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ECONOMIC AND INSTITUTIONAL MECHANISMS FOR ENVIRONMENTAL RISK MANAGEMENT OF TAILINGS STORAGE FACILITIES

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Abstract

Tailings storage facilities (TSFs) are among the most hazardous anthropogenic structures associated with the mining industry due to their potential long-term impacts on surface water, groundwater, soil resources, ecosystems, and public health. Despite significant technological advances in the design, construction, and operation of tailings facilities, numerous environmental accidents continue to occur worldwide, demonstrating that engineering solutions alone are insufficient without effective economic and institutional management mechanisms. The objective of this study is to analyze the economic and institutional instruments used for environmental risk management of tailings storage facilities, evaluate their effectiveness, and identify opportunities for improving environmental safety. Particular attention is given to the application of the Polluter Pays Principle and the User Pays Principle, environmental charges and penalties, financial assurance mechanisms, as well as monitoring and regulatory control systems. The analysis indicates that the safe and sustainable operation of tailings facilities requires the integration of engineering, economic, and governance measures within a comprehensive risk management framework. The study concludes that strengthening financial accountability, improving environmental monitoring systems, and enhancing institutional oversight can significantly reduce environmental risks associated with tailings storage facilities and contribute to the long-term sustainability of mining activities.

***Keywords*:** tailings storage facility, environmental risk, mining industry, pollution control, Polluter Pays Principle, financial assurance, environmental monitoring, institutional governance.

Introduction

Mining is one of the strategic sectors of the global economy, providing essential raw materials for industry, energy production, construction, and high-technology development. At

the same time, the extraction and processing of mineral resources generate significant quantities of waste, among which tailings and tailings storage facilities (TSFs) represent some of the most hazardous components of mining activities [1–3].

Tailings storage facilities are complex hydraulic and geotechnical systems designed for the containment of solid and semi-liquid wastes generated during mineral processing. One of their key characteristics is their ability to exert environmental impacts not only during operation but also for decades or even centuries after mine closure [3,4]. Heavy metals, sulfide compounds, and other hazardous constituents contained in tailings may migrate into the environment, causing contamination of surface water, groundwater, soils, and ecosystems [3].

Over recent decades, numerous major tailings dam failures have occurred worldwide, resulting in significant environmental, social, and economic consequences. These incidents have demonstrated that even under conditions of advanced engineering design and operational practices, tailings safety remains one of the most critical challenges facing the mining industry. International experience further indicates that risks associated with tailings facilities are determined not only by technical factors but also by the effectiveness of management systems, environmental oversight, and financial accountability mechanisms [2–4].

Water resource contamination is considered one of the most sensitive environmental issues associated with tailings storage facilities. Acid mine drainage and metal-rich effluents generated by mining activities can significantly deteriorate water quality and restrict the availability of water resources for human and ecological use [3,5]. Consequently, international environmental policy increasingly relies on economic regulatory instruments based on the Polluter Pays Principle and the User Pays Principle [5].

Economic regulatory mechanisms include pollution charges, environmental penalties, financial assurance systems, insurance instruments, and other economic incentives designed to reduce adverse environmental impacts and ensure the availability of financial resources for environmental restoration and remediation. However, the effective implementation of these instruments requires reliable monitoring systems, environmental supervision, and efficient institutional governance structures [5].

In the Republic of Armenia, mining constitutes an important sector of the national economy, and several large tailings storage facilities are currently in operation. Therefore, the implementation of effective environmental risk management systems for tailings facilities is essential for both environmental protection and the sustainable development of the mining sector. In this context, economic and institutional mechanisms capable of preventing, mitigating, and controlling tailings-related environmental risks acquire particular significance.

Literature Review

The safe management of tailings storage facilities has become one of the most important and widely studied topics in the mining sector during recent decades. Most research has focused on structural safety, causes of failures, environmental impacts, and risk management approaches associated with tailings facilities [3, 13–15, 19, 20].

