ISSN 2411-3336; e-ISSN 2541-9404

JOURNAL OF MINING INSTITUTE
Zapiski Gornogo instituta
Journal homepage: pmi.spmi.ru

Review article
Geotechnical Engineering and Engineering Geology

Problems of monitoring stored mining waste in cold climatic zones: possibilities of using geophysical methods

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How to cite this article: Yurkevich N.V., Eponeshnikova L.Yu., Gureev V.N., Mazov N.A. Problems of monitoring stored mining waste in cold climatic zones: possibilities of using geophysical methods. Journal of Mining Institute. 2026. Vol. 278, p. 163-180.

Abstract
The stored waste from mining, mainly represented by tailings dumps and landfills, needs constant monitoring. On the one hand, they often pose a danger to the environment and people, on the other, with the development of new technologies, they are considered as a source of recycling and extraction of valuable components. In cold climatic zones, waste storage, stable storage facilities, and the organization of a monitoring system have a number of special features. Negative temperatures, freezing and thawing cycles lead both to increased release of potentially toxic substances outside landfills and tailings dumps, and to a violation of the integrity of enclosing structures. The problem is compounded by global warming, which leads to greater mobility of the upper layers due to thawing of frozen ground. The problems of monitoring in cold zones are caused by the high cost of its implementation due to the remoteness of the territories and the difficulties of working during the winter period. In such conditions, geophysical observation methods become promising, since they do not violate the integrity of the studied objects and provide an autonomous energy-saving mode for a long time. The article discusses the possibilities and features of using geophysical technologies for monitoring stored mining waste in cold climatic zones. Examples of study in Russia, Canada, the Nordic countries of Europe and other countries with similar climatic conditions are used.

Keywords
tailings dump; monitoring; permafrost; geoelectrics; electrical resistivity tomography; ground penetrating radar; seismic exploration; seismic tomography; magnetometric methods; X-ray tomography

Funding
The research was performed according to the State assignment of IGM SB RAS (N 122041400237-8).

Received: 11.03.2025 ***Accepted: 09.12.2025*** ***Online: 06.03.2026*** ***Published: 12.05.2026***

Introduction

With the growing public demand for mineral resources, the mining industry is demonstrating a rapid pace of development around the world. One of the negative consequences of mining operations is a large volume of waste – untreated overburden rocks, sulfide-containing waste rock after ore processing, tailings of flotation and cyanidation, waste from sand washing during gold and diamond mining. Waste is usually stored in landfills and tailings dumps. Landfills, as a rule, are poorly recyclable and often undergo reclamation. Tailings dumps, on the contrary, are characterized by a significant content of potentially recyclable elements, often represented by fine particles [1]. A special type includes underwater tailings dumps, which are considered promising because they free up surface space for other purposes and are less susceptible to oxidation due to anaerobic conditions. In cold climates, this

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type is used in Norway, where, due to the rugged terrain, the possibilities of organizing onshore tailings dumps are limited [2], whereas in the USA and Canada it is currently prohibited [3, 4], but has been used in the past [5].

The potential for re-extraction of individual elements often leads to a decision on conservation rather than reclamation of tailings dumps. Depending on the type of pollutants, tailings dumps can be divided into leachable, acidic, cyanide, radioactive, flammable, and containing organic substances [6]. A separate problem is represented by tailings dumps in territories with a long history of ore mining. For such locations, there is often no documentation with mining schemes, which makes it difficult to determine the exact boundaries of the storage facilities or their location itself [7]. A similar situation is observed in regions with predatory mining. In both cases, waste disposal was carried out without compliance with regulations and modern technologies, which is why these types of stored waste require careful monitoring [5].

The negative impact of stored mining waste is characterized by a wide range of harmful effects on the atmosphere, hydrosphere, relief, flora and fauna. It is caused by high concentrations of pollutants for the natural background, which can react with each other and with environmental elements, increasing toxicity. It is not uncommon for chemicals used in processing to be present in the tailings. The penetration of pollutants into the environment is facilitated by mobile forms of trace elements – active agents – due to their ability to pass from solid phases into solutions, where they acquire a bioavailable form [8]. During the transition to the liquid phase, easily soluble and easily oxidized forms of potentially toxic substances demonstrate greater mobility and can penetrate into surface waters, underlying horizons and flow on the territory, spreading radioactive elements, metals, and traces of organic substances [9]. The resulting technogenic waters can manifest themselves in the form of both small watercourses and large watersheds, and act for tens to hundreds of years [10].

Acidic filtrates formed in tailings as a result of weathering pose a special environmental danger. Mining companies are required to prevent their release into the environment [11], despite the fact that the costs of recultivating acidic waste can be many times higher than the costs of recultivating waste of other types. Acid drainage is characterized by a high concentration of sulfate ions and metals and is caused by the interaction of sulfide minerals with water and oxygen [12]. Oxidative leaching of potentially toxic compounds can be neutralized under certain conditions, depending on the content of carbonate minerals in the waste. The neutralization potential is realized at balanced rates of sulfide oxidation and carbonate dissolution [13].

The intensity of oxidation of sulfide minerals, the subsequent release and mobilization of potentially toxic components, primarily heavy metals, the physical and mechanical properties of waste, and the stability of enclosing dams are significantly influenced by the hydrological regime caused by precipitation, surface runoff, evaporation, and pure infiltration [1, 14].

Thus, taking into account the negative effects of stored waste on nature and humans, on the one hand, and their economic potential, on the other, long-term regular monitoring of both the waste itself and the enclosing structures becomes important, necessary for a full understanding of the mechanisms of behavior of stored materials in adverse climatic conditions [15]. Mining waste in areas with a cold climate has pronounced features, and its monitoring is often hampered by weather factors and remoteness, which increases the cost of work. Due to the low degree of study of the issue noted by experts [16-19], it is relevant to study the experience of the northern regions of Russia and other countries with similar climate.

