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Safety improvement in open-pit mines with challenging mining conditions through upgrading avalanche prevention measures

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Abstract
One of the most common problems mining companies face in developing open-cut deposits in complicated geological and climatic conditions is avalanches during the spring-winter work period. This phenomenon is accompanied by a rapid displacement of snow masses, which can lead to catastrophic consequences. In this regard, the article aims to develop a modernized set of measures for avalanche protection. Prevention of avalanches of catastrophic scale, leading to blockages, road closures, and accidents, and the introduction of measures to reduce accidents and injuries in quarries and dumps, is a time-consuming task that requires serious approaches to its solution. The main research method is analyzing the applied anti-avalanche measures for active impact on snow cover and considering the possibility of using safer methods for active impact on avalanches at a particular mining enterprise. This approach allows for the evaluation of the advantages and disadvantages of the avalanche measures used and for choosing a set of measures to ensure more effective avalanche protection. The authors analyzed the existing shortcomings in the regulatory documents related to the provision of avalanche protection and anti-avalanche measures. It was found that they are not able to effectively ensure the development of internal local documents of enterprises in the field of anti-avalanche measures at the present stage. The resulting study showed that a comprehensive solution to the problem is needed through the introduction of several anti-avalanche devices to reduce the likelihood of avalanches of catastrophic scale. For the first time, the authors attempted to justify the possibility of using a modernized set of measures for the preliminary descent of snow avalanches to solve the problem of avalanche protection in the conditions of a real mountain object.
The results obtained can be used to reduce the level of occupational injuries by reducing or eliminating accidents associated with unforeseen avalanches during the operation of an existing quarry.

Keywords
Open pit mining, mining enterprise, anti-avalanche protection, preliminary avalanche descent.

Introduction

Avalanches are one of the most dangerous natural phenomena, leading not only to significant destruction and economic damage but also to the death of people. Every year, an average of about 350 people die due to avalanches (Table 1). Also, the need for avalanche protection is determined by the phenomenon's scale - the area of avalanche-prone territories in Russia occupies almost 20 % of the country's total area (Roshydromet, 2020).

Tab 1. Avalanche statistics for the period 2011-2020 (Avalanche Stats, 2020)

Date of incident		Place	Number of victims
2011	February	Afghanistan, Daikundi	21 dead
2012	January	Afghanistan, Badakhshan	46 dead
	February	India	19 injured
	March	Afghanistan, Nasi	about 20 injured
	March	Afghanistan, Dusty	about 60 dead
	April	Pakistan, Gayari base	138 dead
	September	Nepal, Manaslu	15 injured
2014	April	Nepal, Everest	25 dead
	October	Nepal, Annapurna	43 injured
2015	February	Afghanistan (northeast)	310 dead
	April	Nepal, Everest	24 injured
2017	January	Italy, Abruzzo	about 30 dead
	March	Russia, Kabardino-Balkaria	7 dead
2018	January	Bitlis Province, Turkey	5 dead
	October	Himalayas	9 injured
2019	January	Russia, Sochi	2 injured
	November	India, Ladakh	6 dead
2020	January	Pakistan, Azad Kashmir	57 dead
	February	Turkey, Van Province	33 dead

In January 2021, there were already 3 cases of snow avalanches in Russia, as a result of which at least 4 people were killed and more than 10 people were injured (RIA Novosti, 2021).

In addition to organizing constant observations and developing methods for predicting avalanches to ensure safety, since the late 30s, measures have been taken to influence the snow cover actively. However, these measures are becoming outdated and require modern solutions to protect against avalanches. To prevent avalanches, not only special observations and forecasting are needed, but also the organization of reliable protection, in addition to engineering measures (construction of tunnels, sheds; erection of avalanche breakers, wedges, dams; building with snow-retaining shields, etc.), an active impact on the snow cover is required for preventive descent of snow avalanches, so that a large thickness of snow does not accumulate and avalanches do not become catastrophic for people and businesses that operate in mountainous regions.

Specialists of mining enterprise avalanche services have developed organizational and technical measures (Fig. 1).

