Engineering Journal of Satbayev University
Volume 147 (2025), Issue 4, 23-29

https://doi.org/10.51301/ejsu.2025.i4.04

Assessment of industrial waste disposal practices in the mining sector of Uzbekistan

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Abstract. As a result of the intensive development of the mining and metallurgical industry, the volume of industrial waste continues to grow year after year. These wastes contain highly toxic heavy metals, aggressive chemical reagents, and other environmentally hazardous components threatening the environment and human health. Among the mining sector's most dangerous yet critical infrastructural elements are tailings storage facilities structures designed to accumulate industrial waste (specifically slurry) and typically built from earthen materials. Such facilities' planning, construction, and operation often lack sufficient technical and financial resources, rendering them high-risk structures. Foundation settlement, internal erosion, filtration, breach risk, and seismic instability are all factors that necessitate continuous monitoring to ensure the safety of these storage facilities. Traditional geodetic and mine surveying techniques provide insufficient monitoring capabilities. In current conditions, these methods must be supplemented by geoinformation technologies (GIS, remote sensing, UAVs), which offer spatial coverage, rapid data acquisition, and the capacity for integrated analysis. This paper presents a detailed analysis of the structure, risk level, and monitoring methods of various waste storage facilities operated by the Navoi Mining and Metallurgical Combinat (NMMC), utilizing GIS technologies.

Keywords: *mining and metallurgical waste, geoinformation technologies, GIS, remote sensing, tailings storage, uncrewed aerial vehicles, environmental risk, spatiotemporal analysis.*

Received: 04 June 2025
Accepted: 15 August 2025
Available online: 31 August 2025

1. Introduction

In recent decades, the rapid expansion of the mining and metallurgical industry has been accompanied by a sharp increase in its associated environmental risks. In particular, the continuous growth in industrial waste volumes and the presence of highly toxic heavy metals, aggressive chemical reagents, and radioactive components make this issue one of the most pressing scientific and practical problems, posing significant threats to environmental and public health.

Typically, such waste accumulates over large areas near mining sites, where special hydraulic structures, tailings and sludge storage facilities are constructed for containment and management. These facilities are intended for the temporary or permanent storage of liquid or semi-liquid residues from ore processing and often suffer from inadequate stability, seismic resilience, and operational reliability. Their insufficient investment support and failure to meet modern engineering standards frequently make them some of the mining infrastructure's most vulnerable and hazardous elements. Consequently, they are susceptible to internal erosion, settlement, filtration, flooding, and seismic impacts, requiring continuous monitoring [1, 2].

In recent years, geoinformation technologies (GIS), Earth remote sensing (ERS), uncrewed aerial vehicles (UAVs), digital elevation models (DEMs), and global navigation satellite systems (GNSS) have emerged as promising supplements to traditional mine surveying methods. GIS capabilities, in particular, enable the analysis of the spatiotemporal dynamics of waste distribution, risk zone modeling, real-time warning system development, and interactive visualization of monitoring results.

2. Materials and methods

Uzbekistan's mining and industrial sector includes numerous sites that warrant special attention to environmental safety and waste management systems. These sites are primarily located in the Navoi, Samarkand, Jizzakh, and Khorezm regions, serving as accumulation points for various waste generated through industrial activity (Figure 1). These include slurries (pulp), solid and liquid household waste, non-toxic and non-radioactive industrial waste, and sludges containing suspended substances in wastewater. Each site has distinct parameters, location, surface area, commissioning date, and waste storage capacity, requiring tailored scientific and practical analysis for effective environmental monitoring and regional safety policy development.

This approach enables a comprehensive assessment of potential environmental risks, forming state and corporate ecological oversight priorities, and the development of effective measures to prevent emergencies.

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Engineering Journal of Satbayev University. eISSN 2959-2348. Published by Satbayev University

Specifically, the pulp storage facilities located in the «Muruntau» industrial zone of the Navoi region, under the jurisdiction of the Central Mining Administration (2nd Processing Plant), are among the largest tailings repositories in Uzbekistan. These facilities began operating in 1969 and 1975 and now span over 3,452 hectares. Over 2.5 million tons of industrial slurry have been accumulated there. In the nearby «Besapan» industrial zone, a centralized landfill for solid household and industrial waste is also active, containing approximately 79,000 tons. Both sites have been designated 300-meter sanitary protection zones as necessary epidemiological and environmental safety buffers.