Studies on the environmental impacts of tailings facilities indicate that mineral processing residues may contain heavy metals, sulfide compounds, and other hazardous substances capable of exerting long-term effects on surface water, groundwater, soils, and ecosystems [3,15]. Research conducted by Golik and co-authors demonstrated that the

environmental influence of tailings facilities often extends far beyond their immediate boundaries due to the migration of contaminants through aquatic environments [3].

The investigation of tailings dam failures and their consequences occupies a prominent place in international scientific literature. Studies by Rico and co-authors revealed that tailings dam failures are primarily associated with design deficiencies, hydrological factors, operational violations, and management shortcomings [13,14]. Similar conclusions were reached by Lin and co-authors, who analyzed tailings dam failures across different regions of the world and found that, in addition to technical causes, governance and regulatory deficiencies play a significant role in accident occurrence [19]. The study conducted by Lyu and co-authors further confirmed that tailings dam failures are generally caused by multiple interacting factors, including engineering, organizational, and management-related components [25].

Particular attention has been devoted in recent years to the Mariana (Fundão) and Brumadinho tailings dam disasters in Brazil, which are considered among the largest technological and environmental disasters in the history of the mining industry [16–18]. Investigations of these events demonstrated that even the application of advanced engineering solutions cannot guarantee environmental safety in the absence of effective governance systems, monitoring mechanisms, and accountability frameworks [16–18].

Research aimed at improving the technical safety of tailings facilities has emphasized the application of innovative materials and technologies. Avanesyan demonstrated that the use of polymer-mineral materials can improve the protective characteristics of tailings facilities, reduce filtration losses, and enhance operational reliability [2]. Nevertheless, several authors have emphasized that technical solutions alone cannot completely eliminate environmental risks unless they are accompanied by effective economic and institutional management systems [6,15,20].

International standards and guidelines play a significant role in contemporary tailings management practices. The Global Industry Standard on Tailings Management (GISTM) represents the most comprehensive international framework for tailings governance, emphasizing risk assessment, transparency, stakeholder engagement, accountability, and long-term responsibility throughout the entire life cycle of tailings facilities [6]. Similarly, the guidelines developed by UNECE and ICMM highlight the importance of safety culture, continuous monitoring, emergency preparedness, and preventive risk management measures [8,21]. The literature concerning economic regulatory mechanisms is largely based on the Polluter Pays Principle and the User Pays Principle [10,11]. OECD documents identify these principles as fundamental economic instruments of environmental governance aimed at internalizing environmental costs within production processes and natural resource utilization activities [10,11]. Studies conducted by Tokmajyan, Markosyan, and Simonyan demonstrated that environmental charges, penalties, and other economic instruments can function effectively only when supported by reliable monitoring and enforcement systems [5].

Recent years have also witnessed increasing attention toward financial accountability and financial assurance mechanisms. Studies conducted by the World Bank and the International Institute for Sustainable Development (IISD) indicate that environmental insurance, reclamation funds, financial guarantees, and closure assurance instruments constitute essential components of modern tailings governance. These mechanisms help ensure the

availability of sufficient financial resources for mine closure, land reclamation, environmental remediation, and long-term post-closure management activities [22–24].

The literature review demonstrates that the majority of existing studies focus either on the technical safety of tailings facilities or on the assessment of their environmental impacts. Comparatively few studies examine economic and institutional mechanisms for environmental risk management as an integrated system. In particular, limited attention has been devoted to the interconnected assessment of financial accountability, environmental charges, monitoring systems, regulatory oversight, and governance effectiveness within a unified conceptual framework.

Consequently, there remains a significant need for an integrated approach that combines engineering safety, economic regulation, financial responsibility, and institutional governance within a single environmental risk management framework for tailings storage facilities.

Addressing this scientific gap constitutes the primary objective of the present study.

Conflict Setting

Despite substantial investments in engineering safety improvements, environmental incidents associated with tailings facilities continue to occur worldwide, indicating that technical measures alone are insufficient for ensuring long-term environmental protection. As mining activities continue to expand, environmental risks associated with tailings storage facilities are also increasing. Numerous cases of water, soil, and ecosystem contamination continue to be reported in different countries despite advances in tailings design, construction, and operational technologies.

