UDC Identifier 622.684:629.3 DOI: 10.21440/0536-1028-2018-8-5-15

KIMBERLITE DEPOSITS OPENCAST MINING INNOVATIVE TECHNOLOGY WITH VARIABLE GEOMETRY OF NON-MINING OPEN PIT EDGES

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Research aims *to enlarge the application area of the opencast method of diamond deposits mining by means of introducing an innovative technology of stripping with variable geometry of non-mining open pit edges.*
Research relevance. *At the present time, solution demanding is the problem of peripheral ore reserves final extraction at diamond deposits underlaying the ultimate boundaries of open pits, where the use of traditional technologies is economically inefficient. The suggested innovative technology makes it possible to solve the problem.*
Research methodology. *The given problem is solved in two stages: transition, at the appointed depth of the open pit, from the traditional scheme of stripping to the stripping scheme by steeply inclined ramps, and transition, at the final stage to stripping by peripheral road tunnel driven beyond the zone of displacement. At that, optimum depth of transition to a new stripping scheme has been substantiated together with the required speed of driving a tunnel and crosscuts. When justifying the stripping variant, non-mining benches and edges stability have been estimated in general. The methods of economic-mathematical modelling, engineering-economic and mining-geometric analysis.*
Research results. *By the example of Nyurbinsky open pit of ALROSA PJSC exploitation it has been stated that the innovative technology allows to enlarge the slope angles of open pit edges from 45°–48° to 57°–75°, reduce overburden stripping by 3–8 times, and effectively extract mineral reserves up to the depth of 750 m.*
Results application area. *The suggested technology can be used not only during the exploitation of kimberlite open pits, but also during the opencast exploitation of non-ferrous metal ore deposits and precious-metal ore deposits represented by round shaped steep deposits.*

Key words: *open pit; stripping scheme; ramp inclination; four-wheel drive dump trucks; edge angle of inclination; tunnel; tunneling speed; heading machine; edge stability coefficient; robotization.*

Introduction. Research aims to enlarge the application area of the opencast method of mining diamond deposits by means of introducing an innovative technology of stripping with variable geometry of non-mining open pit edges. In recent years, the trend has been observed of breaking with traditional opencast-underground method of mining primary diamond deposits situated in the cryolithic zone. It is associated with the increased potential of opencast mining by means of introducing new technological solutions to deposits stripping and mining, modern mining and transport equipment possessing new engineering capabilities, and robotization of the main technological processes.

When the transition to underground mining used to be planned from a depth of 500–600 m, at the present time the potential of opencast mining allows to mine open pits effectively to a depth of 850–1000 m. This circumstance allows to revise the concept of mining primary diamond deposits, and in some cases eliminate the expensive and economically inefficient method of pit reserves underground mining [1, 2].

Research methodology. Let us consider the problem of reserves final extraction at Nyurbinsky pipe of ALROSA PJSC, where mining peripheral limited ore reserves within the depth range of 570–750 m using an underground mining method is economically inefficient. In 2015 Yakutniproalmaz Institute developed some recommendations on mining-engineering parameters and the order of open pit mining to a depth of 570 m (*Manager's Report of Investigations by A. N. Akishev "To Work out Recommendations on Mining-Engineering Parameters and the Order of Nyurbinsky Open Pit Mining to a Depth of 570 m with the Account of the Refined Physical-Mechanical Properties of the Enclosing Rocks". Mirny, Yakutniproalmaz, 2015. 50 p*). From a depth of 370 m (mountain –120 m) the project provided for the transition from the traditional stripping scheme to stripping by steeply inclined ramps (i = 21–25%) with a corresponding implementation of four-wheel drive articulated trucks. To a depth of 370 m, rock mass is removed to the surface by dump trucks CAT-777D, CAT-777F, TEREX TR-100 with 4 x 2 wheel arrangement, payload 91 t along the ramps with the inclination of 8–9%. From the lower horizons the rock mass is delivered by four-wheel drive dump trucks CAT-745C with payload 41 t to a loading point situated on the horizon –80 m.