Additionally, waste storage sites operated by the Northern Mining Administration in the Uchkuduk district are of significant ecological concern. These include pulp accumulation areas and industrial waste burial sites commissioned in 1995 and 2000. They hold over 142,000 tons of slurry and over 400 tons of industrial waste. Sanitary protection zones of up to 1,000 meters have been established around these facilities, which is critical in limiting harmful environmental impacts.

Furthermore, three waste storage sites operated by the 1st Mining Administration (Processing Plant) in Navoi city are major accumulation centers for mining industry waste (Figure 2). These facilities, active since 1964, store radioactive, toxic, and non-toxic industrial waste, construction debris, household garbage, and metal residues recovered from industrial filters. In certain sections, over 85,000 tons of trash are stored, with sanitary protection zones reaching up to 800 meters, an essential safeguard due to their proximity to urban areas.

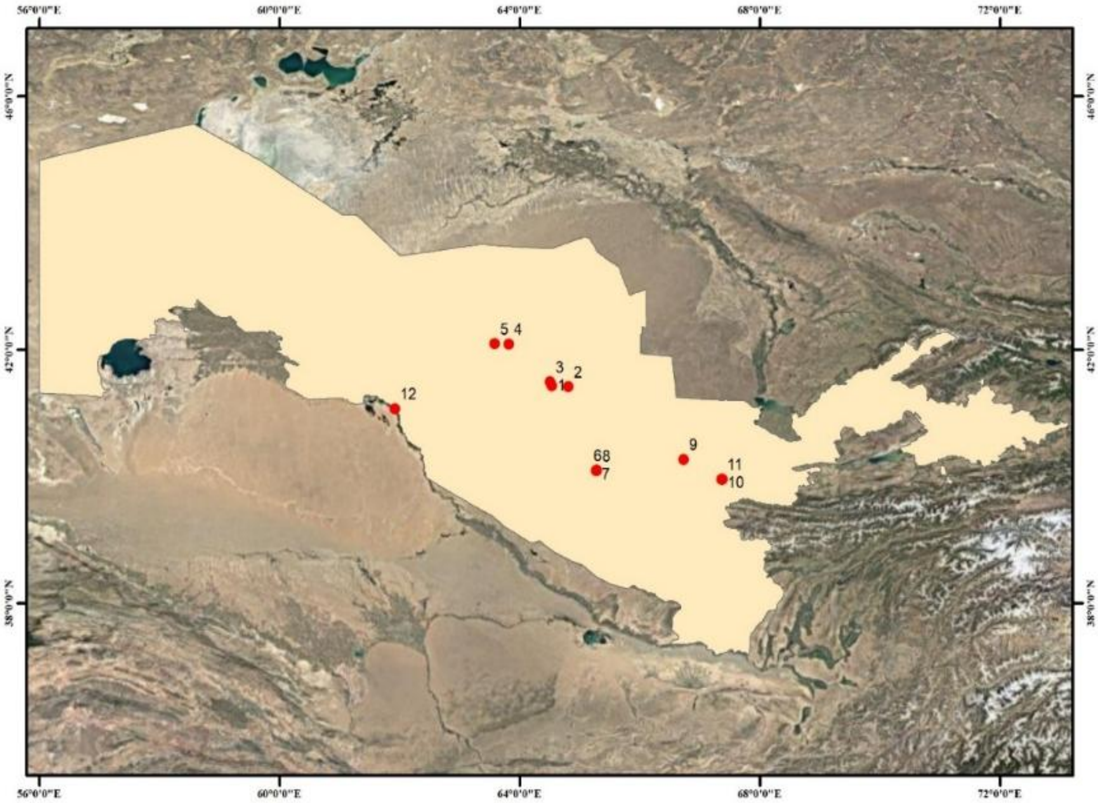

Figure 1. Location of the NMMC tailings facility in the Republic of Uzbekistan. 1 – first-stage tailings accumulation site (tailings storage); 2 - second-stage tailings accumulation site (tailings storage); 3 - centralized landfill for disposal and storage of solid household and industrial waste located in the Besapan industrial area; 4 – 3-HMP tailings accumulation site (tailings storage); 5 – Industrial waste burial site; 6 – 1st «HMP» mining administration industrial waste storage section; 7 – 1st «HMP» mining administration industrial waste storage section; 8 – 1st «HMP» mining administration industrial waste storage section; 9 – 4th «HMP» mining administration industrial waste storage section; 10 – Marjonbuloq waste storage section; 11 – Marjonbuloq old waste storage section (tailings storage); 12 – central mining administration sludge storage site of the industrial area; HMP – hydrometallurgical plant

The Southern Mining Administration's sites, located in Samarkand and Jizzakh regions, are relatively new, having been commissioned between 2017 and 2020. In particular, the «Marjonbulok» industrial zone facilities meet modern environmental standards. They store approximately 35,000 tons of waste and have a 100-meter sanitary protection zone, allowing them to be categorized as relatively safe (Figure 3).

Another ecologically significant site is located in the Tuproqqala district of the Khorezm region. Managed by the Central Mining Administration, this site has been used since 1986 to store sludge from sedimented particles in the Amu Darya River water. The facility covers 15 hectares and contains around 15,000 tons of waste. Such sites are crucial in preserving water resources and preventing hydrosphere contamination.

The state of tailings and sludge storage facilities in these areas is regularly and reliably monitored under existing regulatory guidelines [3], primarily using traditional methods. The main objective is to detect geodynamic processes that could compromise dam stability.

Such facilities' planning, construction, and operation often lack sufficient technical and financial resources, rendering them high-risk structures. Foundation settlement, internal erosion, filtration, breach risk, and seismic instability are all factors that necessitate continuous monitoring to ensure the safety of these storage facilities.

Figure. 2. Tailings facility for industrial waste, Mining Administration No. 4 «Processing Plant»