At the same time, international literature remains primarily focused on engineering and geotechnical aspects of tailings safety, whereas comparatively limited attention has been devoted to economic and institutional mechanisms of environmental risk management. Existing governance systems often fail to provide adequate prevention of environmental impacts, effective compensation for environmental damage, and reliable long-term monitoring of tailings-related risks.

Consequently, a contradiction emerges between the continuous improvement of technical safety measures and the persistent occurrence of environmental impacts associated with tailings storage facilities. This contradiction highlights the need for a more comprehensive approach that integrates engineering solutions with economic regulatory instruments, financial responsibility mechanisms, and institutional governance frameworks.

The objective of this study is to investigate the economic and institutional mechanisms for environmental risk management of tailings storage facilities, analyze international experience in their application, and identify opportunities for improving environmental safety within the context of mining activities.

Research Results

Economic Instruments for Environmental Risk Management of Tailings Storage Facilities

The analysis of international experience demonstrates that economic instruments constitute one of the principal mechanisms for reducing environmental risks associated with

tailings storage facilities. Unlike purely technical measures, economic instruments influence the behavior of mining operators by creating financial incentives for pollution prevention, environmental protection, and long-term responsibility.

Among the most widely applied economic mechanisms are environmental charges, pollution fees, environmental taxes, financial assurance systems, reclamation funds, environmental insurance schemes, and compensation mechanisms. These instruments are generally based on the Polluter Pays Principle (PPP) and the User Pays Principle (UPP), which seek to internalize environmental costs into mining activities and ensure that environmental damage is not transferred to society.

The Polluter Pays Principle requires mining operators to bear financial responsibility for environmental impacts resulting from their activities. In the context of tailings management, this principle is implemented through environmental charges, penalties for regulatory violations, compensation payments, and mandatory remediation obligations. International experience indicates that properly designed pollution charges encourage companies to invest in safer technologies and environmental protection measures, thereby reducing the probability of environmental accidents.

The User Pays Principle complements the Polluter Pays Principle by ensuring that the costs associated with the use of natural resources are incorporated into operational expenditures. This mechanism contributes to more efficient resource utilization and supports the generation of financial resources necessary for environmental monitoring, reclamation, and post-closure management activities.

A growing number of countries have introduced financial assurance mechanisms requiring mining companies to provide financial guarantees prior to project implementation. These guarantees may take the form of reclamation bonds, trust funds, bank guarantees, environmental insurance, or other financial instruments. Their primary objective is to ensure the availability of sufficient financial resources for mine closure, rehabilitation, and environmental restoration regardless of the future financial condition of the mining operator.

The analysis indicates that economic instruments are most effective when implemented as part of an integrated environmental governance framework. Pollution charges alone are often insufficient to prevent environmental damage unless accompanied by effective monitoring systems, transparent reporting procedures, regulatory enforcement, and institutional accountability mechanisms. Consequently, economic instruments should be considered not as independent tools but as components of a broader environmental risk management system.

Institutional Mechanisms for Environmental Risk Management of Tailings Storage Facilities

Institutional governance mechanisms play a crucial role in ensuring the environmental safety of tailings storage facilities. International experience demonstrates that even the most comprehensive systems of environmental charges and financial responsibility cannot effectively manage tailings-related risks in the absence of reliable governance, monitoring, and regulatory oversight mechanisms.

The institutional governance framework encompasses the activities of regulatory authorities, environmental monitoring systems, inspection and enforcement mechanisms, emergency preparedness programs, as well as instruments that ensure stakeholder participation

and transparency. The integrated functioning of these components enables not only the response to environmental problems after they occur but also the prevention of potential risks at an early stage.

Environmental monitoring represents one of the most important institutional instruments in tailings management. Monitoring systems are designed to continuously assess the structural condition of tailings facilities, water quality, groundwater levels, soil contamination, and other environmental indicators. Modern international standards increasingly require real-time data collection and analysis, enabling the early detection of hazardous trends and the prevention of potential accidents.