The main advantages of the articulated trucks (AT) at the stage of the design alternative consist in in the use of the steeply inclined ramps (i = 21–25%) and the haulage berms smaller in width as compared to the dump trucks with 4 x 2 wheel arrangement, which allows to enlarge the angles of inclination of non-mining pit edges from 45°–48° to 57°–63°, reduce additional overburden stripping caused by transport communications arrangement, and to mine the open pit to a depth of 570 m [3]. When substantiating the variant of stripping, the estimation of non-mining benches and edges stability in general has been fulfilled. The estimation has been fulfilled by means of comparing design and allowable stability safety factor according to the methodology of VNImI (*Manager's Report of Investigations by I. B. Bokii "To Study Physical and Mechanical Properties of the Enclosing Rocks in the Vicinity of the Open Pit at Nyurbinsky Pipe by Geological-Engineering Wells to a Depth of – 400 meters above sea level". Mirny, Yakutniproalmaz, 2014. 28 p*). At that, the following physical-mechanical properties of rocks were considered: density, the angle of repose, cohesion in the sample, and structural weakening coefficient in the massif. It has been stated that design values of the stability safety factor is higher than maximum allowable values ($K_д > 1.2$).

In 2017 Yakutniproalmaz Institute in cooperation with the Ural State Mining University suggested the scheme of stripping for the deep horizons of Nyurbinsky open pit by the peripheral road tunnel of a spiral shape, which makes it possible to mine the deposit to a depth of 750 m, which corresponds to a depth of the explored reserves [4].

Transfer to tunnel stripping is carried out from a depth of 530 m (mountain –280 m). An underground ramp, driven beyond the zone of displacement, joins the mining horizons by crosscuts which are driven in non-mining edges and are abandoned as mining depth increases. When using the indicated scheme of stripping, the angle of inclination of a non-miming edge in the zone of tunnel stripping doesn't depend on the width and the inclination of transport communications, but only on the conditions of stability. It has been stated, that taking into account the difference between the values of design and allowable stability safety factors of Nyurbinsky open pit edges, inclination angle of a non-working edge in the zone of tunnel stripping can be increased up to 75°. If the indicated scheme of stripping is used, the edge of an open pit has got a convex cissoidal profile. It reduces overburden stripping and stabilizes benches as its contour is distressed to the maximum [5]. It results in geological environment disturbances reduction and mining safety improvement. Tunnel stripping reduces ground water hydrodynamic pressure on the edge of the open pit, which will also contribute to the increase in the angle of inclination of a non-mining edge. The presence of a tunnel makes it possible to arrange the equipment to observe its state within the limits of the massif. Moreover, out of the tunnel the anchor support can be installed which prevents from adjacent rock mass collapse [6–8]. The use of the articulated trucks and steep ramp inclinations allows to significantly reduce capital investments in underground tunnels driving, which is the main restriction under the implementation of the indicated stripping method.

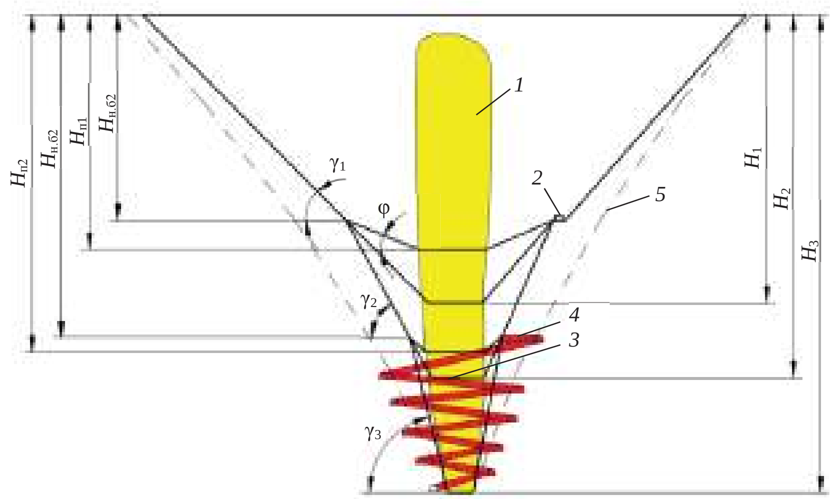


Fig. 1. An innovative scheme of stripping the deep horizons of Nyurbinsky open pit:
1 – ore body; *2* – loading point; *3* – tunnel ramps; *4* – crosscut; *5* – opencast mining coverage boundary (sliding surface)

