An integrated approach to safety in the design and operation of open-pit mining facilities

Ekaterina Ermakova¹*, Igor Skripnik², Sergey Panov³, Tatyana Kaverzneva⁴, Olga Gorbunova⁵, and Dmitry Tsimberov⁶

¹Saint Petersburg Mining University, Saint Petersburg, Russia
²Saint Petersburg University of the State Fire Service of the Ministry of Emergency Situations of Russia, Saint Petersburg, Russia
³Saint Petersburg State University of Industrial Technologies and Design, Saint Petersburg, Russia
⁴Higher School of Technosphere Safety of Peter the Great St. Petersburg Polytechnic University, Saint Petersburg, Russia
⁵Saint Petersburg State University of Architecture and Civil Engineering, Saint Petersburg, Russia
⁶Perm Military Institute of National Guard Troops, Perm, Russia

Abstract. The article presents a pioneering integrated approach to assessing compliance with environmental, fire, industrial safety, and labor protection requirements in open-pit mining operations. The study was conducted at two existing open-pit mining facilities located in the Trans-Baikal Territory of the Russian Federation, analyzing the causes of injuries, statistical data, and comparing the mining technologies used. The key findings emphasize that the efficiency of deposit development and the safety of mining operations are heavily dependent on the quality of the technical design. The article also discusses software systems used for the design of mining facilities, which enable monitoring of the safety and labor protection aspects during quarry operation. The results of the comparative analysis are expected to be of interest to both quarry design specialists and the engineering and technical personnel of existing open-pit mining facilities. This integrated approach represents a significant advancement in the field, providing a comprehensive framework for enhancing safety and operational efficiency in the mining industry.

1 Introduction

Gold is known as one of the most sought-after precious metals. It is, first, a strategic resource of each country, as well as an investment instrument. The Russian Federation has significant reserves of gold and occupies one of the leading places in the world in its mining and production [1, 2, 3]. So, for example, in relation to the location of the gold quarries considered in the article, only in the Trans-Baikal Territory, 454 gold deposits were considered (41 of which are gold ore, 27 are complex and 386 are alluvial). Additionally, according to the strategy for the development of the region and industry, after 2035, at least 14 gold mining facilities can be put into operation [4, 5, 6]. At the same time,

* Corresponding author: 79213258397@mail.ru
because of the use of innovative methods of geophysical exploration of subsoil in undeveloped territories of the region, the number of quarries may increase several times [7, 8]. In turn, this will create additional both positive and negative aspects, since in a limited period it will be necessary to develop large packages of permitting documentation for the right to develop subsoil [9, 10]. At the same time, it will be necessary to consider environmental, fire and industrial safety issues for facilities that are just being designed and will be operated in the future. In this case, it will be necessary to take into account the requirements of a large number of regulatory legal acts (hereinafter referred to as RLA) regulating certain issues related to compliance with and ensuring the requirements of the legislation of the Russian Federation in the design, development and operation of fields at various stages over a long period of their actual operation [11, 12, 13]. It is impossible to foresee everything. Therefore, special attention is paid precisely to the development of project documentation [14, 15]. The main legal regulations of the Russian Federation, which primarily guide specialists in the field of design and conduct of mining operations, are the Russian Federation Law "On Subsoil", “Requirements for the structure and execution of project documentation for the development of deposits of solid minerals, the abandonment and conservation of mine workings and the primary processing of mineral raw materials "and other normative and legal acts of the Ministry of Natural Resources and Ecology of the Russian Federation, as well as "Requirements for the preparation, content and execution of plans and schemes for the development of mining operations and application forms for approval of plans and (or) schemes for the development of mining operations" NLA of the Federal Service for Environmental, Technological and nuclear supervision (Rostekhnadzor) (for the translator - The Federal Service for Environmental, Technological and Nuclear Supervision (Rostekhnadzor; Russian)) (similar documents are available in other countries). At the initial stage, namely the stage of developing project documentation, in our opinion, the simplest question is to write a section on compliance with environmental safety [16, 17]. This can be explained by the fact that all the initial data on the ecology of the quarry site are known, and the technologies used are also known. In the future, it will only be necessary to comply with the requirements of legislation in the field of environmental safety and carry out environmental monitoring when putting the quarry into operation [18, 19, 20]. Compliance with fire and industrial safety requirements, as well as labor protection, despite the presence of these sections in the project documentation, we believe that it will be a more difficult task in the process of conducting open-pit mining. This can be explained not only by mining, geological, aerological and other conditions changing during the development of the deposit, changing as the relief changes, but also by the human factor, the features of which cannot be 100% foreseen. Therefore, this article tries to trace the features of ensuring fire and industrial safety at existing open-pit mining sites. To be able to develop a further research strategy and maximally exclude several mining-geological, climatic and other factors, two quarries located in the Trans-Baikal Territory, 30 km from each other, were selected. The work area is classified as typical mountain taiga with mid-mountain relief. The climate of the region is sharply continental with large fluctuations in daily and seasonal temperatures.