Regulatory oversight constitutes another fundamental element of institutional governance. Government authorities are responsible for supervising the design, construction, operation, and closure of tailings storage facilities. International studies indicate that a significant proportion of tailings-related incidents are associated not only with technical deficiencies but also with inadequate regulatory control, weak enforcement, and insufficient compliance with environmental requirements. Consequently, the effectiveness of regulatory oversight directly influences the level of environmental risk.

In recent years, increasing attention has been devoted to stakeholder participation and transparency. International organizations and professional associations emphasize that information regarding tailings management should be accessible to local communities, non-governmental organizations, and other interested stakeholders. Enhanced transparency contributes to stronger public oversight, increased trust, and earlier identification of potential environmental risks.

Particular importance is also attached to the management of mine closure and post-closure periods. Numerous studies have demonstrated that environmental risks associated with tailings facilities often persist long after mining activities have ceased. For this reason, contemporary institutional approaches require long-term monitoring programs, clearly defined post-closure responsibilities, and organizational mechanisms capable of ensuring environmental protection for decades following mine closure.

The analysis indicates that the effectiveness of institutional mechanisms largely determines the overall success of environmental risk management in tailings storage facilities. Even facilities characterized by advanced engineering design and adequate financial resources may become sources of environmental hazards if effective monitoring, regulatory oversight, accountability, and stakeholder engagement mechanisms are absent. Therefore, institutional governance systems should be regarded as a fundamental component of environmental safety and sustainable tailings management.

Integrated Framework for Environmental Risk Management of Tailings Storage Facilities

The analysis of international experience indicates that neither economic instruments nor institutional mechanisms alone are sufficient to ensure an adequate level of environmental safety in tailings storage facilities. Economic instruments provide financial incentives for environmental protection and responsibility, while institutional mechanisms establish the governance structures necessary for monitoring, enforcement, and accountability.

Consequently, effective environmental risk management requires the integration of these mechanisms into a unified framework.

The proposed integrated framework is based on four interconnected pillars: economic responsibility, financial assurance, institutional governance, and environmental monitoring. The interaction among these pillars creates a comprehensive system capable of preventing environmental impacts, minimizing risks, and ensuring long-term environmental protection throughout the entire life cycle of a tailings storage facility.

The first pillar, economic responsibility, is founded on the Polluter Pays Principle and the User Pays Principle. Through environmental charges, penalties, compensation payments, and resource-use fees, mining operators are encouraged to reduce environmental impacts and invest in safer technologies and management practices.

The second pillar consists of financial assurance mechanisms designed to guarantee the availability of financial resources for mine closure, reclamation, environmental remediation, and post-closure monitoring. Financial guarantees, environmental insurance, reclamation bonds, and dedicated rehabilitation funds reduce the risk of transferring environmental liabilities to governments or local communities.

The third pillar is institutional governance, which includes regulatory oversight, compliance control, emergency preparedness, stakeholder engagement, and transparency mechanisms. Effective governance ensures that environmental requirements are properly implemented and continuously monitored throughout project development and operation.

The fourth pillar is environmental monitoring. Continuous monitoring of water quality, groundwater conditions, soil contamination, structural stability, and ecological indicators enables the early detection of environmental threats and supports timely corrective actions. Modern digital monitoring technologies further enhance the effectiveness of risk management systems by providing real-time information for decision-making.

The proposed framework emphasizes that environmental safety cannot be achieved through isolated measures. Instead, sustainable tailings management requires the simultaneous application of economic incentives, financial guarantees, institutional oversight, and environmental monitoring. The integration of these components strengthens environmental governance, reduces the probability of environmental accidents, and improves the long-term sustainability of mining activities.

The results of the analysis suggest that the implementation of integrated environmental risk management frameworks can significantly improve the environmental performance of tailings storage facilities and contribute to achieving higher standards of environmental protection and sustainable resource development.