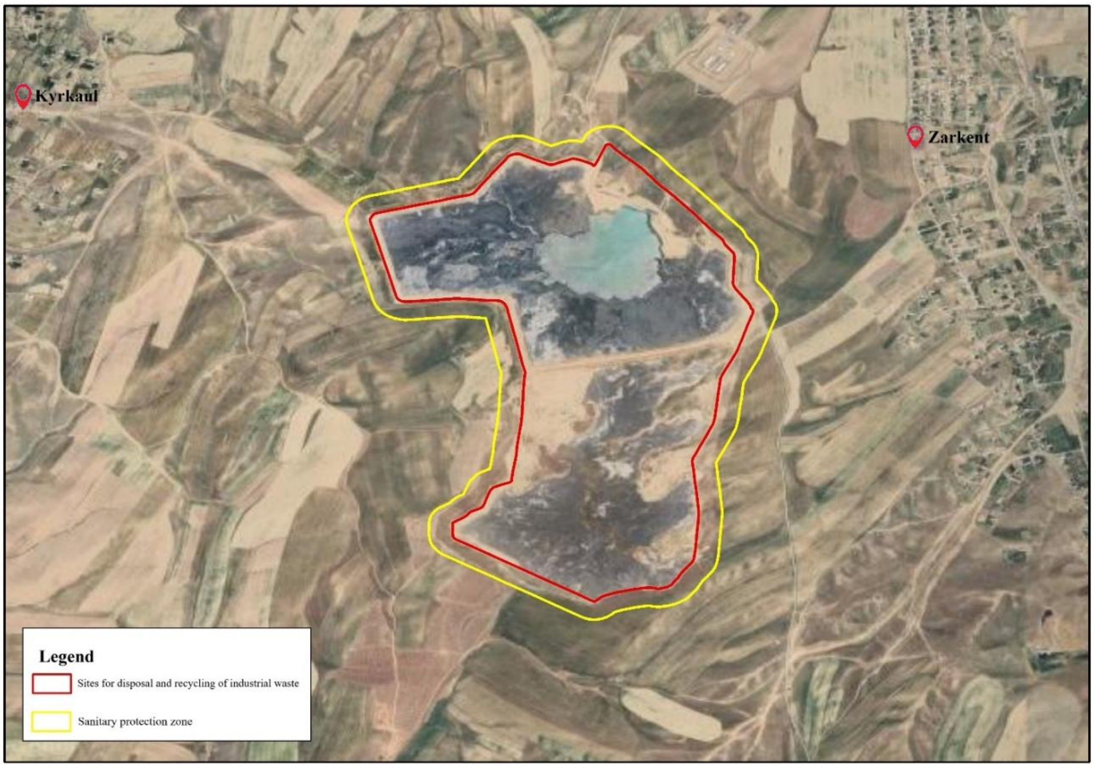

Figure 3. Tailings facility for industrial waste, Mining Administration No. 1 «Processing Plant»

Traditional geodetic and mine surveying techniques provide insufficient monitoring capabilities. In current conditions, these methods must be supplemented by geoinformation technologies (GIS, remote sensing, UAVs), which offer spatial coverage, rapid data acquisition, and the capacity for integrated analysis. This paper presents a detailed analysis of the structure, risk level, and monitoring methods of various waste storage facilities operated by the Navoi Mining and Metallurgical Combinat (NMMC), utilizing GIS technologies [4-6]

This monitoring includes surveying the vertical and horizontal displacements of dam structures. Effective and targeted observation of deformation processes requires thorough preliminary analysis of project documentation, geotechnical conditions (engineering geology and hydrogeology), and structural geometry. These assessments help determine dam stability levels and identify the most deformation-prone areas, guiding the placement of measurement instruments and observation points.

Control points are established in deformation-free zones, considering the maximum dimensions of each structure. Benchmark markers are installed on each moist layer, aligned with longitudinal and cross-sectional profiles. The spacing between markers is determined based on geological, hydrogeological, and technological factors to ensure sufficient data collection on deformation processes.

Field studies indicate that in high-risk areas, this spacing is approximately 50 meters, while in peripheral areas it ranges from 150 to 200 meters.

The geometric leveling method is the most widely used technique for measuring the settlement of engineering structures. The accuracy of third-class leveling is defined by closure discrepancies in leveling loops not exceeding ±10 mm × √L, where L is the length of the run-in kilometers. High-precision or precision levels in this class typically ensure a mean square error of no more than 2.5-3 mm per kilometer of leveling.

