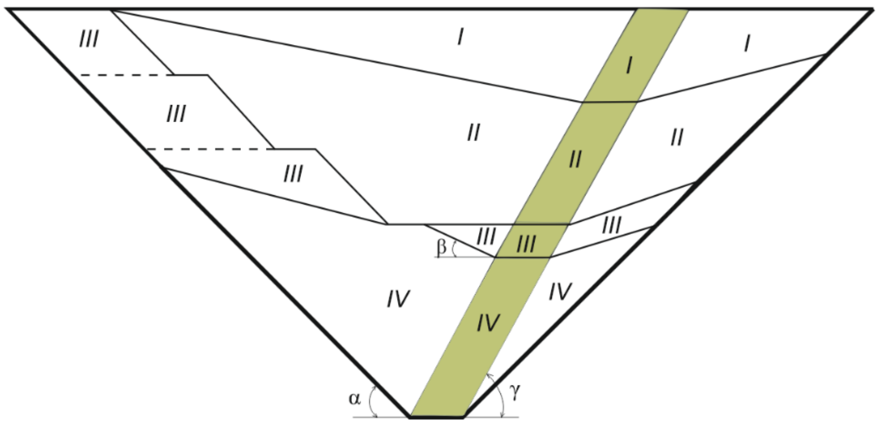



Figure 1 – Sequence of mining operations in an open pit while developing balance reserves of the deposit

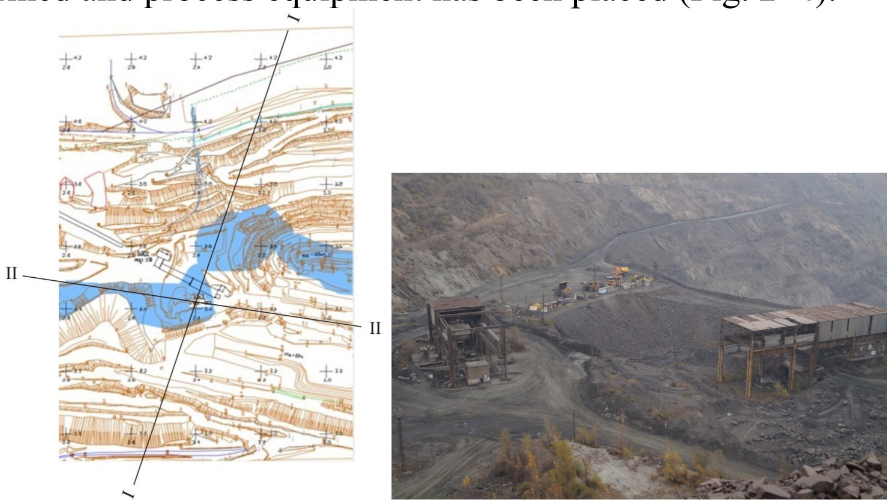
The problem of pillar liquidation arises periodically during the 2nd and 3rd stages; however, during the 4th stage it becomes more serious since alternatives of one vehicle type replacement by another are limited.

The mined-out open pit areas are full of various transport communications complicating the formation of working areas in the open pits as well as mining of minerals. Working area of an open pit is characterized by following parameters: bench height (either inclined or vertical), site width, indices of protective structures, and angle of the bench (both working and nonworking). The selected types of transport communications in an open pit as well as their combinations influence the formation of a working area in the deep open pits concerning the transport communications, reloading points, the required protective structures, and pillars. Use of the combined types of vehicles involves numerous reloading points of the considerable size under which significant balance ore reserves are accumulated. Generally, railroad is applied for the upper open pit levels where loose and semi-crystalline rocks occur; it needs wide and long working areas. Within the lower levels, where crystalline minerals occur, motor vehicles are applied making it possible to use smaller sizes of working areas.

Under the current market conditions, future increase in overburden operations as well as providing communication between heavy transport and surface, temporarily nonworking benches are used with maximally steep face angles and the bench itself. As a result, a problem of their reactivation arises. Use of steep-grade benches is as follows: in the process of open pit development, its working bench from the side of the deposit footwall becomes a boundary one while approaching the ultimate part of the field; the working bench is used to arrange overburden mine workings to provide heavy transport communication between the working levels and the surface. At the same time, the hanging wall, consisting of a number of steep grades located on the top of each other, is placed for the overburden mine workings; stone protection platforms are in their basis.