Рис. 1. Инновационная схема вскрытия глубоких горизонтов Нюрбинского карьера:
1 – рудное тело; *2* – перегрузочный пункт; *3* – тоннельные автосъезды; *4* – квершлаг; *5* – граница зоны действия открытых горных работ (поверхность скольжения)

Based on the open pit rock mass production rate, goods turnover, and dump trucks traffic, one way tunnel with passes-by in niches for the dump trucks has been considered. The distance between the pass-by niches is 450 m.

Thus, the suggested innovative scheme of Nyurbinsky open pit stripping includes the two stages (table 1, fig. 1):

At the first stage in 2024 the transition is carried out from the traditional scheme of stripping to the stripping scheme by the steeply inclined ramps with the use of four-wheel drive articulated trucks with payload 41 t;

At the second stage in 2034 the transition is carried out from the steeply pitching scheme of stripping to the stripping scheme by the peripheral ramp tunnel of a spiral shape.

In fig.1 the following notations are set: H_1 – the target depth of the open pit under the traditional scheme of stripping with the use of the dump trucks with 4 × 2 wheel arrangement, m; H_2 – the target depth of the open pit under the transition to stripping by the steeply pitching ramps and the use of the four-wheel drive dump trucks, m; H_3 – the target depth of the open pit under the transition to tunnel stripping, m; $H_{п1}$ – the depth of the transition to stripping by the steeply pitching ramps, m; $H_{п2}$ – the depth of the transition to tunnel stripping, m; $H_{\text{н.б 1}}$ – the height of a non-mining edge of the open-pit under the transition to stripping by the steeply pitching ramps, m; $H_{\text{н.б 2}}$ – the height of a non-mining edge of the open-pit under the transition to tunnel stripping, m; γ_1 – the angle of inclination of a non-mining edge of the open pit under the traditional scheme of stripping, degrees; γ_2 – the angle of inclination of a non-mining edge of the open pit under stripping by the steeply pitching ramps, degrees; γ_3 – the angle of inclination of a non-mining edge under tunnel stripping, degrees; φ – the angle of inclination of a mining edge, degrees.

Under the implementation of the innovative scheme of striping, apart from the substantiation of open pit non-mining edges stability, the following problems require substantiation:

– the optimum depth of the transition to a new stripping scheme;
– the required speed of driving tunnels and crosscuts;
– the rational scheme of underground workings ventilation.

Table 1. Basic parameters of the innovative scheme of Nyurbinsky open pit stripping
Таблица 1. Основные параметры инновационной схемы вскрытия Нюрбинского карьера

Parameter	Value
The target depth of the open pit H_3, m	750
The depth and the year of the transition from the traditional scheme to stripping by the steeply pitching ramps $H_{\text{п1}}$, m (year)	370 (2024)
The height of a non-mining edge of the open-pit under the transition to stripping by the steeply pitching ramps $H_{\text{н.б1}}$, m	330
The depth and the year of the transition from stripping by the steeply pitching ramps to peripheral tunnel stripping $H_{\text{п2}}$, m (year)	530 (2034)
The height of a non-mining edge of the open-pit under the transition from stripping by the steeply pitching ramps to peripheral tunnel stripping $H_{\text{н.б2}}$, m	510
maximum inclination of automotive communications i, %:	
in a zone of the traditional scheme of stripping	8–9
in a zone of steeply pitching stripping	21–25
in a zone of tunnel stripping	20
Line development coefficient $k_{\text{р.т}}$, unit fractions	1,083
The angle of inclination of a non-mining edge in the enclosing rocks, degrees	54–63
Including:	
in a zone of the traditional scheme of stripping γ_1	45–48
in a zone of steeply pitching stripping γ_2	57–63
in a zone of tunnel stripping γ_3	75
The volume within the contour of the open pit (as of 1st January, 2017):	
ore, million ton	9.7
overburden, million m^3	44.9
Average operating stripping ratio $k_{\text{в.ср}}$, m^3/t	4.7
Annual productive capacity of the open pit for ore, million t/yr:	
2018–2024	0.87–1.05
2025–2033	0.40
2034–2040	0.23
models and payload of the dump trucks, t:	
in a zone of the traditional scheme of stripping	CAT-777D (91 ton)
in a zone of steep and tunnel stripping	CAT-745C (41 ton)
Bench height $h_{\text{у}}$, m:	
mining	15
non-mining	30–45
Average speed of the open pit deepening $h_{\text{г}}$, m/yr	25
The angle of inclination of a mining edge φ, degrees	16–18
The total length of underground openings, m:	
tunnel	1300
horizontal crosscuts	1100
The required speed of tunneling $\cdot_{\text{т}}$, m/mo	greater or equal 19.7