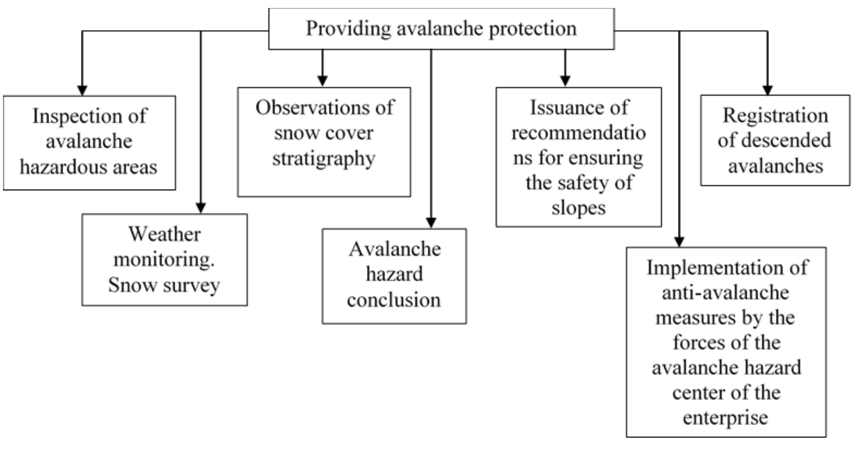

Fig. 1. A set of measures for avalanche protection (Source: Specialists of avalanche services)

The work (Podverbny et al., 2018) reveals the issue of preventive descent of snow avalanches due to active impact on avalanche centers. Special attention was paid to the methods of active influence on the zones of avalanche initiation. In more detail, the authors of the article consider the "Snow Arrow" system - a productive pneumatic active system. The authors analyzed the main technical and technological features of using the system and also presented a calculation that makes it possible to find out when an avalanche should be fired, which, of course, positively affects the level of the entire enterprise's industrial safety. However, it is noted that the systems of active impact on avalanches, particularly the "Snow Arrow", do not provide 100 % efficiency and a decent level of avalanche protection, in general.

The authors (Kortiev et al., 2014) noted that uniform norms, rules, or recommendations for protection against avalanches have not yet been developed for countries with mountainous terrain. In this connection, various countries use primitive and affordable means and knowledge while people continue to die when the snow masses disappear.

To improve anti-avalanche measures for the descent of snow avalanches, it is necessary to study the catastrophic phenomena that have already occurred. The publication (Volodicheva et al., 2014) considered the conditions for forming catastrophic avalanches and their analysis. The authors also note that the greatest avalanche danger is typical for cold winters when the slopes are overloaded by falling snow. Thus, there is a need for the use of avalanche control measures, including the preventive descent of avalanches.

In Russia, there are different avalanche protection techniques. The article (Nogotkova & Soloviev, 2016*)* examines the avalanche control measures applied at the Rosa Khutor ski resort. The article's authors describe the system of active influence on the snow cover - Gazex- in detail, as well as about avalanches and the Daisy Bell complex. Passive means of protection are snow retention nets, avalanche dams, and avalanche breakers. To optimize avalanche control measures, mathematical modeling is used to assess the likelihood of avalanches and determine the possible severity of the consequences. Having studied all the measures used, the authors believe these methods meet all the requirements for avalanche safety.

In addition to introducing modern technical devices, it is also necessary to have modern management of the occupational health and safety system, as mentioned in (Rudakov et al., 2021) and (Kazanin et al., 2018). It is noted that occupational injuries, with all the measures and actions taken, remain a matter of serious concern. Also, the article (Nikulin & Nikulina, 2017) reveals the issue of a systematic approach to labor protection in combination with the introduction of new equipment and new technologies to reduce accidents and increase production efficiency. In the study (Smyslov et al., 2001), it is noted that avalanches are difficult to predict, and the damage from them can reach about $ 1 billion. In (Gevorgian, 1991), it is also noted that due to the cruelty of the climate in high-altitude quarries during periods of heavy snowfall, there is a threat of avalanches on the roads, as a result of which the rhythm of transportation of rock mass is disrupted. Paper (Gusev, 2005) notes the need to replace outdated equipment and methods with modern ones for safe and efficient production.

Currently, one of the ways to prevent avalanches is the use of explosives, which can lead to accidents. The authors (Sabanov et al., 2008) give a table of calculated risks by hazard factors, from which it can be concluded that the risks associated with blasting are of medium probability, have very dangerous consequences, and have significant levels of risk. This highlights the need for other technologies that pose fewer threats. The study (Korshunov et al., 2019) proposes a method for assessing the stability of concrete supports based on finite element analysis to ensure safe blasting operations.