Materials and methods

Papers from 2019-2024 indexed in the bibliographic databases Scopus and eLibrary were used in the article. The search queries were presented by three groups of terms; at least one term from each group was presented jointly in the title, abstract, and keywords:

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• geophysical methods – geophysics, electromagnetic methods, transient method, ground penetrating radar, electromagnetic survey, electrical resistivity tomography, micro-electrical resistivity tomography, seismics, seismotomography, seismic exploration, reflected wave method, refracted wave method, noise interferometry, seismostatic sounding, magnetometry, X-ray tomography;

• stored waste – dumps, tailings dumps, stored waste, waste from mining and ore production;

• cold climatic conditions – cold climate, harsh climate, sharply continental climate, cold climatic zones, permafrost, the Arctic.

Filters were applied by document type – original and review articles; by language – Russian and English; by country – Russia, USA, Canada, Sweden, Finland, Norway, Denmark. According to these criteria, 288 sources were selected. The article includes the most relevant studies, selected based on the results of visual examination of abstracts and article-by-article references.

Results and discussion

Climatic risk factors in keeping stored mining waste. The study of stored waste in cold climatic zones involves, on the one hand, an analysis of the mechanisms of the impact of severe weather conditions on the state and behavior of tailings, and, on the other, the impact of tailings on the environment of these territories. Understanding this bidirectional process is the key to minimizing the damage caused by waste, ensuring the sustainability of technogenic structures and the possibility of recycling tailings.

In the territories of cold climatic zones with low average annual temperatures, there are reduced reactivity of components of stored mining waste with a low rate of chemical and biological reactions [6, 18]. The acid-neutralizing potential often prevails over the acid-producing potential due to limited oxygen access. The absence of water infiltration leads to a slow migration of pollutants. However, under the influence of large seasonal changes in soil and air temperatures, freeze – thaw cycles, precipitation, and permafrost evolution, stored waste can change its mineralogical composition, geochemical, and geophysical properties. Therefore, it is possible to increase the mobility of pollutants and accelerate their release from storage facilities. When studying the effect of tailings on the environment of cold territories, the low capacity of soil profiles, higher fragility and long periods of ecosystem restoration should be taken into account [8].

Low rock and air temperatures do not completely prevent the processes of waste hypergenic transformation, and the removal of potentially toxic substances into the environment is recorded year-round [20]. At below-zero temperatures, as a result of cryogenic processes, there is an increased content of potentially toxic elements in technogenic waters. For example, high acidity was detected in the tailings dumps of tin sulfide deposits in Primorsky Krai at negative temperatures [10]. Similar results were obtained in Canadian sulfide tailings dumps in the province of Quebec, where high rates of oxidation of sulfide minerals were detected in early test cycles [13].

The influence of temperatures on leaching is characterized by the fact that variations in the solubility of compounds of various elements are caused, among other things, by the temperature regime. It was shown at Canadian flotation tailings dumps in Quebec that low temperatures led to an increase in the concentration of Ba, Sr, Ca, Na, Cl^-, NO_3^-, and SO_4^{2-} in pore solutions due to the cracking of large particles [6]. A high degree of binding in cryosystems by fractions of fine dust and silt of Zn, Ni, Cr, Cu, Pb, As was found at the tailings dumps of the Yakutsk Nyurbinsky diamond mining and processing plant [8]. In addition, mobile forms of trace elements accumulated mainly in the upper layer, followed by a decrease in depth, or accumulated in the permafrost layer, which is a geochemical barrier.

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During the cold period, from the end of October to the beginning of May – the average tailings temperature is 0 °C or lower. It is set during several consecutive days with a negative air temperature and does not undergo major changes until the beginning of the thaw. Thus, although air temperature fluctuations can be significant, there is no significant daily relationship between air temperature and rock in winter.

Several factors influence the maintenance of tailings temperature during the cold period. One of them is the upward heat transfer from the zone of exothermic oxidation of sulfides at a depth inside the tailings dumps, where the temperature is always higher regardless of the season. During this period, the volume moisture of the rock drops to zero. Another factor is the snow cover and thickness of the snow cover, which explains the general low fluctuations in tailings temperature and its significant contrast with the air temperature, which can reach several tens of degrees (which is confirmed by observations of permafrost areas in Antarctica [21]). Abundant snow cover provides rapid downward heat flows, while thin snow cover leads to surface freezing. The thick snow cover explains the seemingly paradoxical general decrease in tailings temperature by the end of winter, despite increasing solar radiation and rising air temperatures, as shown by the example of tailings dams in Quebec [15].

The effect of *freeze – thaw cycles* on tailings is more pronounced and complex in comparison with the effect of low temperatures. These cycles are seasonal, not diurnal. Although a more pronounced daily dependence of air temperature and the surface layer of tailings dumps is recorded in summer [22], and night frosts are often observed in summer, they are not enough to start the freezing process. The temperature of the surface layer shows a greater dependence on the air temperature, while the deeper layers correlate with the average 48-hour air temperature [15]. Pronounced changes in temperature and water content in response to freeze – thaw cycles can cover layers up to 2 m deep [22].

The main effect of seasonal freeze – thaw cycles is their effect on hydrological processes. With thawing (usually in late April – early May), a rapid and sharp increase in the water content in the tailings is recorded with an increase in volume humidity to values close to saturation. The volume of snow becomes an important factor: when melting in areas with thick snow cover, water flows are more abundant, and in areas with thin snow, frozen soil prevents water from seeping into the underground layers [23]. In certain territories of cold climatic zones, melting snow is the main source of water in the tailings [24]. Rain also contributes to tailings saturation, and with the end of the summer season, effects associated with a drop in solar radiation levels leading to a decrease in evaporation are noted [24].

In turn, hydrological processes are directly involved in the release of potentially toxic substances into the environment [15, 22]. If during freezing, dissolved solids are released from the ice front and concentrated in the remaining unfrozen water, then during melting, dissolved pollutants escape from the meltwater, reducing the stability of the tailings dumps. In particular, during the spring thawing, a high degree of leaching of potentially toxic substances was detected [11, 24]. The connection of cycles with increased mobility of metals in tailings dumps is also confirmed [18].