A tailings facility operator should not be treated only as an ordinary taxpayer. In addition to standard tax obligations, the operator should finance the environmental costs required to prevent, monitor, control, and remediate both current and future risks generated by tailings storage activities. In this context, environmental responsibility should be understood not as a single payment or penalty, but as a structured system of financial obligations covering monitoring, insurance, reclamation, emergency response, and damage compensation.

Based on the analysis conducted in this study, a conceptual environmental responsibility model for tailings storage facility operators is proposed (Fig.). Unlike the conventional

approach, which primarily relies on taxes, royalties, and permit fees, the proposed model extends financial responsibility to include environmental monitoring, environmental insurance, emergency preparedness, reclamation activities, post-closure management, and environmental damage compensation. This approach seeks to ensure that both current and future environmental costs associated with tailings storage facilities are borne by the operator rather than transferred to society or future generations.

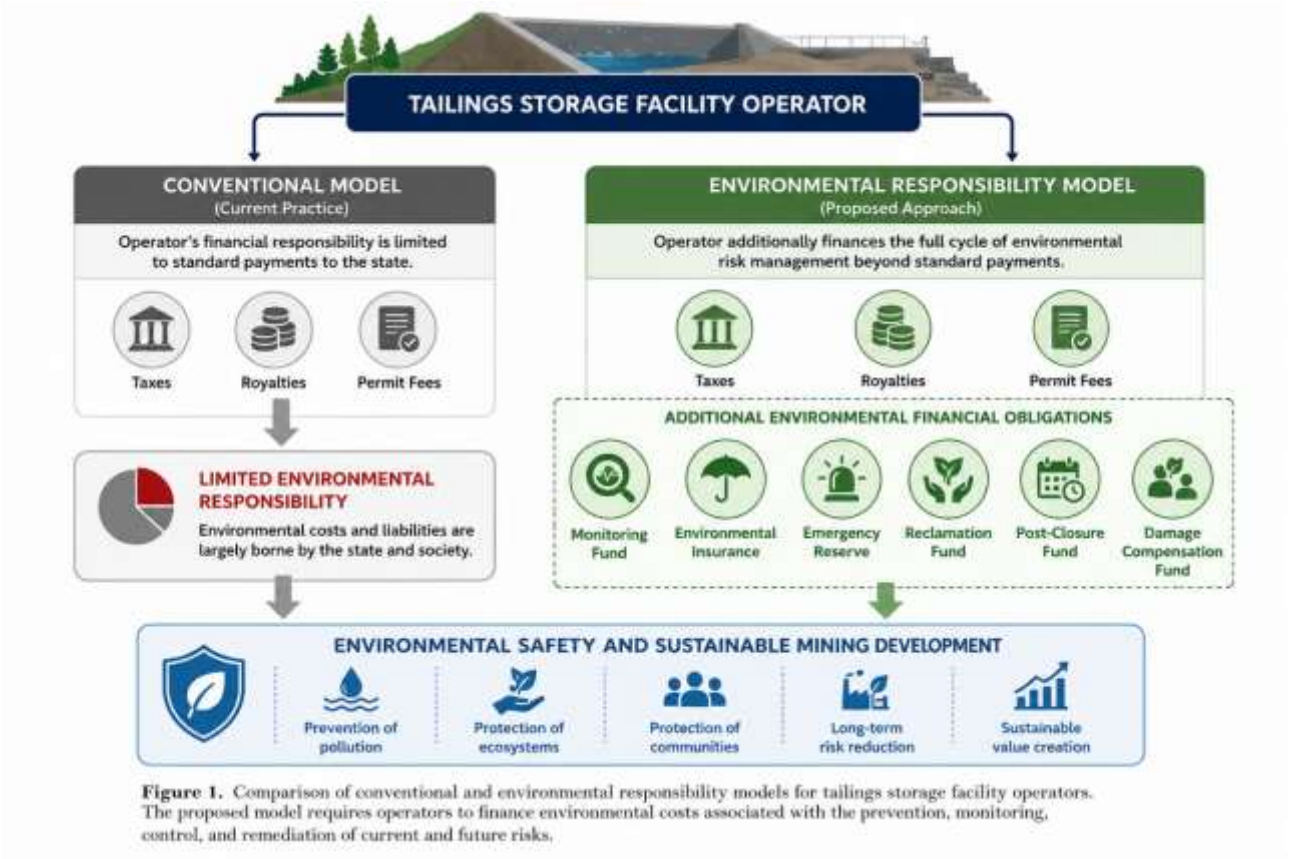

Figure 1. Comparison of conventional and environmental responsibility models for tailings storage facility operators. The proposed model requires operators to finance environmental costs associated with the prevention, monitoring, control, and remediation of current and future risks.

Fig. Comparison of Conventional and Environmental Responsibility Models for Tailings Storage Facility Operators

The proposed environmental responsibility model extends the financial obligations of tailings storage facility operators beyond conventional taxes, royalties, and permit fees. In addition to standard payments, operators are required to finance environmental monitoring, environmental insurance, emergency preparedness, reclamation activities, post-closure management, and environmental damage compensation. This approach aims to ensure that the costs associated with the prevention, control, monitoring, and remediation of current and future environmental risks are borne by the operator rather than transferred to society or future generations.

Conclusions

This study investigated the economic and institutional mechanisms for environmental risk management of tailings storage facilities, analyzed international experience in their application, and evaluated opportunities for improving environmental safety within the context of mining activities.

The results demonstrate that the environmental safety of tailings storage facilities cannot be ensured solely through engineering and technical measures. Despite significant advances in tailings design, construction, and operational technologies over recent decades, environmental incidents and major failures continue to occur worldwide, resulting in contamination of water resources, soils, and ecosystems.