It should be noted that the issue of improving labor safety remains largely unresolved and requires innovative approaches. The analysis of scientific research confirms the issue and concludes that it is necessary to introduce a modernized set of measures for the avalanche protection of the enterprise.

Material and Methods

Calculation of snow cover and avalanche parameters

According to statistical data on snow cover (Avalanches geography, 1992), the following calculations were made (Guidelines for the Calculation of Snow Loads in Structures Designing, 1973):

1) The maximum snow depth is estimated at approximately:

$$h_0 = \frac{h_{max}}{h_{aver}} \left[h_{st} + \frac{\Delta h}{\Delta H}\,(H_x - H_{st})\right], \tag{1}$$

h_{max} – the highest of the maximum snow depths measured vertically at the site of the projected development, m; h_{max} = 0.224 m.

h_{aver} – average maximum height of snow cover, m; h_{aver} = 0.2 m.

h_{st} – maximum depth of snow cover with an observation period of more than 10 years, m; h_{st} = 0.298 m.

Δh – the average difference in the height of snow cover at meteorological stations located in a given area at different absolute heights, m; Δh = 0.95 m;

ΔH – difference in altitude of meteorological stations, m; $\Delta H = H_1 - H_2$ = 1050 – 300 = 750 m;

H_x – the absolute height of the slope section, m; H_x =1050 m;

H_{st} – the absolute height of the nearest meteorological station, m; H_{st} = 300 m.

$$h_0 = \frac{0.224}{0.2}\left[0.298 + \frac{0.95}{750}\,(1050 - 300)\right] = 1.4\ m$$

2) The avalanche speed is approximately calculated by the equation:

$$v = \sqrt{\frac{a*S}{2}}, \quad (2)$$

Where:
$a = 9.8\ (\sin\alpha - f * \cos\alpha)$, m/s^2;
f – friction coefficient taken equal to 0.25 for rock surfaces;
α – slope angle; α = 40°;
S – slope length, m; S = 140 m.

$$v = \sqrt{\frac{9.8 * \ (\sin 40° - 0.25 * \cos 40°) * 140}{2}} = 17.64\ m/s$$

The avalanches with such speed refer to average avalanches, which are considered destructive for young trees, wooden buildings, and cars. The destructive force of such avalanches carried to the road, and the problem of snow accumulation in this region require a timely solution and innovative approaches, which are proposed below.

Results

Applied anti-avalanches measures

Snow Arrow system

The Snow Arrow system is a pneumatic installation with a 4 m or 6 m barrel length, designed to launch a projectile containing an explosive substance – a liquid mixture.

The system is installed on a rotating base, enabling a circular attack on avalanche centers. The explosive for the Snow Arrow is the SECUBEX explosive liquid, which consists of nitromethane (about 93% liquid) and ethylenediamine (Guidance Document РД 52.37.785-2013, 2013).

The advantages of the system are:

- the possibility of using the system in difficult weather conditions and in the absence of visibility;
- relative harmlessness to the environment.

However, there are significant disadvantages:

- possible system failure, which can lead to the arrow's flight, but without an explosion. In such situations, access to the shot zone is prohibited for 48 hours, which allows a greater accumulation of snow on an avalanche slope and increases the likelihood of an avalanche self-descent;
- the high cost of a shot. One shot costs about 100 thousand rubles (1110 €), and 4 - 5 shots are required for one avalanche-prone zone.

Anti-avalanche complex Nuris

Anti-avalanche complex Nuris is a portable device used for the preventive descent of avalanches to protect against snow masses in mountainous areas.

The set of this anti-avalanche system includes 2 units:

- Nuris-P – the installation is mounted on a platform for use on an unequipped snow area;
- Nuris-S – designed for work from prepared stationary sites on the slopes or the bodies of vehicles (Guidance Document РД 52.37.849-2016, 2016).

The advantages of this anti-avalanche complex are:

- ease of transportation;
- small dimensions;
- the ability to use in unprepared snow areas.

The disadvantages are:

- the complex is inconvenient for pedestrian transportation, which may be necessary in case of a critical situation with a high probability of an avalanche;
- electric descent, the probability of a shot of which decreases to 0.85;
- high cost of shots.