In addition to the concentration of metals in the ice front during freezing and their subsequent leaching during thawing of frozen soils, the formation of oxygen supply routes is noted, which accelerates the oxidation of waste matter. The access of oxygen and water flows into the deep layers of tailings, as well as the mobility of pollutants, is restrained by a low-reactivity upper solidified layer with a thickness of several millimeters to several centimeters. These effects are provided by the low porosity and hydraulic conductivity of solid horizons [25, 26]. Freeze – thaw cycles can lead to their erosion and decrease in strength [26]. As a result, the formed barrier between the two horizons of the tailings dumps is disturbed, which increases the water saturation of the tailings, leading to an increase in oxidation and weathering.

A promising method of reducing the acidity of tailings dumps is the capture, injection and subsequent storage of carbon dioxide in tailings dumps. The prospects of mineralization of CO_2

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released during mining processes along the way of carbonate deposition are noted. This reduces the penetration of oxygen into the environment and prevents the oxidation of sulfides. There are two ways of carbon mineralization – *in situ*, in which pure CO_2 is pumped into a tailings dump to form carbonate minerals, and *ex situ*, in which mining or industrial waste is used as a carbon sink. The method has been tested at nickel mining tailings dumps in Finland [27] and in Quebec, Canada [28].

The dependence of the geochemical behavior of tailings on low temperatures and seasonal cycles of freezing and thawing is described using the example of flotation tailings dumps in Quebec, where the potential for extracting REM (rare earth metals) from tailings was studied [6]. The carbonate nature of the tailings with a high neutralizing potential relative to the acidity potential led to a low level of drainage acidity. At the same time, increased leachability of Cd, Pb, and Zn and the formation of solutions with their concentrations exceeding the natural background was revealed. The dependence of element leaching on seasonal cycles is shown by the example of high-sulfide waste from the Ursky tailings dump facility in the Kemerovo Region [20].

When considering the effects of freeze – thaw cycles, it is important to assess the role of microorganisms, including microscopic fungi, which make a significant contribution to oxidative processes, the formation of sulfuric acid, and the extraction of metals into the solution. Their effect on the formation and transfer of mobile forms of elements was evaluated in the storage tanks of polymetallic ores in Primorsky Krai, where microorganisms showed an increase in abundance over a wide temperature range [29].

Thus, the cyclical nature of processes, which has a multifactorial effect on the composition and structure of waste, and the stability of storage sides, should be taken into account when designing and constructing stable tailings dumps, and during reclamation work, as shown by the example of designing insulating coatings with the effect of a capillary barrier for nickel ore tailings in Quebec, Canada [12].

The influence of *warming* is another factor that must be taken into account to ensure the stable behavior of stored waste. The analysis of the effects of warming in cold areas is especially relevant, since it is there that the average temperature increases significantly faster than in other climatic zones [30]. According to permafrost monitoring data in Europe under the PACE (Permafrost and Climate in Europe) program, permafrost could warm up to depths of 50 m over the past 25 years [31]. The average permafrost temperature has increased by 0.4 °C over the past 100 years [23]. The greatest temperature changes were recorded near the Earth's surface, increasing the shift frequency. The area of the active layer, for example in the Alps and Svalbard, increased from 10 to 200 %, with maximum growth in the most remote and coldest territories.

The main and closely interrelated risk factors caused by warming and permafrost evolution include an increase in the area of the active layer; shift of the active layer, affecting the stability of technogenic structures with stored waste; formation of technogenic taliks; leakage of technogenic waters; increased mobility of potentially toxic substances and their accelerated release into the environment; impact on global carbon cycle [14, 32].

An increase in average temperatures leads to thawing of cryogenic soil, as a result of which a permafrost transition environment is formed, where areas of previously permanently frozen soil become non-frost, affecting microbial and soil processes, hydrology, flora and fauna. The activity and mobility of pollutants increases, which accelerates their release into the environment [17]. The release of potentially toxic substances is also accelerated due to the increased hydraulic conductivity of the soil. The effect of snowmelt in such locations can reach a depth of 10 m, and the more intense interaction of surface and groundwater leads to a change in their composition [23].

Another consequence of warming is a decrease in stability and a violation of the integrity of rocks and stored waste from mining and processing plants caused by landslides, rockfalls, subsidence, seepage and leakage of circulating water through the sides and beds of dams [14, 17, 33]. This can

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lead to major accidents and environmental disasters with significant economic, environmental and social damage in the short term (from several hours to several months) and in the long term (from several years to several centuries).

Climatic risk factors in the storage and maintenance of stored waste need to be permanently monitored. Monitoring makes it possible to determine the characteristics of stored waste in cold climatic zones and record the changes that occur, and provides an opportunity to identify potential pollutants. Due to this, it becomes feasible to develop an adequate management strategy for their disposal, conservation, recycling or reclamation. With the development of technology, the transition of monitoring studies to an automatic mode is becoming more relevant [4, 18], preferably with public access to its results [5, 34]. In addition, if monitoring of surface, underground runoff, wind drift or evaporation requires field work using geochemical and geotechnical methods, then a number of tasks can be solved in remote automatic and autonomous modes using geophysical approaches. Geophysical methods are indispensable in delineating the body of a technogenic system, estimating total waste volumes, determining underground drainage migration routes, identifying zones of active oxidation of sulfide minerals, and determining the integrity and stability of storage sides. The use of geophysical methods makes it possible to optimize the geochemical sampling scheme in an express mode, reduce the total number of observation points and focus on areas requiring the most control, which in turn leads to cost savings and improved accuracy of results.

Geophysical methods for monitoring stored mining waste. Geophysical methods that allow determining the physical properties of soils are mainly used in mineral exploration [7]. Recently, due to advances in computer technology and data processing, they have been increasingly used in a wide range of interdisciplinary research [35], including those related to technogenic systems. In cold climatic zones, geophysical methods are rarely used in relation to mining waste storage facilities [14, 23], and there is insufficient data representation in global monitoring networks in areas of permafrost [32]. In addition, geophysical methods demonstrate advantages over other approaches, including aerial photogrammetry, visual monitoring, geochemical analysis, or drilling [14, 36-38].

Visual examination of tailings and enclosing structures does not provide information about internal processes, and drilling wells for monitoring in cold climates involves additional costs, locality of application, and leads to disruption of fragile northern ecosystems. Non-invasive geophysical approaches involve carrying out work without violating the ground cover and the integrity of the object, they enable to cover larger areas, and obtain data from great depths [39]. In addition, the geophysical equipment allows conducting research in an autonomous and economical mode, which reduces time and financial costs.