The literature review revealed that environmental risks associated with tailings facilities are determined not only by technical factors but also by governance effectiveness, regulatory oversight, financial accountability, and institutional performance. International experience from major tailings disasters indicates that deficiencies in management and supervision frequently constitute key contributing factors to environmental accidents.

The study confirms that the Polluter Pays Principle and the User Pays Principle represent important economic instruments for environmental risk management in the mining sector. Environmental charges, penalties, compensation mechanisms, and financial assurance instruments can encourage more responsible environmental behavior and contribute to risk reduction.

At the same time, the effectiveness of economic instruments largely depends on the quality of institutional governance. Effective monitoring systems, regulatory oversight, transparency, stakeholder participation, and accountability mechanisms are essential prerequisites for ensuring environmental safety and reducing long-term environmental risks.

One of the principal outcomes of the study is the development of an integrated environmental risk management framework and a conceptual environmental responsibility model for tailings storage facility operators (Fig.). The proposed framework consists of four interconnected components: economic responsibility, financial assurance, institutional governance, and environmental monitoring. This approach enables tailings management to be viewed as a unified system and enhances the overall effectiveness of environmental risk management.

Based on the findings of the study, the following recommendations are proposed:

1. Strengthen the implementation of the Polluter Pays Principle within tailings management systems.
2. Expand the application of financial assurance mechanisms and environmental insurance instruments in mining projects.
3. Improve environmental monitoring systems through the adoption of modern digital technologies and real-time data collection methods.
4. Enhance regulatory oversight and environmental auditing procedures.
5. Promote greater participation of local communities and civil society organizations in environmental decision-making processes.
6. Develop long-term strategies for mine closure and post-closure management of tailings facilities.
7. Implement integrated environmental risk management systems that combine technical, economic, and institutional measures.

Overall, the study demonstrates that improving the environmental safety of tailings storage facilities requires a comprehensive and multi-dimensional approach in which

engineering solutions, economic responsibility, and institutional governance operate as mutually reinforcing components of a unified environmental management system.