Use of explosive ammonite 6ZhV

Preliminary descent of avalanches using ammonite 6ZhV is widely used. The explosive is placed in the avalanche initiation zone at the moment when the stress of the accumulated snow mass reaches a critical value.

Usually, 2 kg or 4 kg explosive charges are used, depending on the thickness of the snow or the avalanche center. The detonation is carried out using a machine with a waveguide, through which an electrical impulse is transmitted, and then the explosive is initiated.

The advantage of this method is its relatively low cost since this explosive is purchased in large quantities due to its widespread use in production.

Fixed remote avalanche control system Gazex

The Gazex system was patented by the French company T.A.S. (Technologie Alpine de Securite) in 1989 after 15 years of avalanche control experiments.

This system is designed to release avalanches in a forced plan due to the explosion of a mixture of oxygen and propane.

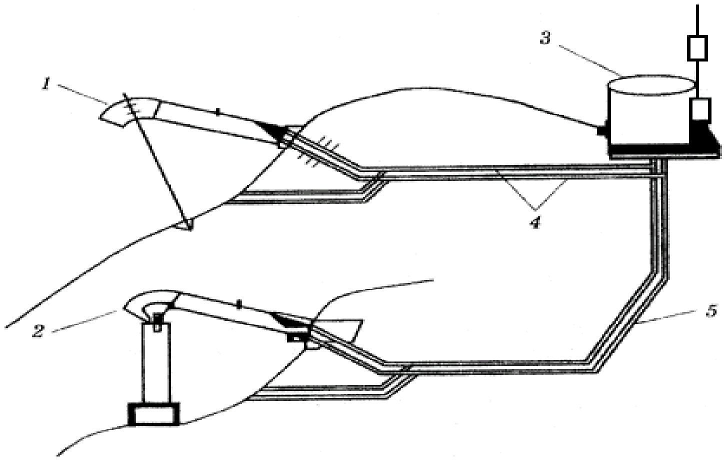

Fig. 2. Gazex system: 1 - standard gas cannon; 2 - inertial gas cannon; 3 - caponnier; 4 - pipelines; 5 - plastic pipes (Source: Guidance Document РД 52.37.659-2004, 2004)

The Gazex system (Fig. 2) includes the following structural elements:

1) a gas cannon (it can be in a standard version for installation on rocky soils and an inertial version - for installation in soft rocks);

2) caponnier – a shelter in which all types of process controls are located;

3) 2 pipelines through which gases are supplied. Connect the gas cannon and the caponnier;

4) operator's room.

In the working volume, it is necessary to provide a mixture containing 5/6 of oxygen (stored in a gaseous state in cylinders) and 1/6 of propane (stored in compressed form). Gas cannons are available in 0.8 m^3, 1.5 m^3, 3 m^3 and 4.5 m^3 versions.

The system works by radio commands. Information processing is carried out in a software package, and operators must always be in a safe place. At the same time, the program transmits information about all surface movements within a radius of more than 1000 m.

As a rule, the preventive descent of avalanches is carried out at night or early in the morning, warning in advance about the active impact on the avalanche centers so that people do not end up in the area of the avalanche.

An important feature of this system is the possibility of its operation in any weather conditions. The highest efficiency will be achieved directly during or after snowfalls since, during such periods, the density of the snow cover is reduced, and there is much air in it (Guidance Document РД 52.37.659-2004, 2004).

Currently, this system is used in almost 20 countries around the world. Russia also already has some experience with its application (Krasnaya Polyana since 2002).

The system has a number of advantages:

- environmental friendliness: the product of combustion of the gas mixture is water vapor;
- the presence of radio control, which allows the system operator not to be in avalanche-hazardous areas;
- the ability to operate in any weather conditions;
- economic feasibility of using: one shot costs less than 100 rubles (1.1 €);
- maximum technical and technological efficiency of the system since the accumulation of snow is monitored and the forced descent of avalanches is initiated.

Possible disadvantages:

- complex installation of the system;
- the need for maintenance at the installation site, which is difficult to access.

Preventive descent of avalanches from the air by the Daisy Bell system

The basis of the Daisy Bell system is the effect of an explosion of oxygen-hydrogen mixture on the snow cover. This system is a metal cone – a bell attached to the helicopter with a cable and a remote control panel. All special equipment is fixed on the cone.