When solving the indicated problems, the methods of economic-mathematical modeling, engineering-economic and mining-geometric analyses have been used.

Results. Analysis and discussion. Table 2 introduces analytical dependences for basic parameters of stripping calculation: the transition depth, the non-mining edge height, and the open pit depth increase under the transition to a new scheme of stripping. It can be observed, that these parameters are determined basically by the target depth of the open pit and the difference between the values of the non-mining edges angles under various stripping schemes. It is recommended to use the dependences for preliminary estimation of the depth of the transition to a new stripping scheme. Exceeding the indicated depth leads to the need for the fundamental reconstruction of the open pit starting from the higher horizons. Otherwise, it will be impossible to mine the open pit to the target depth allowed by the new stripping scheme. The final decision on the transition optimum depth is made according to the economic criterion, which takes into account the reduction of stripping and transportation by various types of dump trucks, the prime cost of stripping and automobile transportation, costs for driving and maintenance of the underground workings, as well as these factors dynamics [9]. In the considered variant, the depth of the transition to the new stripping schemes ($H_{п1}$ = 370 m; $H_{п2}$ = 530 m) is set according to the economic criterion.

Table 2. The calculation of the basic stripping parameters
Таблица 2. Расчет основных параметров вскрытия

Parameter	Stripping scheme	
	Steeply pitching ramps (1st stage)	Road tunnel (2nd stage)
A depth of the transition to a new scheme of stripping under the known target depth of the open pit	$H_{п1}=\dfrac{H_1-(H_2-H_1)\cos\gamma_2\sin(\gamma_2-\varphi)}{\sin(\gamma_2-\gamma_1)\cos\varphi}$	$H_{п2}=\dfrac{(H_3-H_2)\cos\gamma_3\sin(\gamma_3-\varphi)}{\sin(\gamma_3-\gamma_2)\cos\varphi}$
The increase of the open pit depth under the transition to a new stripping scheme	$\Delta H=H_2-H_1=$ $=\dfrac{(H_1-H_{п1})\sin(\gamma_2-\gamma_1)\cos\varphi}{\cos\gamma_2\sin(\gamma_2-\varphi)}$	$\Delta H=H_3-H_2=$ $=\dfrac{(H_2-H_{п2})\sin(\gamma_3-\gamma_2)\cos\varphi}{\cos\gamma_3\sin(\gamma_3-\varphi)}$
The height of a non-mining edge under the transition to a new stripping scheme	$H_{н.б1}=H_1-\dfrac{(H_2-H_1)\cos\gamma_2\sin\gamma_1}{\sin(\gamma_2-\gamma_1)}$	$H_{н.б2}=H_2-\dfrac{(H_3-H_2)\cos\gamma_3\sin\gamma_2}{\sin(\gamma_3-\gamma_2)}$

When considering the innovative stripping scheme, the problem of substantiating the required speed of tunneling is of great significance. For continuous functioning of the stripping scheme, the period of abandoning the connecting crosscut at the higher horizon should correspond to the period of putting the new crosscut into operation at the lower horizon of the open pit. Thus, the speed of tunneling should be consistent with the development of mining in the functioning part of the open pit as well as with the period of the open pit edge formation into the target position at a note of an entrance. The vertical distance between the tunnel entrances in the upper zone of the tunnel stripping is 30 m, which corresponds to the height of a non-mining bench; in the lower zone – 15 m.