The trigonometric leveling method is employed when it is necessary to determine the settlement of points located at significantly different elevations or in hard-to-reach areas. When using optical or electronic instruments with an angular measurement error not worse than 2 seconds, the vertical elevation accuracy ranges from 0.3 mm to 8 mm for distances up to 500 meters. However, this accuracy rapidly decreases as distance increases beyond 1 kilometer; only decimeter-level precision is achievable.

The alignment method (or collimation method) is most commonly applied in hydro-engineering and irrigation infrastructure to monitor displacements. It is viable where working benchmarks can initially be placed in a straight line and approximately at the same elevation. However, implementing this for tailings dam monitoring is nearly impossible due to the deformations inherent in such structures [7, 8].

Angular or linear resection methods are used when it is possible to place observation benchmarks within line-of-sight from two baseline points situated on elevations. Horizontal and vertical angles are measured in these linear-angular networks and resections using high-precision electronic-optical instruments.

In all observation methods, it is advisable to use electronic distance meters (EDMs), which ensure high accuracy in distance measurements. For example, modern EDMs and electronic total stations can provide measurement accuracy defined as:

– $m_L = 1 + 1 \cdot 10^{-6} L$, mm (for short baselines);

– $m_L = 5 + 1 \cdot 10^{-6} L$, mm (for general applications).

Satellite coordinate determination methods, utilizing modern GPS equipment, offer extremely high measurement accuracy:

– $m_L = 5 + 1 \cdot 10^{-6} L$, mm for single-frequency,

– $m_L = 3 + 1 \cdot 10^{-6} L$, mm for dual-frequency systems.

3. Results and discussion

Measurements of baselines up to 2 km using GPS show discrepancies of less than 1 mm. However, due to certain limitations (signal obstructions, time requirements), GPS cannot entirely replace traditional observation methods. Instead, GPS is more appropriate for tracking reference (baseline) points.