Groups of electromagnetic and seismic methods are particularly promising for determining the physical characteristics of tailings. Magnetometric, nuclear, and X-ray tomography methods are also promising for monitoring tasks. The main tasks solved by geophysical methods include the following:

• *Planning of efficient tailings placement* with assessment of natural landscapes for storage. An urgent task is to ensure the long-term stability of tailings and enclosing structures, which takes into account stratigraphic information, data on the location of groundwater and drinking water horizons, the seismicity of the region and the features of the relief.

• *Assessment of the zonality and internal structure of the stored waste,* where the volume of waste and the degree of its heterogeneity are determined. This concerns tailings located in relief depressions or open quarries, direct access to which is difficult, as well as tailings left after predatory processing, or old tailings dumps for which there is no documentation [7]. Solving the mapping problem is important for assessing the possibility of re-extracting minerals from stored

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waste, which is relevant when developing new methods for extracting and enriching mineral resources.

• *Assessment of the condition and behavior of tailings.* Geophysical methods make it possible to determine the migration directions of acid drainage streams, the degree of contamination of soil and hydrological horizons with harmful substances, and thus identify dangerous internal changes in time even before they appear on the surface [40-42]. To ensure stability, permanent analysis of the temperature of permafrost soils is used, which can be provided by geophysical methods that are effective in any temperature conditions. In particular, at near-zero temperatures, the analysis of soil warming and cooling is largely influenced by latent thermal effects associated with "water – ice" phase transitions, whereas geophysical methods make it possible to assess spatial and temporal changes in soil properties under these conditions [43].

• *Organization of continuous and autonomous data acquisition in the process of geophysical monitoring,* which is ensured by low energy consumption and control of geophysical equipment via satellite communication, which allows optimizing the frequency of measurements and making other adjustments [32]. As a result, researchers have the opportunity to study waste and enclosing structures in dynamics and monitor the dependence of their state on external conditions in real time [31, 32, 37, 44]. Dynamic assessment is carried out both at the microlevel of daily changes, and at longer seasonal and annual distances. Studies of tailings in dynamics in a cold climate are of particular importance, since harsh environmental conditions can significantly affect the parameters being measured. The spatiotemporal variability of frozen tailings can often be investigated exclusively by geophysical methods.

Electromagnetic methods (electrical exploration). The study of stored mining waste by electrical exploration methods began in the 1990-2000s, which have now become the most common monitoring methods. They are based on an assessment of the dependence of the electromagnetic properties of the geological environment on humidity, mineral composition, temperature, pressure, porosity, chemical composition of water and some other parameters [42, 43]. Electrical resistivity or its inverse, electrical conductivity, takes into account particle conductivity (applicable for materials containing metals), surface conductivity (for distinguishing minerals, ice, and water), and electrolytic conductivity (associated with liquids and applicable for porosity and saturation control) [38, 43].

When determining the zonation, the electrical resistivity assessment makes it possible to clearly identify the boundaries of tailings reservoirs with higher electrical conductivity than their neighboring rocks. The definition of the internal structure is based on the difference in the resistance of coarse and small waste, where it declines with decreasing fraction sizes. In cold climatic zones, electrical exploration makes it possible to effectively separate frozen and thawed rocks. Upon freezing, the electrical resistivity of rocks can significantly increase, since frozen gravitational water becomes practically an insulator, and electrical conductivity is determined only by loosely bound unfrozen water near the surface of mineral particles. The increase in electrical resistivity during freezing of different rocks varies: in rocks it increases by no more than 10 times, in fine-grained loose rocks (clays, loams) – by 10-100 times, in coarse-grained (sands, gravel-pebble deposits) – up to 1000 or more times [37].

The advantages of using electrical exploration methods in the study of stored ore mining and processing waste include optimizing the sampling scheme to determine their chemical composition and promptly collecting information to assess the volume of technogenic deposits and mapping the filtration area of drainage solutions [45]. The results of electrical exploration studies are geoelectric sections, which are interpreted at a qualitative level with some predictive estimates of the localization of horizons of highly mineralized pore solutions. Attempts are being made to clearly outline the oxidation zones of sulfide-containing minerals in the waste.

The data obtained by the authors in previous studies indicate that with the same water saturation and lithological structure, sulfide-containing wastes from different zones have electrical conductivity

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that differs by an order of magnitude [46]. The results of the application of electrical exploration methods in combination with geochemical approaches in the study of stored mining waste made it possible to localize areas with relatively high electrical resistivity with high concentrations of sulfide minerals of iron and arsenic, which, when in contact with groundwater and atmospheric waters, become sources of acidic highly mineralized solutions [45]. Understanding the mechanisms of migration and deposition of chemical elements inside the waste body and their removal outside the technogenic system will be clearer with the correct interpretation of electrical exploration data. This requires accurate knowledge of the nature of the electrical conductivity of waste, the contribution of the conductivity of the mineral core and pore formation to it, which will enable to predict the development of the technogenic system based on geophysical data. In addition, the use of electrical exploration methods can be useful for identifying horizons accumulating metals, the so-called geochemical barriers [46].

Such methods of electrical exploration as electrical resistivity tomography, ground penetrating radar, frequency electromagnetic sensing, electrical resistivity tomography by the method of induced polarization, etc. are often used in monitoring. Depending on the conditions of the field sites, a combination of two or more methods may be used. When interpreting the electrical exploration data, it is possible to obtain an estimate of the thickness of technogenic deposits, a description of the geoelectric zone, localization of drainage water filtration areas or accumulation of sulfide minerals [7, 19].

Transient electromagnetic sensing method (TEM) is based on the study of the transient process field excited in the subsurface when the current in the source is pulsed. The method is characterized by the absence of galvanic grounding, the possibility of use in winter, and is well adapted to areas in cold climates due to the lack of shielding from the frozen horizon. It is suitable for detecting thawed rocks characterized by low electric resistivity against the background of frozen soils, in which low temperature is a distinctive feature with the same humidity, lithology, and mineralization of pore moisture. The method was used to assess the stability of a tailings dump in conditions of thawing of permafrost soils at one of the Siberian diamond mining companies [14]. The fault zones along which the tailings dump was drained were investigated, the type of their fracturing and filtration properties was revealed. The results obtained are promising for planning antifiltration measures.