The condition must be followed (fig. 2):

$$\left(T_{т}+T_{кв}\right)\geq T_{б}, \tag{1}$$

where $T_б$ – the period of a non-mining edge of the open pit formation to the height $h_п$, years; $h_п$ – the vertical distance between the tunnel entrances, m; $T_т$ – the period of the tunnel construction to a depth $h_п$, years; $T_{кв}$ – the period of constructing the crosscut providing the way out to the functioning zone of the open pit, years;

$$T_б = h_п / h_б, \tag{2}$$

where $h_б$ – vertical speed of forming the non-mining edge of an open pit, m/yr;

$$h_б = h_г\left(\text{ctg}\varphi - \text{ctg}\sigma\right) / \left(\text{ctg}\varphi - \text{ctg}\gamma\right), \tag{3}$$

where $h_г$ – the vertical speed of the open pit deepening, m/yr; φ – the angle of inclination of an operating edge of the open pit, degrees; σ – deepening directional angle, degrees; γ – the angle of inclination of a non-mining edge of the open pit, degrees;

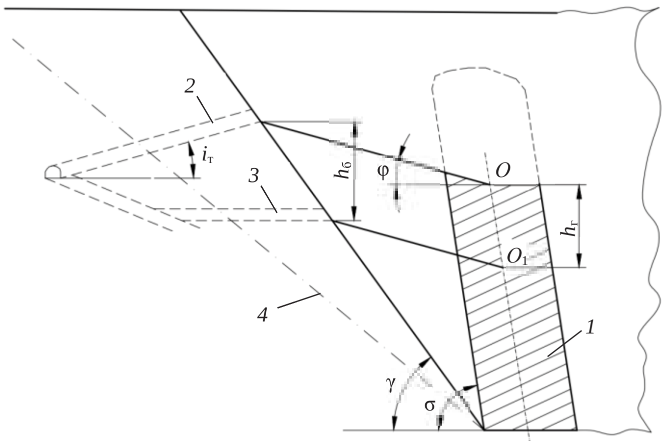


Fig. 2. The calculation scheme of the required speed of tunneling:
1 – ore body; *2* – tunnel; *3* – crosscut; *4* – opencast mining coverage boundary; $h_г$ – the vertical speed of the open pit deepening, m/yr; $h_б$ – the vertical speed of forming a non-mining edge of the open pit, m/yr; σ – deepening directional angle, degrees; γ – the angle of inclination of a non-mining edge of the open pit, degrees; φ – the angle of inclination of a mining edge of the open pit, degrees; $i_т$ – the inclination of the tunnel ramp, unit fractions

Рис. 2. Схема к расчету необходимой скорости проходки тоннеля:
1 – рудное тело; *2* – тоннель; *3* – квершлаг; *4* – граница зоны действия открытых работ; $h_г$ – вертикальная скорость углубки карьера, м/год; $h_б$ – вертикальная скорость формирования нерабочего борта карьера, м/год; σ – угол направления углубки, град; γ – угол откоса нерабочего борта карьера, град; φ – угол откоса рабочего борта карьера, град; $i_т$ – уклон автодороги в тоннеле, доли ед.

$$T_т = l_т / \upsilon_т, \tag{4}$$

where $l_т$ – the tunnel length under stripping to a depth $h_п$, m; $\upsilon_т$ – speed of tunneling, m/yr;

$$l_т = h_п k_{р.т} / i_т, \tag{5}$$

where $i_т$ – the inclination of the tunnel ramp, unit fractions; $k_{р.т}$ – line development coefficient, unit fractions;

$$T_{кв} = l_{кв} / \upsilon_т, \tag{6}$$

where $l_{кв}$ – crosscut length, m.

The ratios (2)–(6) substitution into the inequality (1) yields

$$v_{\text{т}} \geq \frac{h_{\text{г}}\left(\text{ctg}\varphi - \text{ctg}\sigma\right)\left(h_{\text{п}}k_{\text{р.т}} + i_{\text{т}}l_{\text{кв}}\right)}{h_{\text{п}}\left(\text{ctg}\varphi - \text{ctg}\gamma\right)i_{\text{т}}}. \qquad (7)$$

The expression (7) determines the requirements to the speed of peripheral tunneling.