Many countries have implemented large-scale research and practical systems for monitoring mining and metallurgical waste alongside traditional methods. Adopting geoinformation technologies in geotechnical risk analysis, environmental monitoring, and remote waste management has significantly changed the industry.

International experience highlights the importance of integrating geoinformation technologies in the monitoring, assessment, and risk management of mining waste. Adapting technologies like UAVs, remote sensing, and digital modeling to national contexts can significantly improve waste storage safety [9, 10]

A detailed comparison of traditional mine surveying methods and modern GIS-based approaches reveals distinct strengths and limitations, as outlined in Table 1.

Table 1. Key comparative parameters

Criterion	Traditional mine surveying methods	Modern GIS-based approaches
Coordinate accuracy	Millimeter-level precision, but limited to localized points	High accuracy via GNSS; lower with satellite data (10–30 m for Sentinel-2)
Area coverage	Limited; requires on-site visits for each location	Broad area coverage (up to 1,000 km² per satellite image)
Operational timeliness	Monitoring requires field expeditions; frequency is monthly or yearly	Sentinel-2: every 5 days; UAVs: real-time, frequent and automated
Data analysis	Manual or Excel-based; lacks spatial analysis	Multi-layer spatial analysis, 3D modeling, spatiotemporal trend detection
Environmental risk analysis	Subjective; based on visual on-site inspection	Analysis via spectral indices (NDWI, SAVI, MSI) for dust, moisture, and vegetation changes
Subsurface deformation detection	Only surface-level deformation is detectable.	InSAR technology enables the detection of profound structural shifts (foundation settlement)
Cost and resources	Initially low cost, but time and labor-intensive	High initial investment, but long-term efficiency via automation and speed
Visualization and reporting	2D graphs and printed maps	Interactive Web-GIS, 3D visualization, real-time dashboards
Human factor dependency	High, prone to error and subjectivity	Low; automation reduces subjectivity
Monitoring frequency	Periodic (monthly or quarterly), bureaucratically constrained	Weekly, daily, or near real-time

The methodological analysis conducted as part of this study highlights that the effectiveness of monitoring techniques for industrial waste depends on the purpose, geophysical conditions, complexity of the sites, and level of anthropogenic risk. The research compared traditional geodetic and mine surveying approaches with modern GIS-based methods, evaluating their responsiveness and applicability (Figure 4).

Traditional geodetic techniques offer high-precision measurements of physical surface changes and are particularly useful for local site-specific monitoring and structural deformation assessment. However, they are limited in tracking spatiotemporal dynamics, real-time monitoring, and environmental evaluation [11-13].

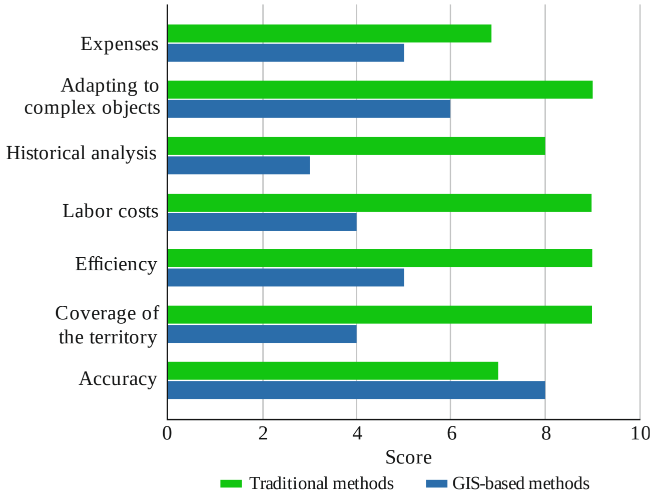

Figure 4. Comparison of traditional and GIS-based monitoring in the mining and metallurgical sector

In contrast, modern tools, including GIS, remote sensing (RS), UAVs, DEMs, and GNSS, elevate monitoring to a new level. These technologies provide broad temporal and spatial coverage; enable digital modeling, automated analysis, forecasting, and integration with management systems. GIS tools are especially indispensable for identifying risk zones involving slurry and toxic waste, modeling geodynamics, and detecting seismic instability. Their implementation demands advanced technical infrastructure, skilled personnel, and financial investment.