The deposits are confined to a complex of rocks with a steep, inclined rock formation and the presence of tectonic disturbances of various orders. Ore-bearing zones can be divided into sheet-like and highly elongated lens-shaped bodies with an angle of incidence of 45-60 degrees. Minerals mined in addition to gold: copper, magnetite iron, silver and antimony. Overburden rocks are granites, limestones, siltstones, and sandstones.

The deposits discussed in this article differ significantly in their productivity: large-scale – 10,000 thousand tons of ore/year and small-scale deposit – 80 thousand tons of ore/year. The significant difference in enterprise productivity serves as an additional reason
for comparing the two deposits, since the results of the analysis can be useful for both planned and operating quarries with large and small balance reserves.

2 Problem statement

Based on the above and the data for comparison and analysis obtained during a practical study, directly at the site of mining operations, we formulated the main problem of our research. It lies in the fact that environmental safety issues can first be analyzed based on the data included in the project and then based on the results of environmental monitoring. While compliance with fire and industrial safety requirements can only be verified during the examination of the relevant section of the project, in fact we believe that identifying certain shortcomings leading to incidents and accidents of various kinds is only possible by analyzing the operation of the existing facility [2, 6]. The same applies to a greater extent to compliance with labor safety requirements by personnel involved in a gold mine [7, 10, 17]. Therefore, we believe that most issues related to ensuring the safe conduct of mining operations and the development of preventive measures need to be approached comprehensively, having studied not only the design documentation for the future mining facility, but also the available statistical data, for example, from Rostechnadzor on incidents and accidents at similar sites. objects.

3 Materials and methods

This work applies complex scientific research methods, such as theoretical and empirical methods. When applying the theoretical method, preference was given to methods of analysis and synthesis of information obtained from open sources, both for the preparation of project documentation and for the implementation of environmental monitoring. The empirical research method was based on the results of observation and comparison of the applied engineering solutions obtained directly at the site of ore mining operations.

Application software systems specialized in the field of mining operations are analyzed in detail. Moreover, some of them are used both at the stage of quarry design and during various types of monitoring, primarily monitoring the state of industrial safety during quarry operation (Table 1) [1, 12, 15].

Table 1. Software systems for designing mining facilities and ensuring industrial safety during quarry operation.

<table>
<thead>
<tr>
<th>Наименование программы</th>
<th>Основные функции программы</th>
</tr>
</thead>
<tbody>
<tr>
<td>AutoCAD</td>
<td>Design of a mining plan, calculation and modeling of drilling and blasting operations</td>
</tr>
<tr>
<td>KOMPACS 3D</td>
<td></td>
</tr>
<tr>
<td>Micromine Alastri</td>
<td></td>
</tr>
<tr>
<td>Datamine</td>
<td></td>
</tr>
<tr>
<td>Geomix</td>
<td></td>
</tr>
<tr>
<td>Blastmaker</td>
<td></td>
</tr>
<tr>
<td>ANSYS Multiphysics</td>
<td></td>
</tr>
<tr>
<td>Geo 5</td>
<td>Monitoring the condition of sides, slopes of ledges and dumps</td>
</tr>
<tr>
<td>Geostudio SLOPE/W</td>
<td></td>
</tr>
<tr>
<td>Geo-Stab</td>
<td></td>
</tr>
<tr>
<td>Rocscience Slide2/3D</td>
<td></td>
</tr>
<tr>
<td>Plaxis</td>
<td></td>
</tr>
<tr>
<td>PromRisk</td>
<td>Modeling emergency situations for each type</td>
</tr>
</tbody>
</table>
4 Results and discussion

The main results of the research work we began in the field of labor protection were data on occupational injuries and analysis of traumatic factors. In the field of fire and industrial safety, the conditions for conducting mining operations are in accordance with the design documentation and the actual technologies used for the development of gold deposits, considering the logistics of each of the quarries.

Detailed analysis of cases of industrial injuries at metal ore mining sites for 2010-2023, located directly in the Trans-Baikal Territory (Fig. 1) allows us to see that at enterprises there is no tendency to reduce the number of accidents (including fatal ones) [4, 18, 19].

Fig. 1. Indicators of industrial injuries in the mining of metal ores for 2010-2023, in the Transbaikal region. Compiled together with V.A. Rodionov.

We believe that ensuring the safety of mining operations at any open-pit mine or quarry begins with the design stage and the implementation of various types of work strictly in accordance with design decisions.

In this case, accidents, as a rule, occur due to insufficient engineering and geological justification, insufficient knowledge of the natural and climatic conditions of the work region, incorrect parameters of quarry roads and the transport used on them, etc. It is important to note that the reason for the deliberate violation of design decisions and work passports; the operation of a worn-out fleet of mining equipment is an attempt to save enterprises, and this human factor is fundamental in most accidents and accidents.