Ground penetrating radar (GPR), is based on the emission and registration of high-frequency radio waves that pass through a layer of dams and tailings and are reflected from various geological structures. Ground penetrating radar is effective for mapping underground structures and identifying areas of high humidity, and also provides qualitative results on the structural integrity of the sealing layer in mining waste [47]. The method is preferred for the analysis of near-surface structures (1-2 m) [47]. In territories of cold climatic zones, it can be used to determine the depth (up to 15-30 m) of permafrost rocks, isolate taliks with moisture analysis of the zone-thawed layer, analyze the thickness of vegetation and snow cover, monitor the permafrost roof, but is not applicable for the analysis of clay, silty and saline soils [7, 37]. The advantage of the GPR method on a flat surface is its ease of handling, although reliable measurement is more difficult to implement on steep ledges.

Ground penetrating radar is of interest for the research of mining waste in the territories of cold climatic zones. In particular, the method was used on the island of Svalbard to record spatial and temporal changes in the state of permafrost rocks in different seasons and to identify the groundwater level [48]. The use of GPR for research of stored waste is reflected in the work on the analysis of the properties of waste dumps during gold mining in Yakutia [49]. The sounding was carried out in winter and summer with an assessment of the dump layers up to 8 m deep. The characteristics of the wave fields were used to detect morphostructural inhomogeneities in the structure of landfills, to conduct spatial

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analysis to determine the boundaries of layers of various waste, cryogenic structures. The presence of metallic inclusions, boulder sites, and high humidity zones was determined. Uncontaminated soils were characterized by smooth GPR paths with even time delays and signals with uniform amplitude, unlike landfills. The pebble layer on the radiogram is manifested by a large number of hyperbolas, and the zones of increased humidity are continuous axes of common mode formed by high-amplitude reflected signals.

At the tailings dump of a mining plant in the Murmansk Region, GPR was used to assess the degree of deformation and leakage [36]. The analysis of the electromagnetic wave velocity made it possible to identify the zonal filtration heterogeneity of the soils, to categorize them, to determine the water-saturated soils and to clarify the structure of the enclosing dam. The sounding was carried out annually in the fall period, the depth of the sounding reached 30 m when using shielded antennas with a signal frequency of 100 MHz. The reduced speeds of electromagnetic waves indicated the presence of moist soils, while denser and drier soils were found beneath them, characterized by increased wave speeds. The systematic monitoring made it possible to track the process of dam degradation over time.

Ground penetrating radar was used at the tailings dump of a copper-tungsten mine in Sweden, where it made it possible to determine the groundwater level and obtain data on the vertical and lateral distribution of tailings [50].

Electromagnetic survey (ES) allows obtaining information about the electromagnetic properties of the medium at the same depth at each point of the profile. For this purpose, constant or little-changing distances between the supply or receiving lines are selected, as well as the studied frequencies or transition times. As a result of the interpretation of ES materials, areas abnormal in electromagnetic properties are identified.

For the first time, the method of ES was applied by the authors at the initial stages of research of a technogenic object to identify areas with contrasting environmental resistances and plan the location of electrical resistivity tomography profiles in the waste storage of the Komsomolsk gold mining plant (Kemerovo Region) [40]. Later, at the dumps of the Beloklyuchevsky gold deposit (Kemerovo Region), a technique was developed for the combined use of ES and flat geochemical surveying to localize zones of maximum accumulation of tailings material with increased concentrations of metals.

Within the framework of the Finnish Program for the detection and monitoring of polluted waters in mines, the effectiveness of the ES method was investigated. The approach was used to monitor the territory of the tailings storage facility. It has been shown that the zones of change in electrical conductivity correlate well with the results of direct sampling of electrolyte from groundwater. The monitoring also helped in the placement of new water intake pipes [51].

Electrical resistivity tomography (ERT) / *Electrical resistivity imaging* (ERI) is the main method of geophysical measurements for the study of near-surface structures due to its simplicity and fast results [44]. The method is a combination of electrical sensing and profiling and allows obtaining two-dimensional and three-dimensional geoelectric structure of the medium. The essence of the measurement method is the repeated use of the same electrodes located on the observation profile as feeding and measuring electrodes. The separation of the installation (the distance between the receiving and feeding electrodes) affects the depth of the study and the resolution. The details of the method are described in many papers and are often accompanied by open source software [32, 44].

The monitoring takes into account the relationship between electrical resistivity and physico-chemical, petrophysical parameters and chemical composition unique to each tailings dump: salinity and acidity of pore water, humidity, temperature, granulometric composition, texture, porosity, permeability, degree of fracturing. Visualization of the results is most often performed in the form of a 2D section, although more and more complex, including four-dimensional, models have recently appeared [33].

Electrical resistivity tomography is most applicable to the study of objects in harsh climatic conditions due to the possibility of autonomous configuration, which reduces the cost of work [32, 37]. When assessing the prospects of using the method for monitoring, it is important to take into account the

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results of general geophysical research in the territories of cold climatic zones, where the impact of climatic conditions on underground processes is studied.

Since the degradation of ice and frozen rocks can pose a threat to the stability of waste storage facilities, it is important to assess the boundaries, thickness and lateral continuity of the frozen area, as well as changes in the thickness of the surface layer of melting. Long-term electrotomographic studies are of interest, which have revealed an increase in the volume of unfrozen water over the past 20 years in European territories of cold climatic zones, where a general decrease in electrical resistivity was recorded over the analyzed period [31, 43].

In monitoring tailings dumps, ERT provides high-quality results, since most tailings are electrically conductive relative to loose sediments or bedrock in the depressions of which they are located [44]. Electrical resistivity tomography can solve the following problems:

• determination of geometry, boundaries and lithological structure of tailings dumps, morphology of waste and bedrock contact, detection of potentially fractured zones in the underlying rocks;

• tailings volume estimation and localization of oxidation zones;

• identification of migration routes of drainage solutions and their volume.