After the scheduled steep-grade surfaces of temporarily nonworking wall are formed, their reactivation starts as well as mining of a pillar containing significant volumes of rock mass put transiently between the nonworking bench and boundary wall of the open pit. The pillar is extracted in the form of horizontal layers; quarry excavators are used. In this vein, overburden mine working driving and making the operations to extract peripheral mineral safe, hydraulic backdiggers are applied. Along with the pillar mining, a boundary wall is formed to place overburden mine workings on it; through them, the extracted rock is delivered to the surface.

Hence, field development is combined with step-by-step scheduling of mining operations. Each step needs its transport support depending upon which protective pillars are formed; among other things, it concerns location of reloading points, transport communications etc. To perform transition to a following step or final open pit development, a problem is formulated to extract pillars. Its solution is extremely important for Hannivskyi open pit of Pivnichnyi MPP having a burning issue to extract balance reserves occurring under reloading point of a cyclic-flow technology within ±0 level while liquidating the latter. To develop a procedure for ore pillar mining under the technological complex, geological ore formation and rock mass have been performed and process equipment has been placed (Fig. 2–4).




a) b)

Figure 2 – Copy of the mining plan with the placement of cuts (a) – through the available reloading CFT point located on the pillar, and (b) – picture of the reloading point

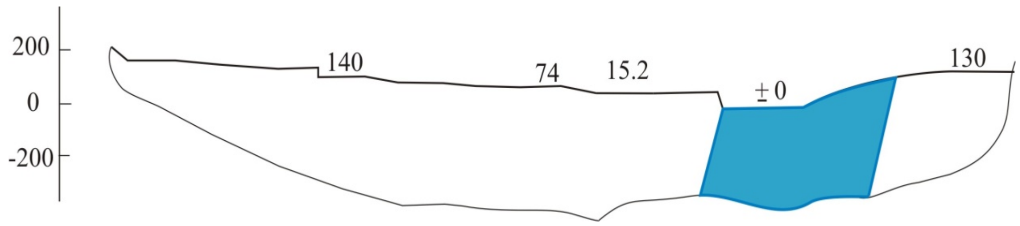



Figure 3 – I – I cut through the reloading CFT point in line with the open pit mined-out area. Scale is 1:20000

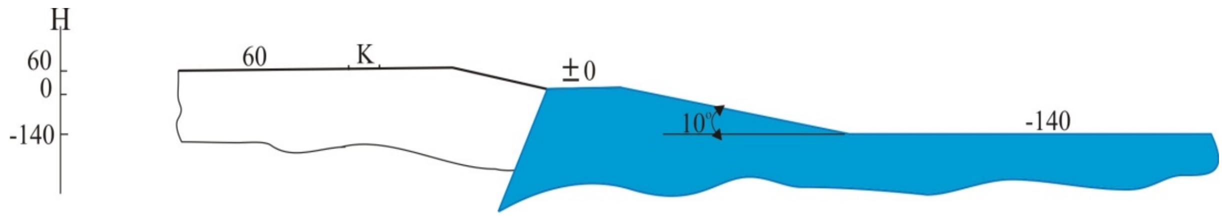



Figure 4 – II – II cut through the reloading CFT point across the open pit bench. Scale is 1:20000

While planning mining operations, and projecting certain stages of deposit opening, intermediate technological decisions are made as for the reloading point placement. According to the scientific CFT foundations [1], reloading points should be relocated depending upon transportation by motor vehicles and open pit bottom deepening. However, the restricted production possibilities concerning capital costs of the future development of the enterprise delays temporarily extraction of the pillars involving its convenient transport services. In this context, arrangement of crushers near pillars seems to be an inexpedient idea. It is wiser to apply such a drilling and blasting procedure helping obtain fragments, which are convenient to be delivered using a conveyor. Moreover, new technical solutions regarding excavating and transport facilities have been got. Hence, certain technological solutions have been obtained to mine pillars in terms of the restricted technical and technological possibilities.

Following operation schedules have been developed and analyzed:

# 1 being a cyclic-based procedure using electric excavators with large bucket capacity (i.e. EKG (Ukr. ЕКГ) - 8, 10, 12); heavy motor vehicles (i.e. 160-200-t haulers) perform transportation over the working site as well as up to the earth’s surface;

# 2 being a cyclic flow-based using electric excavators with large bucket capacity (i.e. EKG - 8, 10, 12), heavy motor vehicles (i.e. 160-200-t haulers), and the active reloading motor-conveyor point with a cone coarse crusher (i.e. KKD (Ukr. ККД) - 1500/180);