Let count $v_{\text{т}}$ for the conditions of Nyurbinsky open pit. Initial data (table 1) are the following: $h_{\text{г}}$ = 25 m/yr; γ = 75°; φ = 16°; σ = 85°–90°; $i_{\text{т}}$ = 0.20; $l_{\text{кв}}$ = 100 m; $k_{\text{р.т}}$ = 1.083; $h_{\text{п}}$ = 30 m. Получим $v_{\text{т}} \geq 237$ m/yr or $v_{\text{т}} \geq 19.7$ m/mo.

In the course of the research, modern technologies of driving and supporting road tunnels in the mining-engineering conditions similar to the kimberlite pipes conditions have been considered. Two methods of driving tunnels and crosscuts have been examined: the drilling and blasting method and the method with the use of road headers. Based upon the physical-mechanical properties of the enclosing rocks at Nyurbinsky open pit, the method with the use of a road header is preferable; it ensures better economic-engineering indices and higher speed of tunneling. As excavating equipment, a selective heading machine AM-105 of "Fest Alpine" company has been chosen. The anchor support installation is carried out by a Spraymec 7110 shotcrete machine. Rock removal during tunneling is carried out by technological dump trucks CAT-745C (41 t). Calculations show, that the use of the accepted technology when tunneling one way tunnel with the section area of 29.7 m^2 ensures maximum speed of tunneling 60–70 m/mo which is 3.0–3.5 times higher than required [10].

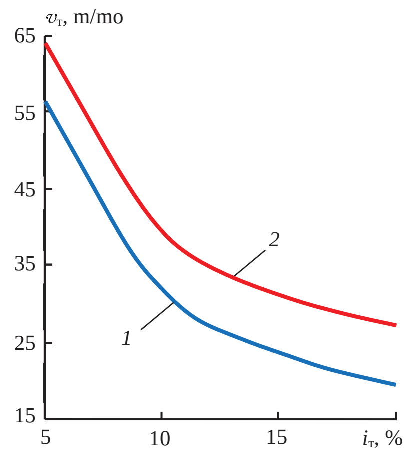


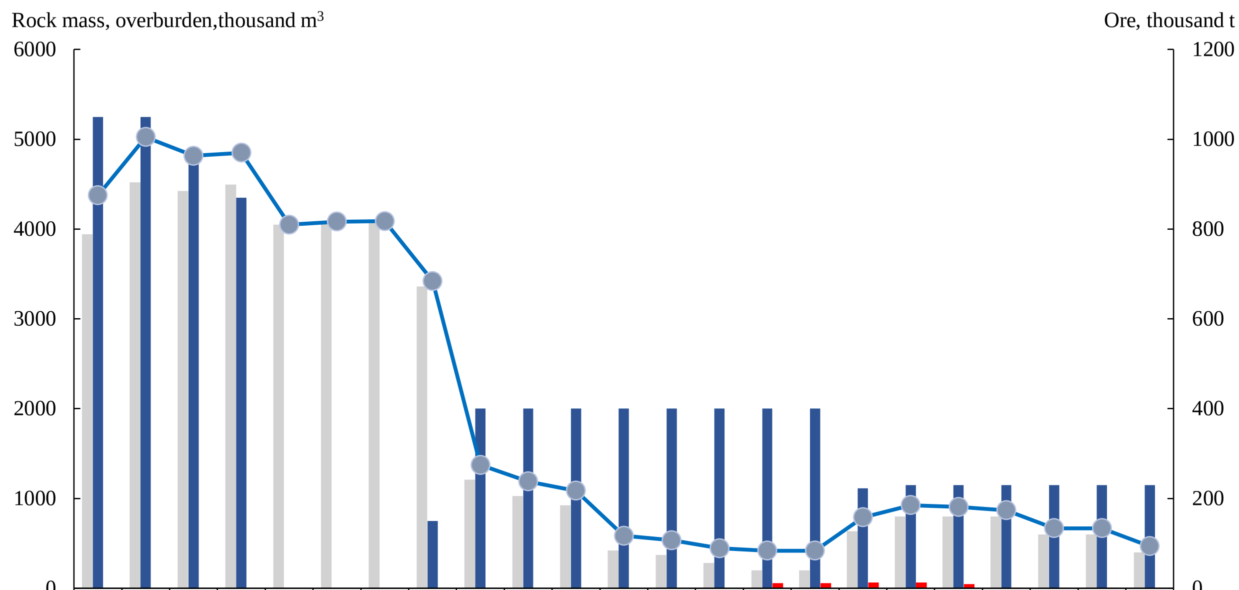
Fig. 3. The dependence between the required tunneling speed $v_{\text{т}}$ and ramps inclination $i_{\text{т}}$:
$h_{\text{п}}$ – the vertical distance between the entrances; *1* – $h_{\text{п}}$ = 30 m; *2* – $h_{\text{п}}$ = 15 m