Dynamic analysis, in addition to identifying seepage paths, makes it possible to estimate its rate and enables recording reactions occurring in the tailings associated with changes in external conditions. Research conducted by institutes of the Siberian Branch of the Russian Academy of Sciences is among the leaders in the study of stored waste from mining and processing of ores. The first work, consisting in probing a technogenic object by ERT, constructing two-dimensional geoelectric sections and predicting the spread of underground drainage, was carried out at the waste storage facility of the Belovsky zinc plant (Kemerovo Region) and continued at the storage facilities of the Dukov Log Salair mining and processing plant (Kemerovo Region) [41] and waste from the Karabash copper smelter in the valley Sakelga River (Chelyabinsk Region) [45]. Work on clarifying the interrelationships of electrophysical, petrophysical and geochemical parameters of the medium continued in 2016, and methods of micro-ERT, dynamic (time-lapse) ERT were developed to study the processes occurring in the "tailings – pore solution – gas" system, and to describe hypercryogenesis [19, 52]. The cooperation of specialists in the field of geochemistry and geophysics led to the development of hardware and methodological support and the formation of the concept of an integrated study of technogenic systems [46, 53].

The high efficiency of ERT in the study of several uncultivated landfills in Siberia and the Far East is shown in [7], where the uniformity of the distribution of electrical resistivity for stored waste was revealed, which made it possible to detect untreated and intact areas with abnormally high resistance in their upper part. Electrical resistivity tomography was used at the Finnish tailings dump, where it made it possible to identify the stratigraphic profile of the tailing dump area with further determination of facies, delineate the groundwater level, show the flow paths of highly mineralized underground drainage and distinguish between saturated and unsaturated zones [54].

Time-lapse electrical resistivity tomography (TL-ERT) is an actively developing subspecies of ERT and is applicable to various types of geophysical monitoring – hydrogeothermal, geotechnical, and environmental. Each TL-ERT monitoring survey is described by two groups of parameters: spatial parameters include the length, depth of the study and spatial resolution, and temporal parameters include the monitoring period and temporal resolution. A detailed review of the use of the method with an emphasis on the analysis of stored waste was carried out on the rich material of Canadian mining companies [38]. In recent years, TL-ERT has been used in the study of stored waste from the Salair deposit (Kemerovo Region) in the territories of cold climatic zones. It was shown how the daily temperature fluctuations of the air and then of the soil are interconnected with the intensity of gas generation and variations in the values of the electrical resistivity [9]. The daily and seasonal variations of the electrical conductivity of the mineralized pore solution are shown,

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and gas concentrations in the near-surface air layer are revealed depending on changes in environmental parameters. Electrical resistivity changes during the day can reach 8 %, while they will vary in different parts of the tailings dumps depending on the humidity and granulometric composition of the waste substance.

Micro-electrical resistivity tomography (micro-ERT) is another subspecies of ERT, which makes it possible to determine the state of the subsurface space and establish a correlation between the electrophysical parameters and the structure of the studied technogenic deposits. Its features are the small distance between the electrodes (30 cm) in comparison with conventional measurements and the possibility of detailing the geoelectric section in 15 cm depth increments. Micro-ERT made it possible to identify geochemical barriers and localize zones of active hypercryogenesis at the waste storage facility of the Darasunsky ore cluster (Transbaikalia Region) [19].

Spectral induced polarization (SIP) is an improved type of alternating current ERT, which, in addition to electrical resistivity, records the phase shift between the introduced current and the measured signal. The phase signal differs in different fractions of the tailings, for example, with an increase in the metal content, the phase effect also rises. This shift provides information about the concentrations of dispersed ore minerals. It can be used to quantify the volumes of stored waste, determine their exact boundaries [47], and establish the presence of gold sulfide mineralization zones [7]. The method has the potential to characterize stag dump in the case of ore minerals in the waste. The details of the method in relation to the assessment of frozen rocks and ice are revealed in the paper [55].

Seismic methods. Seismic methods applied to the study of stored waste in the territories of cold climatic zones are used less often than electromagnetic methods. However, they can provide a lot of useful information, especially for assessing the stability of fencing structures in mining companies. The collection of seismic data is becoming relevant even in non-seismic regions, as mining operations themselves become sources of seismic events due to stress redistribution and balance disturbances in various layers of the geomedium during ore extraction. These events can disrupt the integrity of the tailings and their enclosures and contribute to the release of pollutants into the environment.

Seismic survey is based on the study of the propagation features of elastic seismic waves in rocks. Caused by an artificial source, elastic vibrations propagate in the thickness of the Earth's crust. There, they undergo reflection and refraction at boundaries with different elastic properties and partially return to the daytime surface, where they are recorded by seismic equipment.

The propagation velocities of seismic waves in various rocks can vary widely. This is explained by the fact that a large number of geological and physical factors affect the elastic properties of rocks: density, porosity, type of pore fluid, fracturing, depth of occurrence, reservoir pressure, age, and rock temperature.

Reflected, refracted, refractive, diffracted, and other waves can form at the boundaries of layers where elastic properties change, and when they are recorded on the Earth's surface, information about the velocity profile can be obtained and the geological structure can be judged from it. In seismic exploration, there are two main methods – reflected and refracted waves. Methods using other types of waves are less widely used.

Reflection seismic survey is based on the use of waves reflected from the boundaries of media with different acoustic rigidity. The condition for the formation of a reflected wave is the difference in acoustic rigidity (the product of density and velocity) from above and below the interface.

Many metal deposits have sufficient contrasts of physical properties, in particular density, so they can be detected using seismic methods. The reflected wave 3D seismic survey method has been successfully used in Sweden at the Bletberget mine to search for deposits of iron oxide and its host rocks [56]. The work demonstrated the applicability of the method to determining the boundaries of technogenic deposits for one of the old tailings dumps.

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Refraction seismic survey is a suitable seismic survey method for the study of stored waste. The method uses refracted waves formed at a velocity difference between the top and bottom of the interface. Thus, the refraction seismic survey will work effectively in the case of high contrast between the two layers and is well suited for determining the groundwater level, mapping the permafrost roof, and describing the internal structure of tailings storage facilities. The method makes it possible to effectively detect higher-density underlying soil from the tailing medium, and is suitable for delineating zones of drainage stream migration routes and searching for potential breaches in dams.

