ТЕХНИЧЕСКИЕ НАУКИ
И ТЕХНОЛОГИИ

ҚҰРЫЛЫС
СТРОИТЕЛЬСТВО
CONSTRUCTION

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MONITORING OF TECHNOLOGICAL APPROACHES TO IMPROVE THE RELIABILITY OF HYDRAULIC ENGINEERING FACILITIES

ГИДРОТЕХНИКАЛЫҚ ОБЪЕКТІЛЕРДІҢ СЕНІМДІЛІГІН АРТТЫРУ МАҚСАТЫНДА ТЕХНОЛОГИЯЛЫҚ ТӘСІЛДЕРДІҢ МОНИТОРИНГІ

МОНИТОРИНГ ТЕХНОЛОГИЧЕСКИХ ПОДХОДОВ С ЦЕЛЬЮ ПОВЫШЕНИЯ НАДЕЖНОСТИ ГИДРОТЕХНИЧЕСКИХ ОБЪЕКТОВ

Abstract. *Modern industrial production is one of the main sources of environmental pollution, actively consuming natural resources. The construction industry, in turn, despite the significant impact on the environment, is not an exception to this trend.*

The authors analyze the theoretical aspects of research on the environmental problems of tailings management, review of regulatory and legal regulation, as well as the development of the project of accident elimination, on the example of a company "Kazzinc". In addition, the implementation of similar projects in real practice is analyzed.

Thus, the scientific significance is expressed in the systematization of the study of theoretical and methodological aspects of risk management in case of accidents at tailings facilities. This is of key importance for improving environmental safety in the construction industry and effective implementation of technological solutions in this area.

Keywords: *Ecology, disposal area, risk management, containment dams, remote sensing.*

Аңдатпа. *Қазіргі заманғы өнеркәсіптік өндіріс табиғи ресурстарды белсенді тұтынатын қоршаған ортаны ластаудың негізгі көздерінің бірі болып табылады. Құрылыс индустриясы, өз кезегінде, қоршаған ортаға айтарлықтай әсер еткеніне қарамастан, бұл үрдістен ерекшелік емес.*

Авторлар құйрық шаруашылығының экологиялық проблемаларына қатысты зерттеулердің теориялық аспектілеріне талдау жүргізеді, нормативтік-құқықтық реттеуге шолу жасайды, сондай-ақ «Казцинк» компаниясы мысалында аварияларды жою жобасын әзірлейді. Сонымен қатар, мұндай жобаларды нақты тәжірибеге енгізуге талдау жасалады.

Осылайша, ғылыми маңыздылығы қалдық қоймаларында апаттар туындаған кезде тәуекелдерді басқарудың теориялық және әдіснамалық аспектілерін зерттеуді жүйелеуде көрінеді. Бұл құрылыс индустриясындағы экологиялық қауіпсіздікті арттыру және осы салада

технологиялық шешімдерді тиімді енгізу үшін маңызды.
Түйін сөздер: *Экология, қалдық қоймасы, қауіптерді басқару, қоршау бөгеттері, қашықтықтан зондтау*

Аннотация. *Современное промышленное производство представляет собой один из главных источников загрязнения окружающей среды, активно потребляя природные ресурсы. Строительная промышленность, в свою очередь, несмотря на значительное воздействие на окружающую среду, не является исключением из этой тенденции.*

Цель данной статьи заключается в исследовании теоретических и практических аспектов технологических решений для предотвращения и ликвидации аварий на хвостохранилищах в сфере строительной промышленности.

Авторами проводится анализ теоретических аспектов исследований, касающихся экологических проблем хвостового хозяйства, обзор нормативно-правового регулирования, а также разработка проекта ликвидации аварий, на примере компании «Казцинк». Помимо этого, производится анализ внедрения подобных проектов в реальной практике.

Таким образом научная значимость выражается в систематизации исследования теоретико-методологических аспектов управления рисками при возникновении аварий на хвостохранилищах. Это имеет ключевое значение для повышения экологической безопасности в строительной промышленности и эффективного внедрения технологических решений в данной области.
Ключевые слова: *Экология, хвостохранилище, управление рисками, ограждающие дамбы, дистанционное зондирование.*

Introduction. The examination of scientific studies and empirical observations regarding development practices in mining and processing industries suggests a significant environmental hazard emanating from the operational infrastructures of these sectors. Strategically situating these infrastructures within mining areas emerges as a critical measure for mitigating adverse environmental impacts. Within the framework of formulating environmental rationales for project undertakings, the choice of locations for industrial facilities profoundly influences a series of environmental issues. This selection process involves technical solutions and escalates risks, thereby substantially increasing project costs [1–3].

Literature, including "Environmental Assessment of Options for the Location of the Surface Complex and Tailings Facilities of the Talitsky Mining and Processing Combine" and "Modern Problems of Improving the Safety of Hydraulic Structures Operation (illustrated by the Voronezh Region case)", underscores the significance of selecting appropriate catchment basins for facility placement [4]. These studies corroborate that distributing hazardous operations across a territory, ensuring adequate separation from residential areas, aids in diminishing potential environmental dangers [5-6].