Traditional mine surveying methods provide accurate local data but are reactive and fragmented. They are not efficient for rugged or environmentally sensitive areas. GIS technologies significantly enhance monitoring by automating processes, visualizing spatial-temporal dynamics, forecasting risk factors, and integrating with management systems.

The most effective approach is a hybrid monitoring system**,** combining the precision of traditional methods with the coverage, efficiency, and analytical depth of GIS technologies (Table 2).

Table 2. Functional Logic of the Hybrid Model

Component	Function
Traditional Measurements	Localized accuracy and registration of primary deformations
UAV + DEM	Detection of surface-level changes and subsidence
GNSS	High-precision geolocation of dynamic points
GIS + RS	Spatiotemporal threat analysis
InSAR + IoT	Monitoring of subsurface pressures and oscillations
Visualization Tools	Web-GIS, 3D maps, real-time risk dashboards

Such a system is essential for ensuring industrial waste's safe and efficient monitoring, enabling real-time detection of subsidence, deformation, and other hazards in mining zones [14, 15].

The hybrid monitoring model combines both traditional and modern technologies. Classical methods include surface displacement monitoring using theodolites, levels, and total stations and surveying deformation benchmarks. Sequential measurements within a network of reference points remain essential, along with regular visual inspections at fixed intervals, which ensure localized accuracy and direct observation of critical areas.

At the same time, modern technologies significantly expand the scope and efficiency of monitoring. GIS systems allow advanced spatial analysis and the creation of detailed risk maps, while remote sensing provides valuable data through spectral indices such as NDWI, SAVI, and MSI from satellites like Sentinel-2 and Landsat. UAVs enhance the process by enabling 3D terrain modeling and detection of surface changes, and GNSS ensures precise geolocation of shifting points. In addition, InSAR technology makes it possible to identify deep subsurface deformations by analyzing radar signals, which adds a crucial predictive dimension to hazard monitoring.

4. Conclusions

Amid growing global environmental concerns, the issue of identifying and managing risks associated with industrial waste in the mining and metallurgical sector has become increasingly urgent. Based on the Navoi Mining and Metallurgical Combinat (NMMC) example, this study demonstrated that although traditional mine surveying methods offer high precision, they lose effectiveness in large-scale spatial monitoring. This limitation significantly hampers the assessment of safety conditions and the ability to generate real-time forecasts.

In contrast, modern geoinformation technologies such as GIS, remote sensing (RS), UAVs, digital elevation models (DEMs), and GNSS have ushered in a qualitatively new phase of monitoring for industrial infrastructure. These technologies enable spatiotemporal analysis of changes, risk zone detection, interactive visualization, and integration with environmental management systems.

Based on the conducted analysis, a hybrid monitoring model was proposed, combining the accuracy of conventional geodetic methods with the extensive capabilities of GIS. This model allows for assessing tailings dam stability through field observations and advanced digital analytical tools in near real-time. Furthermore, drawing on international experience, integrating Digital Twin platforms and automated Web-GIS systems can provide high safety and efficiency for environmental monitoring within Uzbekistan's mining infrastructure.

Thus, the outcomes of this research offer scientifically grounded, technologically advanced, and practically significant solutions for managing industrial waste in the mining and metallurgical sector. These findings contribute to developing long-term strategies for ecologically sustainable industrial growth.

Author contributions

Conceptualization: ATN; Data curation: AKR; Formal analysis: AKR, DRM; Funding acquisition: AKR; Investigation: DRM; Methodology: ATN; Project administration: ATN, AKR; Resources: DRM; Software: DRM; Supervision: ATN; Validation: ATN; Visualization: ATN; Writing – original draft: ATN, AKR; Writing – review & editing: ATN, AKR. All authors have read and agreed to the published version of the manuscript.

Funding

This research was carried out as part of the research plan of Tashkent State Technical University on the topic: «Scientific Foundations of Mine Surveying for Rational, Comprehensive, and Safe Mining and Subsoil Protection».

Acknowledgements

The authors express their sincere gratitude to the editor and anonymous reviewers for their constructive comments and valuable suggestions, which have significantly improved the quality of this manuscript.

Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Өзбекстанның тау-кен секторындағы өнеркәсіптік қалдықтарды кәдеге жарату тәжірибесін бағалау

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Аңдатпа. Тау-кен және металлургия өнеркәсібінің қарқынды дамуы нәтижесінде өнеркәсіптік қалдықтардың көлемі жылдан жылға өсуде. Бұл қалдықтардың құрамында өте улы ауыр металдар, қатты химиялық реагенттер және қоршаған ортаға және адам денсаулығына қауіп төндіретін басқа да экологиялық қауіпті компоненттер бар. Тау-кен өнеркәсібі инфрақұрылымының аса қауіпті және аса маңызды элементтерінің қатарына өнеркәсіптік қалдықтарды (атап айтқанда, шламдарды) жинақтауға арналған және әдетте жер материалдарынан салынған қалдық қоймалары жатады. Мұндай нысандарды жоспарлау, салу және пайдалану көбінесе жеткілікті техникалық және қаржылық ресурстарды қамтамасыз ету үшін жеткіліксіз, бұл оларды жоғары қауіпті құрылымдарға айналдырады. Іргетас шөгінділері, ішкі эрозия, сүзу, бұзылу қаупі және сейсмикалық тұрақсыздық – бұл қоймалардың қауіпсіздігін қамтамасыз ету үшін үнемі бақылауды қажет ететін факторлар. Дәстүрлі геодезиялық және маркшейдерлік әдістер жеткілікті бақылау мүмкіндіктерін қамтамасыз етпейді. Қазіргі жағдайда бұл әдістер кеңістіктік қамтуды, деректерді жылдам жинауды және кешенді талдау мүмкіндігін қамтамасыз ететін геоақпараттық технологиялармен (ГАЖ, қашықтықтан зондтау, ҰҰА) толықтырылуы тиіс. Бұл мақалада ГАЖ технологияларын қолдана отырып, Навои тау-кен металлургия комбинатының (НГМК) қалдықтарын сақтаудың әртүрлі объектілерінің құрылымын, тәуекел деңгейін және мониторинг әдістерін егжей-тегжейлі талдау ұсынылған.

Негізгі сөздер: *тау-кен металлургия өндірісінің қалдықтары, ГАЖ, қашықтықтан зондтау, қалдық қоймалары, ұшқышсыз ұшу аппараттары, экологиялық тәуекел, кеңістіктік-уақыттық талдау.*

Оценка практики утилизации промышленных отходов в горнодобывающем секторе Узбекистана

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Аннотация. В результате интенсивного развития горнодобывающей и металлургической промышленности объём промышленных отходов продолжает расти из года в год. Эти отходы содержат высокотоксичные тяжёлые металлы, агрессивные химические реагенты и другие экологически опасные компоненты, представляющие угрозу окружающей среде и здоровью человека. К числу наиболее опасных и критически важных элементов инфраструктуры горнодобывающей отрасли относятся хвостохранилища, предназначенные для накопления промышленных отходов (в частности, шламов) и, как правило, построенные из земляных материалов. Планирование, строительство и эксплуатация таких объектов зачастую недостаточны для обеспечения достаточных технических и финансовых ресурсов, что делает их высокорискованными сооружениями. Осадка фундаментов, внутренняя эрозия, фильтрация, риск прорыва и сейсмическая нестабильность – всё это факторы, требующие постоянного мониторинга для обеспечения безопасности этих хранилищ. Традиционные геодезические и маркшейдерские методы не обеспечивают достаточных возможностей мониторинга. В современных условиях эти методы должны быть дополнены геоинформационными технологиями (ГИС, дистанционное зондирование, БПЛА), которые обеспечивают пространственный охват, быстрый сбор данных и возможность комплексного анализа. В данной статье представлен подробный анализ структуры, уровня риска и методов мониторинга различных объектов хранения отходов Навоийского горно-металлургического комбината (НГМК) с использованием ГИС-технологий.

Ключевые слова: *отходы горно-металлургического производства, ГИС, дистанционное зондирование, хвостохранилища, беспилотные летательные аппараты, экологический риск, пространственно-временной анализ.*

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