# 3 being a cyclic-based procedure with an individual approach to drilling and blasting operations involving the increased explosive energy load on the rock mass to regulate its granulometric composition; over the working site, front wheel Hitachi loaders with 3.0×10 m$^3$ perform excavation and transportation [16, 17]; conveyors execute delivery up to the earth’s surface; sieve and hopper are applied to load the rock mass on a conveyor; and oversize is liquidated using a hydraulic hammer;

# 4 being a flow-based procedure with an individual approach to drilling and blasting operations involving the increased explosive energy load on the rock mass to regulate its granulometric composition; cutting is performed using either hydraulic excavators with a small bucket or a loader [17]; the rock mass is loaded on a conveyor through a mobile crusher (i.e. jaw breaker of secondary crushing); conveying is applied for transportation over the working site and up to the earth's surface; and oversize is liquidated using a hydraulic hammer;

# 5 being a cyclic-based procedure using electric excavators with large bucket capacity (i.e. EKG - 8, 10, 12); heavy motor vehicles (i.e. 160-200-t haulers) perform transportation over the working site; and skip hoist delivers the mineral up to the earth's surface[18]; and

# 6 being a cyclic-based procedure with the traditional drilling and blasting parameters where loaders perform both excavation and transportation over the working site; and skip hoist delivers the mineral up to the earth's surface.

Combination of the findings helps systematize operation schedules to extract pillars depending upon technological processes, taking place in an open pit, and a complex of equipment to be applied (Table 1).

Table 1 – Systematization of the equipment in terms of technological schemes of pillar development

| Operation schedule | Equipment | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Drilling and blasting | Excavator | Motor vehicles | Loader | Sieve | Hydraulic hammer | Hopper | Crusher | Conveyor | Skip hoist |
| # 1 | Traditional activities | + | + | – | – | – | – | – | – | – |
| # 2 | Traditional activities | + | + | – | – | – | – | + | + | – |
| # 3 | Increased loading | – | – | + | + | + | + | – | + | – |
| # 4 | Increased loading | + | – | – | – | – | – | + | + | – |
| # 5 | Traditional activities | + | + | – | – | – | – | – | – | + |
| # 6 | Traditional activities | – | – | + | – | – | – | – | – | + |

Cyclic, cyclic-flow, and flow techniques may be applied to extract protective pillars. First of all, rock mass can be mined under the standard enterprise conditions without any extra preparation (i.e. equipment and blasting). They are operation schedules ## 1 and 2 depending upon a technique used by the open pit. In terms of scheme # 2, coarse crusher should be located on another protective pillar.

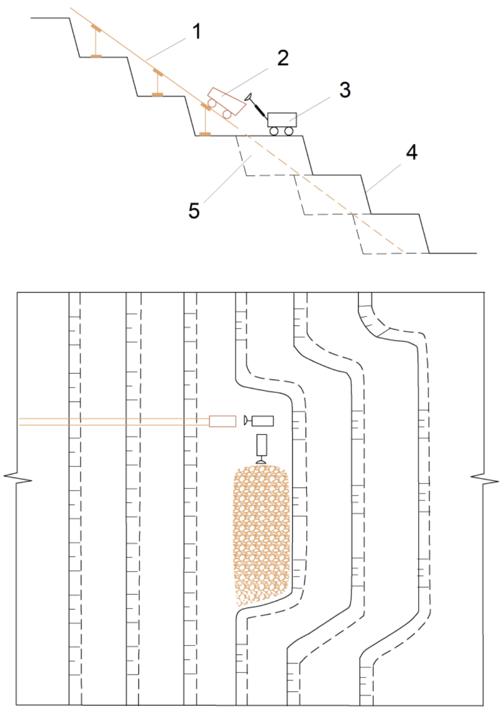
Operation schedules ## 3–6 have been developed for the individual and/or open pit-wide transport support of pillar mining.

Use of conveyors in terms of operation schedules ## 3 and 4 is restricted due to the rock mass lumpiness. Analysis of the operation schedules as well as substantiation of the technological complexes has helped understand that the inclined conveyors are applicable if only such lumpiness is not more than 350 mm; the size should be 200 mm if steeply-inclined conveyors operate [1, 2]. Hence, to meet the conditions and limitations, one has to prepare granulometric composition of the rock mass in terms of the largest lump. If a technique of the increased explosive energy load on the rock mass is applied and the defined lumpiness is achieved then coarse crusher is not required. Hydraulic hammer is used if a share of oversize is minor; if the share is greater, a sieve is applied.