In the territories of cold climatic zones, the refraction seismic survey was used in Finland for subsequent stratigraphic and facies analysis of tailings dumps. The refraction seismic survey helped to assess the depths of the underlying soil and bedrock in the area of the tailings dump and determine its geometry. Further interpretation of the results obtained, together with ERT data, made it possible to segment the tailings storage area into identifiable zones or facies, and to estimate the groundwater level [54].

Seismic tomography (ST) determines the continuous 2D and 3D distribution of seismic properties of the medium based on data on the travel times of elastic waves [57]. The method has proven itself positively in regional and global seismology, where it is widely used to obtain velocity models of the Earth's crust and mantle. During seismic surveys, the method is used to build a high-speed model of the upper part of the section, where the presence of high-speed layers of permafrost rocks may be a complicating factor [58].

Seismic tomography demonstrates promising application in cold climatic zones, as seismic properties change during the freeze – thaw cycles. The method makes it possible to measure the seismic wave velocities, which will differ for frozen and unfrozen soils [59]. Velocity changes in the rock glacier and permafrost mainly depend on the porosity of precipitation and its saturation with air, ice, or water, and therefore are more pronounced in coarse-grained soils. There is an increase in the velocities of *P*-waves in the direction from the active layer of the rock glacier to the permafrost zones.

During the analyzed period, there was no data on the use of ST in the study of stored waste, however, in the territories of cold climatic zones, the method was used in the PACE network to analyze the degradation of permafrost soils in the Alps and in Norway [31]. Seismic tomography was also used to quantify the content of underground ice and permafrost thickness in the high-altitude regions of the Central Andes [39, 59]. Thus, the effectiveness of using the method in locations with a harsh climate indicates the prospects for its use in relation to stored waste from mining industries.

Ambient noise interferometry (ANI) is a seismic monitoring method for volcanoes, landslides, and dams, rarely used to analyze stored waste. The method is based on the detection of seismic waves from the cross-correlation of seismic noise [60]. The construction of the seismic noise cross-correlation function makes it possible to restore the Green's function between two seismic stations, with one of the stations acting as a virtual wave source and the other as a receiver. The method does not require high computing power and can be used for efficient data processing with constant monitoring. In the study of stored waste, noise interferometry can be useful for the extraction of volumetric transverse waves. The speed of propagation of transverse waves is interrelated with the rigidity of the soil and can be used to evaluate other geotechnical parameters, such as stress state, liquefaction resistance, and degree of cementation. Thus, this approach is applicable to the detection of potential causes of destruction of enclosing structures.

Standard ANI processing was used to monitor a tailings dump in Northern Canada, where seismic velocity changes of less than 1 % showed a strong correlation with changes in the water level in adjoining tailings dumps, and a link was also established with precipitation during the observation period [60]. Passive seismic interferometry was used to estimate seismic velocities in the area of the

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tailings dumps and in the surface rocks at mining sites in Finland [61]. The results made it possible to clarify the structure of the tailings, their physical and geotechnical state. The potential of noise interferometry for notifications about potential problem areas is presented by setting a threshold level of response based on zone fluctuations.

Seismic cone penetration test (SCPT) is aimed at measuring the pressure of pore water and the velocity of seismic waves. The analysis of the wave velocity distribution depending on the depth of the profile makes it possible to identify soil zones with varying degrees of saturation. Therefore, seismostatic sounding is well suited both for assessing the degree of liquefaction of stored waste in order to prevent it, and for analyzing the stability of enclosing structures [60]. It can also be used to assess the water regime of tailings, the distribution of pore pressure of water and saturation. The method was used in the study of tailings dumps for flotation processing of copper ore in Poland [62].

Magnetometric methods (magnetic exploration) are based on measuring the Earth's magnetic field and its variations. The values of the measured parameters are influenced by the intensity of magnetization of geological formations due to different magnetic properties of rocks (anomalous field). Magnetic exploration is often carried out in conjunction with one or more electrical exploration methods. Although no information has been found on the use of magnetometric methods in the territories of cold climatic zones, nevertheless, the technique seems promising for these territories, since it is actively used to study landfills and assess the risk of heavy metal contamination in deposits.

In [63], an example of long-term exploitation of an ore deposit in Poland was considered, which led to the formation of about 60 million t of waste. Acid drainage processes have developed in the vicinity of the tailings dump as a result of soil and groundwater contamination. It was proposed to use a set of geophysical methods to monitor the processes in tailings dumps: shallow-depth magnetometric survey, ERT and ES. Electrical exploration methods enabled to identify the spread of pollution zones around the tailings area. Magnetometry has proved to be a good tool for detecting environments contaminated with unstable metal-containing minerals, making it possible to determine the range of dust distribution from a tailings dump.

Accidents related to the leakage of filtrate from tailings dumps cause serious environmental pollution. In China [64], the use of aeromagnetic imaging was considered to clarify information about the leakage of filtrate from a tailings dump. As a result of the aeromagnetic survey, four fault zones formed around the tailings dump. One of the faults served as a channel for leaking filtrate, which led to it getting into the groundwater through a network of cracks. The technique helped to identify the mechanism of migration of filtrate from the tailings dump and analyze the sources of pollution of the aquatic environment.

Another rare method is based on the magnetoresistive effect, which is a change in the electrical resistance of a material in a magnetic field (Magnetometric resistivity method, MMR). Although this effect has already been well studied, it has not yet found wide application in geophysics, especially in Russia. The MMR approach consists of introducing a current of a known magnitude and frequency into the ground and detecting the components of the induced magnetic field using magnetic sensors on the surface. In the field of hydrogeophysics, the method has found application for detecting the mechanisms of transport of dissolved substances at shallow depths and groundwater contamination. MMR is used to identify and map the flow paths of groundwater. The conductivity of groundwater flow paths is much higher than the background conductivity due to their high mineralization. For example, in China, this method was used to identify leakage paths in the area of earth mounds to reduce the risk of instability of their structures [65].