Рис. 3. Зависимость необходимой скорости проходки тоннеля $v_{\text{т}}$ от уклона автодорог $i_{\text{т}}$:
$h_{\text{п}}$ – вертикальное расстояние между порталами; *1* – $h_{\text{п}}$ = 30 м; *2* – $h_{\text{п}}$ = 15 м

Thus, the required speed of tunneling is determined by the speed of the open pit deepening, the ramps inclination, and the vertical distance between the entrances; it depends on the angles of mining and non-mining edges of the open pit, and the direction of deepening. The greatest impact is made by three factors: $h_{\text{г}}$, $i_{\text{т}}$, and $h_{\text{п}}$.

When reducing the inclination of the tunnel from 20 to 5%, the required speed of tunneling is increased by 2.4–3.0 times and approaches its maximum in technical conditions (fig. 3). This conditions the need for and the effectiveness of four-wheel drive dump trucks and increased inclinations when carrying out tunnel stripping of open pit deep horizons.

The effectiveness of the suggested deep open pits exploitation technology can be improved by means of robotized mining-transport equipment introduction, particularly dump trucks. At that, the width of the transport berms may be decreased by 20–30%, and the angle of inclination of a mining edge may be increased by 4°–6°. Under the use of the robotized dump trucks, the width of the transport berms is determined by the width of the roadway and the tolerance connected with the accuracy of the positioning systems. The robotized dump trucks are built up with a 3D scanner which makes it possible to control the state of roads and rock massif. The elements of safety are excluded from the structure of a berm. The transition to the use of the robotized dump trucks can be effective at the first stage of the innovative technology implementation already, i.e. during the transition from the traditional scheme of stripping to the scheme



	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
Overburden, thousand m³	3943	4519	4425	4494	4049	4083	4088	3360	1209	1026	923	423	373	283	200	200	635	800	800	800	600	600	400
Underground workings, thousand m³															56	56	64	64	45	8	8	8	8
Ore (expl.), thousand t	1050	1050	950	870	0	0	0	150	400	400	400	400	400	400	400	400	223	230	230	230	230	230	230
Rock mass, thousand m³	4376	5024	4815	4849	4049	4083	4088	3421	1373	1189	1086	585	535	446	418	418	789	925	906	868	668	668	468

Fig. 4. The diagram schedule of Nyurbinsky open pit exploitation according to the innovative technology
Рис. 4. Календарный график разработки Нюрбинского карьера по инновационной технологии

of stripping by the steeply pitching ramps (2024). It will allow to reduce stripping and to ensure maximum value of a non-mining edge angle of inclination. At the present time there is the experience of using the robotized dump trucks in foreign open pits. Intensive research in this field is carried out by a domestic company called VIST Group [11, 12]. At the second stage of the transition from the steeply pitching scheme of stripping to the scheme of stripping by the peripheral road tunnel, the additional effect can be provided by means of reducing the costs for ventilation of the underground workings which are 20–25% as large as the costs on tunneling. This problem requires further detailed investigations and coordination with Rostekhnadzor.