Daisy Bell can complement stationary forced avalanche systems, as it can be used in hard-to-reach places. In this case, the slopes are processed precisely since the cones are installed exactly in the required zones (Guidance Document РД 52.37.771-2012, 2012).

The advantages of using such a system are:

- lack of explosive systems;
- system mobility;
- low operating and maintenance costs.

A significant disadvantage of using the Daisy Bell system is the possible danger to people on board the helicopter. Also, the use of this method of forced avalanche descent is possible only in clear and calm weather.

Avalanche control system O'Bellx

In this system, the initiation of an avalanche occurs under the action of an explosion of an oxygen-air mixture. It is controlled from an operator room, where a computer with GAZEX software is installed.

The avalanche-initiating device comprises a support that is attached to the side of the mountain and a chamber, the lower end of which is open. The camera is mounted on a support with the possibility of removal, and its open end faces the snow cover. The chamber is mounted on a perforated support element in the inner part, which receives a mixture of oxygen and hydrogen. At the same time, it is energetically autonomous, meaning that the means for storing gases and igniting a gas mixture are fixed on it. As a result, maintenance and recharging work can be moved to a more accessible location than where the device is installed.

Thanks to the design of the chamber and the support, assembly and disassembly are quick and effortless since assembly is performed by sliding the chamber onto the supporting element of the support. Thus, assembly and disassembly work is reduced to translational movements along an axis that is slightly deviated from the vertical. The device also contains a protective system that controls the operation of the means of ignition and filling with gases that are turned off when the camera is not installed on the support. This ensures the safety of its transportation.

The valves, with the help of which the gas cannons are filled with a mixture of oxygen and propane, are opened by radio command. The explosion takes place directly at the snow surface to maximize the impact on the snow cover. The O'Bellx system allows up to 40 explosions from one filling (Anti-avalanche systems, 2021).

The following advantages of using the system are highlighted:

- environmental friendliness: the product of combustion of the gas mixture is water vapor;
- the presence of radio control, which allows the system operator not to be in avalanche-hazardous areas;
- the ability to operate in any weather conditions;
- gentle impact on the ground: there is no need for a heavy foundation and a pipeline that would take up a large area.

Output

As a result of a detailed analysis of the most widely used systems of active influence on snow avalanches, it can be concluded that the fixed remote avalanche control system Gazex is most applicable in conditions of quarrying in regions with difficult meteorological and mining-geological conditions. This is due to the low cost of a shot, the absence of problems with the purchase of gases (oxygen and propane), and the ability to operate in any weather conditions.

However, all the methods considered, as we can see, have their own advantages and disadvantages; therefore, it would be more rational to introduce an individually developed set of measures for avalanche protection. In this case, the system will be difficult to install, and it will be most effective in areas with a large number of avalanche centers to reduce the length of pipelines. For isolated centers, we suggest using the O'Bellx system, which has the same principle of operation and is controlled by the same operating system as Gazex.

Variations of providing avalanche protection on the selected avalanche-prone hearth

Taking into account the mining and geological conditions of the avalanche-prone zone of the selected Russian quarry, which develops a field in a complicated mountainous area, to cover the avalanche-hazardous center of the quarry with avalanche devices, it is necessary to install either 2 gas cannons of the Gazex system or a combination of 1 gas cannon of the Gazex system and 1 O'Bellx device. It is impossible to use only O'Bellx devices since this system is an addition to the Gazex anti-avalanche system. Thanks to two devices, it is also possible to regulate the direction of the avalanche. Let's consider both options for using the equipment.

Option no. 1: installation of 2 gas cannons of the Gazex anti-avalanche system (Fig. 3). To ensure a sufficient level of avalanche protection, it is necessary to install 2 gas cannons with a volume of 0.8 m^3, the TNT equivalent of each cannon must be equal to 7 kg.

According to the declared technical characteristics of this avalanche protection system, it will provide sufficient avalanche protection in the specific conditions of a mining enterprise. The required distances for installing the devices are shown in Fig. 3.