X-ray tomography enables to examine the core using X-ray radiation. It is based on differences in the density of rock, mineral inclusions, voids, cracks, and reservoir fluids filling them. The output images are grayscale images, the brightness of which characterizes the degree of absorption of X-ray

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radiation. Then, a three-dimensional volumetric model of the sample is reconstructed, which makes it possible to judge the structure of the rock matrix and the distribution of pore channels. The practical application of this method is quite rare in the study of tailings dumps.

In cold climates, X-ray tomography was used to analyze the hardened layers of one of the sulfide tailings dumps in the Canadian province of Quebec [25]. The porosity of the hardened layers was examined using an X-ray microscope, which confirmed the immobilization of pollutants.

Nuclear methods. Nuclear geophysics combines physical methods of prospecting and exploration of radioactive ores based on their natural radioactivity (radiometry) and element-by-element analysis of rocks by studying induced radioactivity (nuclear geophysical methods). Nuclear methods are rarely used, but they have prospects for studying tailings dumps in cold climatic zones. In Norway, radiation methods were used to track the process of Mn and Zn leaching from titanium ore, Cu mining tailings, and Zn-Pb mining tailings [66]. A technique of neutron activation analysis was proposed to determine the concentrations of elements in a sample. It was found that Zn leaching increases with increasing leaching time. Mn leaching increases with time, HCl concentration, and temperature rise.

In Russia, there was no information about the use of the method in the cold climate zone during the analyzed period. However, it was used in the Stavropol Krai, where the radiation situation at the dumps of the Almaz mine N 1 for the extraction and processing of uranium ores was studied five years after the reclamation [67]. The radiometry method was used to monitor the gamma radiation power after tunnel recultivation. Radiometry is based on the different radioactivity of ores and rocks, as well as on the migration of radioactive elements and decay products in groundwater and subsurface air. Of all the types of radioactive radiation, gamma-quanta have the greatest penetrating power, so gamma-ray imaging methods are mainly used. These methods are designed to study the intensity of natural gamma radiation. The radiometry method can be used to monitor the state of landfills after extraction of radioactive ore.

Conclusion

Systematic monitoring using a wide range of geophysical equipment and approaches remains the basic tool in the management of mining waste storages. The results of geophysical research contribute to solving a variety of tasks, including assessing the risk of waste, ensuring the stability of enclosing structures, and exploring the possibilities of reclamation or reuse of such facilities. The main problems and limitations of using geophysical methods to study the waste in areas with a sharply continental climate are low temperatures (–40 °C and below) that disable electronics in equipment, seasonal cycles of freezing and thawing of sulfide-containing tailings lead to intense oxidation of matter and metal leaching, remoteness of objects. The lack of infrastructure and the short field season (3-4 months) make it difficult to organize work. The main geophysical methods used to study mining waste storage facilities production in cold climates:

- electromagnetic sensing by transient processes, GPR, ES, ERT, time-lapse-ERT, micro-ERT, SIP;
- seismic – refracted wave method, refracted wave method, ST, ANI, seismostatic sounding;
- magnetometric;
- X-ray tomography;
- nuclear geophysics.

Advantages of using geophysical methods in the study of stored waste from mining and processing ores:

- rapid collection of information to assess the boundaries of technogenic deposits;

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• optimization of the geochemical monitoring system, including by reducing the number of sampling points;

• waste volume assessment;

• mapping the filtration area of underground drainage solutions;

• localization of leakages of filtrates and groundwater pollution.

The prospects for the development of geophysical methods are associated with the development of integrated approaches based on methods of electrical exploration, seismic tomography, aerial photography with verification by geochemical testing for the study of stored mining waste. They will eventually lead to an increase in the accuracy of interpretation of geoelectric and structural models of technogenic objects and will enable to solve new urgent tasks. These include the search for geochemical barriers-metal concentrators, the delineation of oxidation zones of sulfide minerals, the localization of areas of degradation of permafrost rocks due to the underground acid drainage, the determination of the seasonal dynamics of a technogenic body with the determination of the total amount of heat generated and the volumes of greenhouse and sulfur-containing gases.

Limitations and prospects of the study. Despite the extensive possibilities of using geophysical methods for monitoring stored mining waste demonstrated in the work, which are largely confirmed by the actual practice of their application, difficulties arise when trying to rank among the identified approaches themselves and identify the most promising among them. This is largely due to the frequent unavailability of information on the methods used, plans for their modernization, integration or replacement, due to the commercial nature of these data and the existing competition in the mining industry. In addition, technological innovations, besides journal articles and conference proceedings, are often reflected in such specific types of documents as reports and patents that were not covered in the current work. The inclusion of these additional data sources in the subsequent analysis, together with a study of government programs in the field of ecology and the mining industry, may provide an opportunity to quantify the prospects for the application of certain geophysical methods and their needs in Russia.

It is important to note that the use of geophysical methods in the future can significantly reduce the cost of monitoring stored mining waste, in particular in comparison with drilling observation wells for the same purposes. However, already at the stage of choosing specific geophysical methods, it is necessary to take into account the financial costs of carrying out different types of work, which can also be a significant indicator in assessing the prospects of using a particular method in the future. For example, a number of factors, such as the high cost of equipment, labor intensity, complexity of logistics and data processing, make seismic exploration more financially costly than, electromagnetic work. This circumstance can be a significant argument in favor of the preference for electromagnetic research, which is reflected in a large number of modern scientific papers. In any case, the final choice of method depends on the research objectives, the required depth, geological conditions, and the required accuracy, as well as an economic assessment of the feasibility of using the method in each specific case.

Based on the information from scientific sources, it can be concluded that further development of geophysical methods for studying mining waste storage facilities in Russia may be associated with the development of mobile complexes for electrical exploration. They should be adapted to temperatures up to –50 °C, using drones with hyperspectral cameras, integrating remote sensing data (Landsat, Sentinel) with field geochemical samples, the introduction of artificial intelligence algorithms for processing geophysical data. For successful research of technogenic systems in cold conditions, the adaptation of methods to local climate features and an interdisciplinary approach are critically important.

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The authors declare no conflict of interests.

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