Table 3. Parameters of various schemes of Nyurbinsky open pit stripping and mining
Таблица 3. Параметры различных схем вскрытия и разработки Нюрбинского карьера

Parameter	Stripping scheme		
	Traditional	Steeply pitching ramps	Innovative scheme with variable geometry of non-mining edges
Open pit depth, m	750		
The angle of inclination of a non-mining edge, degrees	45–48	49–57	54–63
The volume within the contour of the open pit (as of 1st January, 2017):			
ore, million ton	9.7	9.7	9.7
overburden, million m^3	358.0	135.0	44.9
rock mass, million m^3	361.9	138.9	48.8
Average operating stripping ratio, m^3/t	37.7	14.2	4.7

Conclusions and results application area. Fig. 4 presents a diagram schedule of Nyurbinsky open pit exploitation according to the innovative technology. Table 3 presents comparative parameters of various schemes of open pit stripping and mining.

Preliminary calculations have stated that the introduction of the innovative technology will allow to reduce stripping by 3–8 times as compared to the traditional stripping scheme and the schemes of stripping by the steeply pitching ramps. Economic benefit will be rub13.7 billion according to the preliminary estimation. The suggested technology can be used not only during the exploitation of kimberlite open pits, but also during the opencast exploitation of non-ferrous metal ore deposits and precious-metal ore deposits represented by round shaped steep deposits.

At the present time Yakutniproalmaz Institute and the Ural State Mining University carry out the detailed economic-engineering substantiation for the suggested innovative technology of exploitation with variable geometry of non-mining open edges. The research results have been granted the second class certificate in the nomination “The Innovative Project” of ALROSA PJSC innovative projects open competition in 2017.

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Received 10th July, 2018

For citation: Akishev A. N., Lel' Iu. I., Bokii I. V., Isakov S. V., Glebov I. A. Kimberlite deposits opencast mining innovative technology with variable geometry of non-mining open pit edges. Izvestiya vysshikh uchebnykh zavedenii. Gornyi zhurnal. 2018. No. 8. Pp. 5–15.

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ИННОВАЦИОННАЯ ТЕХНОЛОГИЯ ОТКРЫТОЙ РАЗРАБОТКИ КИМБЕРЛИТОВЫХ МЕСТОРОЖДЕНИЙ С ИЗМЕНЯЕМОЙ ГЕОМЕТРИЕЙ НЕРАБОЧИХ БОРТОВ КАРЬЕРА

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Цель исследований *заключается в расширении области применения открытого способа разработки алмазорудных месторождений за счет внедрения инновационной технологии вскрытия с изменяемой геометрией нерабочих бортов карьеров.*
Актуальность исследований. *В настоящее время требует решения проблема доработки законтурных запасов руды алмазорудных месторождений, залегающих ниже предельных границ карьеров, где применение традиционных технологий экономически неэффективно. Предлагаемая инновационная технология позволяет решить эту проблему.*
Методика проведения исследований. *Решение поставленной задачи производится в два этапа: переход с определенной глубины карьера с традиционной схемы вскрытия на схему вскрытия крутонаклонными автосъездами и переход на завершающем этапе на вскрытие законтурным автомобильным тоннелем, проходимым за зоной сдвижения. При этом обосновывались оптимальная глубина перехода на новую схему вскрытия и необходимая скорость проходки тоннеля и квершлагов. При обосновании варианта вскрытия произведена оценка устойчивости нерабочих уступов и бортов в целом. Использова-*

лись методы экономико-математического моделирования, технико-экономического и горногеометрического анализа.
Результаты. *На примере разработки Нюрбинского карьера АК «АЛРОСА» установлено, что инновационная технология позволяет увеличить углы откосов бортов карьера с 45°–48° до 57°–75°, уменьшить объемы вскрыши в 3–8 раз и эффективно доработать запасы полезного ископаемого до глубины 750 м.*
Область применения результатов. *Предлагаемая технология может найти применение не только при разработке кимберлитовых карьеров, но также при открытой разработке месторождений цветных и благородных металлов, представленных крутопадающими залежами округлой формы.*

Ключевые слова: *карьер; схема вскрытия; уклон автосъезда; полноприводные автосамосвалы; угол откоса борта; тоннель; скорость проходки; комбайн; коэффициент устойчивости борта; роботизация.*

DOI: 10.21440/0536-1028-2018-8-5-15

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