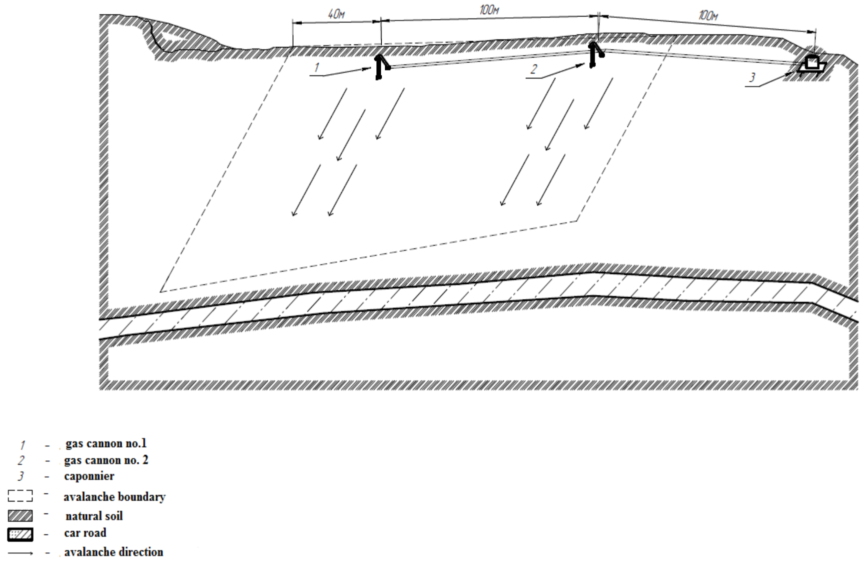

Fig. 3. Location of anti-avalanche devices of the Gazex system in an avalanche-prone area (Source: Guidance Document РД 52.37.659-2004, 2004)

Option No. 2: installation of 1 gas cannon of the Gazex avalanche anti-avalanche system and 1 O'Bellx anti-avalanche device (Fig. 4). In this case, the volume of the gas cannon should be 0.8 m^3, the TNT equivalent of which is 7 kg, and the O'Bellx device should be 5 kg of TNT equivalent.

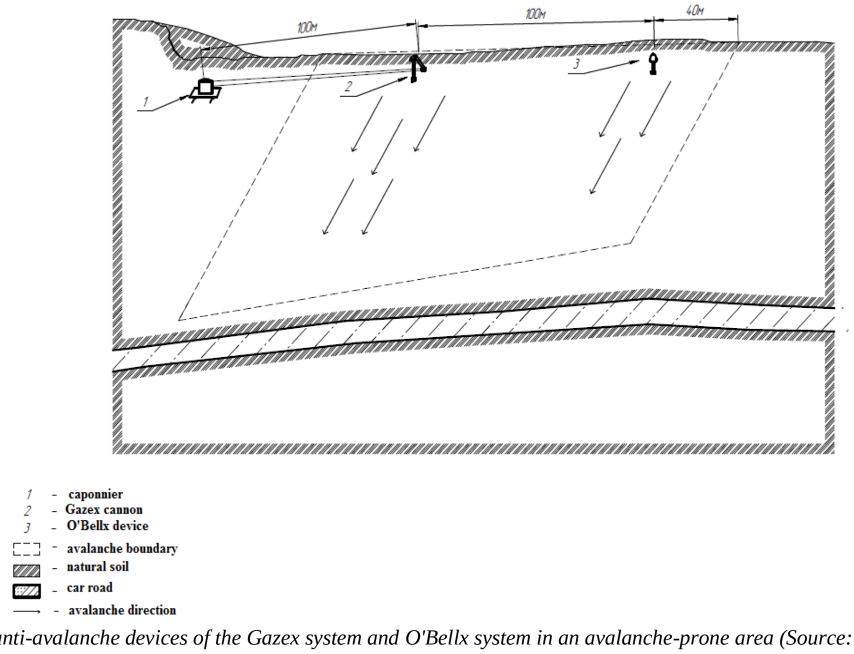

Fig. 4. Location of anti-avalanche devices of the Gazex system and O'Bellx system in an avalanche-prone area (Source: Guidance Document РД 52.37.659-2004, 2004)

This arrangement of anti-avalanche elements will also provide a sufficient level of anti-avalanche safety in accordance with the technical characteristics of anti-avalanche devices and the length of the avalanche-prone area.

Therefore, from a technical and technological point of view, both options can be applied to a specific Russian quarry.

The cost of implementing the complex

The forced anti-avalanche system can be designed in two different variations - with and without the O'Bellx system. Let's compare the estimated costs for both options. The equipment required for the implementation of only the Gazex system and its estimated cost are presented in Table 2.