Having analyzed cases of fatal industrial injuries (Fig. 1), we found that the main traumatic factors are: collapse of rock mass, transport and improper operation of mechanisms, etc. The results of the analysis of traumatic factors are presented in more detail in Fig. 2 [19, 20].
To understand the conditions of mining and the difference in issues of ensuring fire and industrial safety, we provide some tactical and technical characteristics of each of the quarries. At the same time, we will pay more attention to industrial safety issues. This is explained by the fact that, according to the information we received, a detailed description of which is beyond the scope of this article, the difference in compliance with fire safety requirements lies only in the significant difference in the circulating explosive and fire hazardous substances and materials, primarily fuel for equipment used in quarries, as well as the fact that the share of accidents due to explosion/fire accounts for less than 3% of their total number. The first deposit, according to the requirements of the Russian Federation regulations, is large-scale and belongs to hazard class II. The second deposit, small-scale, is classified as hazard class III. At the same time, both quarries use a transport development system with external dumping.

In the practice of quarry design, it is always necessary to determine the optimal value of the bench height. This is determined by a feasibility study and is explained by profitability. In our case, in the first quarry (large-scale), the height of the ledge is 8 m, and in the second - 5 m.

Drilling and blasting operations at the fields under consideration are carried out by contractors. The feasibility of keeping explosives directly in developed quarries, as well as equipment for drilling and blasting operations, is determined to a greater extent by the productivity of the quarry [8].

Loading operations in quarries are carried out mainly by excavators. When developing a small-scale gold deposit, hydraulic straight shovel excavators with a small-volume bucket capacity are used as the main excavation and loading equipment for stripping and mining operations. On a large scale - hydraulic backhoe excavators with large-volume buckets, as well as a front-end loader.

Dumping is carried out by bulldozers. Along with the stability of quarry sides, dump slopes must be monitored to avoid collapse. Summarized data on the technology used and type of work are given in Table 2.

Fig. 2. Distribution of fatal injury cases by traumatic factors. Compiled together with V.A. Rodionov.
Table 2. The results of a comparative analysis of field parameters depending on the type of work.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Large-scale deposit</th>
<th>Small-scale deposit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drilling and blasting operations</td>
<td>Contracting organization</td>
<td>Diesel hydraulic &quot;straight shovel&quot; excavators with a bucket capacity of 1.8 m³.</td>
</tr>
<tr>
<td>Excavation and loading works</td>
<td>Diesel hydraulic “backhoe” excavators with a bucket capacity of 4.5; 12 and 22 m³.</td>
<td>Diesel hydraulic &quot;straight shovel&quot; excavators with a bucket capacity of 1.8 m³.</td>
</tr>
<tr>
<td></td>
<td>Front loader with a bucket capacity of 12 m³.</td>
<td></td>
</tr>
<tr>
<td>Transportation of rock mass</td>
<td>Dump trucks with a carrying capacity of 40, 90 and 180 tons.</td>
<td>Dump trucks with a carrying capacity of 20 tons.</td>
</tr>
<tr>
<td>Dumping</td>
<td>Bulldozers with blade capacities of 8, 17 and 22 m³.</td>
<td>Bulldozers with a blade capacity of 4.5 m³.</td>
</tr>
<tr>
<td>Mining operating mode</td>
<td>Shift duration – 11 hours;</td>
<td>Shift duration – 12 hours;</td>
</tr>
<tr>
<td></td>
<td>Number of work shifts per day – 2;</td>
<td>Number of work shifts per day – 2;</td>
</tr>
<tr>
<td></td>
<td>The working week is continuous;</td>
<td>The working week is continuous;</td>
</tr>
<tr>
<td></td>
<td>The number of working days is 365 days.</td>
<td>Number of working days – 250 days.</td>
</tr>
</tbody>
</table>

Minimizing the impact of harmful and dangerous factors on facility personnel is ensured, among other things, by properly selected ventilation schemes. However, as our analysis showed, for the first deposit, when the quarry bowl is deepened, natural ventilation will not be enough.

Considering the different mining technologies adopted at the sites (in terms of logistics), we propose to carry out an explosion/fire risk assessment to ensure fire safety during the operation of quarries. It is based on zoning the quarry space according to the most dangerous explosion and fire hazardous areas, and the location of the necessary and sufficient fire extinguishing forces and means must be determined, which, if necessary, can be used by members of auxiliary mine rescue teams.

Widespread implementation with personnel training of applied software systems for design, including those that allow for three-dimensional modeling, will make it possible to calculate the most optimal parameters for safe mining operations. In addition, we believe that the use of software systems during the operation of the quarry will allow maintaining the level of industrial safety at the enterprise at a sufficiently high level.

5 Conclusion

Considering the information provided above and acknowledging the current literature and ongoing research in this domain, we advocate for a comprehensive approach to enhancing environmental, fire, and industrial safety, along with labor protection in mineral resource enterprises. To ensure the effective development of deposits, it is imperative to delve into statistical data and draw insights from the operational experiences of comparable enterprises. This strategic analysis will pave the way for elevating safety standards and optimizing operational practices within the mineral resource sector. The selected (best) engineering solutions should be tried with reason and applied (implemented) directly at your enterprise. In this case, one should rely not only on the successful experience of companies, but also consider negative experience in order not to repeat, and, if possible,
completely eliminate mistakes that lead to incidents and accidents. In addition, we consider it necessary and appropriate to typify the functionality and wider distribution of application software systems that allow for 3D modeling of both designed and existing mining facilities to respond more quickly to certain changes in the situation that could lead to an accident of one kind or another.

References