Skip hoist is a part of operation schedules ## 5 and 6. The key disadvantage of the device it its limited output. Different scientific sources represent its efficiency variation from 2–3 mln up to 8 mln tons a year depending upon the skip capacity and hoist depth. Hence, the machinery is rarely used in deep open pits where producing capacity is high. In our case with reactivation of temporarily nonworking wall and the development of protective pillars, the complex efficiency is calculated depending upon the mining amount. As a result, the restricted output of skip hoist is advantageous; in such a way, idle time of the equipment decreases.

Following plus of skip hoist concerns rock mass lumpiness. Conveyor use needs thorough preparation of rock mass in terms of its fractions; in turn, skip hoist does not require that restriction.

The authors believe that schedule # 6 (Fig. 5) is the optimal one where improvements of engineering solutions concern excavating facilities. Since operation of excavators needs electric supply, it is proposed to apply open pit loaders for rock mass delivery [17]. The abovementioned will help avoid the use of heavy motor vehicles. The aspect is quite important in the process of the final open pit mining; as a result, it becomes possible to narrow width of motor transport communications as well as reloading points.




1 – railway; 2 – skip; 3 – loader; 4 – bench; 5 – pillar

Figure – 5 Equipment arrangement while pillar mining

While comparing operation schedules with skip hoist and conveyor transport, one can conclude that advantages of the schedule one concern the following: nonavailability of a hopper (i.e. loader unloads right in a skip [18]); lesser size of a reloading point (conveyor needs extra design of both horizontal and inclined path with gradual curvature of a conveyor line [2, 19]); and saving of time, capital costs, and additional equipment to lengthen the line and transfer it to the lower levels.

## 4. Conclusions

Consequently, the research concerning protective pillar disassembly has been carried out, operating schedules have been developed, and the use of equipment has been substantiated. The abovementioned helps draw following conclusions. Technical and technological expedience to use skip hoist while reactivating temporarily nonworking benches for rock mass transportation from pillars up to the earth's surface has been substantiated. It has been proved that in the context of final open pit mining, and complexity of electric line installation to a protective pillar, it is efficient to apply loaders in one operation schedule. A plan to extract a protective pillar with the use of loaders and skip hoist is the optimum one. It has its advantages as for conveyor transport application.

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## ТЕХНІКО-ТЕХНОЛОГІЧНІ РІШЕННЯ ЩОДО РОЗРОБКИ ЦІЛИКІВ ПРИ ДОРОБЦІ ГЛИБОКИХ КАР'ЄРІВ

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**Анотація.** При досягненні гірничими роботами кінцевої глибини кар'єрів в їх граничних контурах знаходиться значна частина балансових запасів руди в ціликах під транспортними комунікаціями та перевантажувальними пунктами. При ліквідації існуючих транспортних комунікацій необхідно створити нові. Тому досліджені етапи відпрацювання крутоспадного родовища та періодичність виникнення ціликів на робочому та тимчасово неробочому бортах кар'єру.

На прикладі Ганнівського кар'єру обґрунтовано доцільність виїмки балансових запасів під дробарно-перевантажувальним пунктом на горизонті ±0 м. Для обгрунтування техніко-технологічних рішень щодо розробки запобіжного цілику виконані розрізи геологічної товщі руди, які підтверджують наявність законсервованих запасів і доводять актуальность обраної проблеми.

Для загальних умов були розроблені технологічні схеми відпрацювання ціликів та проаналізований необхідний комплект обладнання. Отримані нові технологічні рішення за допомогою використання сучасного екскаваційного і транспортного обладнання. Обґрунтовані технологічні рішення стосовно можливості розкриття і ліквідації ціликів при обмежених технічних і технологічних можливостях. Зроблена систематизація технологічних схем відпрацювання ціликів за складом технологічних процесів в кар'єрі та комплектом обладнання, яке буде застосоване.

Наукова значимість роботи стосується розробленої систематизації обладнання за технологічними схемами відпрацювання ціликів.

Практична значимість у розроблених технологічних схемах розробки і ліквідації ціликів.

Обґрунтовано технічну та технологічну доцільність застосування скіпової підйомної установки при розконсервації тимчасово неробочих бортів для транспортування гірничої маси з ціликів до земної поверхні. Доведено, що при доробці кар'єру і складності заведення електричної енергії на запобіжний цілик, ефективно застосувати навантажувачі в одній технологічній схемі. Оптимальною технологічною схемою є схема розробки запобіжного цілика при застосуванні навантажувачів і скіпової підйомної установки. Обґрунтовано, що запропонована схема має переваги по відношенню до застосування конвеєрного транспорту.

**Ключові слова:** відкриті гірничі роботи, запобіжні цілики, транспортні комунікації, перевантажувальні пункти, доробка, балансові запаси, технологічні комплекси.