Tab 2. Gazex equipment costs

№	Name	Cost, thousand rubles
1	Gazex main technological equipment	8436
	Standard gas cannons	4200
	Caponnier (command post, valves, electronic control systems, communication device, device for determining the parameters of snow cover)	3760
	Pipelines	476
2	Operators' room	190.2
	Computer and UPS	112
	Communication device	2.2
	Radio station	32
	Furniture set and additional equipment	44
3	Total	8626.2

From Table 2, the total cost of Gazex equipment will amount to 8.6 million rubles (97 thousand euros). The costs of the Gazex and O'Bellx complex are presented in Table 3.

Tab 3. Gazex and O'Bellx complex equipment costs

№	Name	Cost, thousand rubles
1	Gazex main technological equipment	4376
	Standard gas cannons	2100
	Caponnier (command post, valves, electronic control systems, communication device, device for determining the parameters of snow cover)	1880
	Pipelines	396
2	O'Bellx main technological equipment	503
	Support	113
	Chamber	390
3	Operators' room	190.2
	Computer and UPS	112
	Communication device	2.2
	Radio station	32
	Furniture set and additional equipment	44
4	Total	5069.2

From Tables 2 and 3, using a complex of two systems is an economically more profitable option since the cost of equipment in this case is just over 5 million rubles (57 thousand euros), and the benefit will be about 3.5 million rubles (39.5 thousand euros).

Discussion

It is well known that at present in Russia, the conditions for the development of deposits, both by open and underground methods, are becoming more and more complicated, which requires companies to develop modern, innovative approaches to ensure industrial safety and labor protection of employees (Kazanin, O. I., & Sidorenko, 2017; Nikulin et al., 2019). In particular, to date, Russian mining companies do not have a definite concept for protection against avalanches. However, all companies located in mountainous regions and at risk of snow accumulation on the slopes understand that they need a new, more efficient, and systematic approach to prevent avalanches. A cardinal solution to prevent damage associated with the descent of snow masses could be a ban on constructing facilities in avalanche-prone areas. However, this approach is also unacceptable due to the significant reserves of minerals located precisely in difficult mountainous regions.

It is obvious that for avalanche protection, it is not enough to carry out only an active method of influencing snow avalanches; passive methods of struggle are also required. It is also necessary to timely predict the likelihood of an avalanche (in some situations; an additional application of the standard risk-based approach is required (Gendler et al., 2017; Gendler et al., 2020; Kovshov et al., 2020), which is possible with the use of modern methods of combating avalanches.

The presence of an integrated approach will allow the company to significantly improve safety at work in mountainous regions and reduce injuries as a result of accidents associated with avalanche danger.

Conclusions

Various control systems have been described to address the avalanche problem in the current quarry. The most effective Gazex and O'Bellx were considered, and variations of their installation on the slope were proposed. Both options provide a decent level of anti-avalanche protection. However, by reducing the length of the pipelines when installing 1 gas cannon of the Gazex system and replacing the second gas cannon with the O'Bellx anti-avalanche device, the economic costs will be reduced.

The main advantage of using these devices is remote control, which completely eliminates the risk of injury to service personnel. The most effective application of the Gazex system will be in areas with many avalanche sources to reduce the length of pipelines between isolated sources. Also, for the same reason, it is necessary to additionally use the O'Bellx system, which has the same operating principle and is controlled by the same operating system as Gazex.

This set of measures will fundamentally reduce the avalanche danger in the quarry and, due to remote control, will reduce the risk to the life of explosives working in avalanche-prone areas and in any weather and circumstances.

Methods for the forced descent of avalanches using explosives were also analyzed in detail. Possible negative consequences: unforeseen avalanches during the movement of people towards an avalanche-hazardous center, which can lead to death and significant material damage.

It should be objectively noted that the anti-avalanche protection methods used in Russian conditions are not always adequate to the existing threats. In conditions of climate variability and an increase in the number of abnormally warm winters, catastrophic avalanches are more and more often recorded, which are destructive and pose a threat not only to enterprises (Tskhadaya, 2018; Korshunov et al., 2020) but also to the population, as well as ski resorts. That is why this problem will constantly arise and require a radical revision of approaches to its solution, a possible variation of which was proposed by the authors in the work.

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