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Վ.Ռ. Գրիգորյան
Ակադեմիկոս Ի.Վ. Եղիազարովի անվան ջրային հիմնահարցերի և հիդրոտեխնիկայի ինստիտուտ

Պոչամբարները հանքարդյունաբերության առավել վտանգավոր տեխնածին օբյեկտներից են, որոնք կարող են երկարաժամկետ ազդեցություն ունենալ մակերևութային և ստորերկրյա ջրերի, հողային ռեսուրսների, էկոհամակարգերի և բնակչության առողջության վրա: Չնայած վերջին տասնամյակներում պոչամբարների նախագծման և շահագործման ոլորտում գրանցված տեխնոլոգիական առաջընթացին, բազմաթիվ բնապահպանական վթարներ շարունակում են արձանագրվել աշխարհի տարբեր երկրներում՝ վկայելով, որ տեխնիկական լուծումները բավարար չեն առանց արդյունավետ տնտեսական և ինստիտուցիոնալ կառավարման մեխանիզմների: Հետազոտության նպատակն է վերլուծել պոչամբարների բնապահպանական ռիսկերի կառավարման տնտեսական և ինստիտուցիոնալ գործիքները, գնահատել դրանց կիրառման արդյունավետությունը և բացահայտել բնապահպանական անվտանգության բարձրացման հնարավոր ուղղությունները: Աշխատանքում ուսումնասիրվել են «աղտոտողը վճարում է» և «օգտագործողը վճարում է» սկզբունքները, բնապահպանական վճարների և տուգանքների համակարգերը, ֆինանսական երաշխիքների կիրառումը, ինչպես նաև մոնիթորինգի և վերահսկողության ինստիտուցիոնալ մեխանիզմները: Վերլուծության արդյունքները ցույց են տալիս, որ պոչամբարների անվտանգ շահագործումը պահանջում է ինժեներական, տնտեսական և կառավարման միջոցառումների համակցված կիրառում: Հիմնավորվում է, որ ֆինանսական պատասխանատվության, շարունակական մոնիթորինգի և արդյունավետ վերահսկողության համակարգերի զարգացումը կարող է էականորեն նվազեցնել պոչամբարների հետ կապված բնապահպանական ռիսկերը:

Բանալի բառեր. պոչամբար, բնապահպանական ռիսկ, հանքարդյունաբերություն, աղտոտման վերահսկում, աղտոտողը վճարում է, ֆինանսական երաշխիքներ, մոնիթորինգ:

V.R. Grigoryan

ECONOMIC AND INSTITUTIONAL MECHANISMS FOR ENVIRONMENTAL RISK MANAGEMENT OF TAILINGS STORAGE FACILITIES

ЭКОНОМИЧЕСКИЕ И ИНСТИТУЦИОНАЛЬНЫЕ МЕХАНИЗМЫ УПРАВЛЕНИЯ ЭКОЛОГИЧЕСКИМИ РИСКАМИ ХВОСТОХРАНИЛИЩ

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Хвостохранилища относятся к числу наиболее опасных техногенных объектов горнодобывающей промышленности, способных оказывать долговременное воздействие на поверхностные и подземные воды, почвенные ресурсы, экосистемы и здоровье населения. Несмотря на значительный технологический прогресс в области проектирования и эксплуатации хвостохранилищ, во многих странах мира продолжают фиксироваться экологические аварии, свидетельствующие о том, что технических решений недостаточно без эффективных экономических и институциональных механизмов управления. Целью исследования является анализ экономических и институциональных инструментов управления экологическими рисками хвостохранилищ, оценка их эффективности и выявление направлений повышения экологической безопасности. В работе рассмотрены принципы «загрязнитель платит» и «пользователь платит», системы экологических платежей и штрафов, механизмы финансовых гарантий, а также институциональные инструменты мониторинга и экологического контроля. Результаты исследования показывают, что безопасная эксплуатация хвостохранилищ требует комплексного применения инженерных, экономических и управленческих мер. Обосновано, что развитие систем финансовой ответственности, непрерывного мониторинга и эффективного экологического надзора способно существенно снизить экологические риски, связанные с эксплуатацией хвостохранилищ.

***Ключевые слова*:** хвостохранилище, экологический риск, горнодобывающая промышленность, контроль загрязнения, принцип «загрязнитель платит», финансовые гарантии, мониторинг.

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