The analysis of accidents, such as the Voronezh region pond cascade failure, indicates that neglecting hydraulic structure safety can result in grave repercussions. Identified causes of such incidents encompass design flaws, substandard repair efforts, unsuitable material application, foundation degradation, and acts of sabotage [7].

Research by the Mining Institute of the Kola Scientific Centre of the Russian Academy of Sciences highlights the inherent risks associated with hydraulic installations at mining sites, like tailings dam systems and enclosing dams, as potentially perilous. Incident investigations at facilities including the Kachkanarsky Mining and Processing Combine (Russian Federation), El Cobra mine (Chile), Karamkensky Mining and Metallurgical Combine (Russian Federation), and the Buffalo Creek coal preparation plant (USA) attribute dam failures primarily to the creation of water conduits within dam bodies and erosion [8–18].

In the context of monitoring subterranean entities, space surveillance represents a primary focus within the framework of state oversight concerning subsoil or geological environmental conditions. The substantial scale of construction activities and the envisaged implementation of extensive projects within the Republic of Kazakhstan underscore the imperative of promptly making informed management decisions pertaining to subsoil utilization. An essential consideration in such decision-making processes involves the monitoring of infringements concerning subsoil utilization. This necessity arises from the considerable adverse ramifications of quarrying activities on the environment, encompassing the removal of fertile soil layers, frequent destruction of forested areas, intermittent emergence of illicit waste disposal sites subsequent to sand and gravel extraction, disruption of hydrological regimes, ecological degradation, and hazards posed to nearby populations. Additionally, these activities inflict economic detriments, such as diminished tax revenues, compromised infrastructure, and substandard construction materials [19].

Despite the challenges inherent in automated detection, certain recommendations exist to discern the utilization dynamics and boundaries of subsoil exploitation sites. The salient characteristics of visually interpreting quarries can be succinctly delineated as follows: irregular outlines and concentric bands of varying hues encircling the perimeter, discernible access roads and their tributaries, and the presence of earthmoving machinery; excavations, whether inundated or dry, waterlogged sections, and areas exhibiting disrupted vegetation cover along with their respective extents.

For accessing the outcomes of subsoil utilization operations through space surveillance, a geoservice has been established [19]. This geoservice provides foundational layers (comprising settlements, road networks, railways, and hydrographical features) sourced from the Ministry of Industry and Infrastructure Development of the Republic of Kazakhstan, along with analytical insights furnished by JSC "NC Kazakhstan Garysh Sapary". Notably, Kazakhstan is at the nascent stage of integrating space imagery into practical applications, with the cost of such imagery being prohibitive for certain commercial entities. Consequently, local firms resort to foreign counterparts for space surveillance solutions. Nonetheless, leveraging space monitoring technologies facilitates a reduction in labor overheads and enhances operational efficiency [20].

The examination of territorial transformations relies on multi-temporal space imagery. Archival space imagery is sourced from the catalog maintained by JSC "NC Kazakhstan Garysh Sapary", the operator for Earth remote sensing. The interpretation process employs space imagery from domestic satellites like KazEOSat-1, offering high spatial resolution of 1 meter, in addition to super high-resolution space imagery ranging from 0.3 to 0.5 meters sourced from foreign satellites. The utilization of high and ultra-high spatial resolution imagery enables precise delineation of open pits, waste disposal sites, and infrastructural installations within contracted and licensed areas.

A pivotal insight is the necessity for meticulous management of dam and tailings dam systems, adhering to industrial safety standards to avert emergencies that could inflict significant socio-economic losses, including financial liabilities, rehabilitation expenditures, and environmental degradation [21].

Furthermore, the integrity of mining operations is contingent upon the geological stability of the rock mass, resilience to climatic and seismic influences, and adherence to environmental safety protocols during extraction processes [22-23]. The authors also highlight the ongoing issue of environmental pollution in mining districts, notably in Kazakhstan, illustrating the urgency of addressing these challenges (Figure 1).

Recent findings increasingly substantiate the notion that the environmental degradation of transboundary watercourses and international lakes may stem from the unintentional cross-border dispersal of hazardous substances on a substantial scale, attributable to incidents involving tailings dams. These emergencies facilitate the transboundary contamination by extensively mobilizing waste materials, notably tailings infused with heavy metals and other hazardous or toxic substances, both as particulates and solutes [24-25].

Such incidents precipitate pollution across watercourses, engendering potential harm or risk to human health, infrastructure, and ecological assets, potentially souring diplomatic relations between adjacent nations. The threat extends across the spectrum of tailings management facilities, encompassing operational, non-operational, poorly monitored, mothballed, permanently shut down, abandoned, or derelict sites. The absence of active monitoring or maintenance at a substantial number of these sites, particularly those inadequately supervised, abandoned, or derelict, is a significant concern [26].

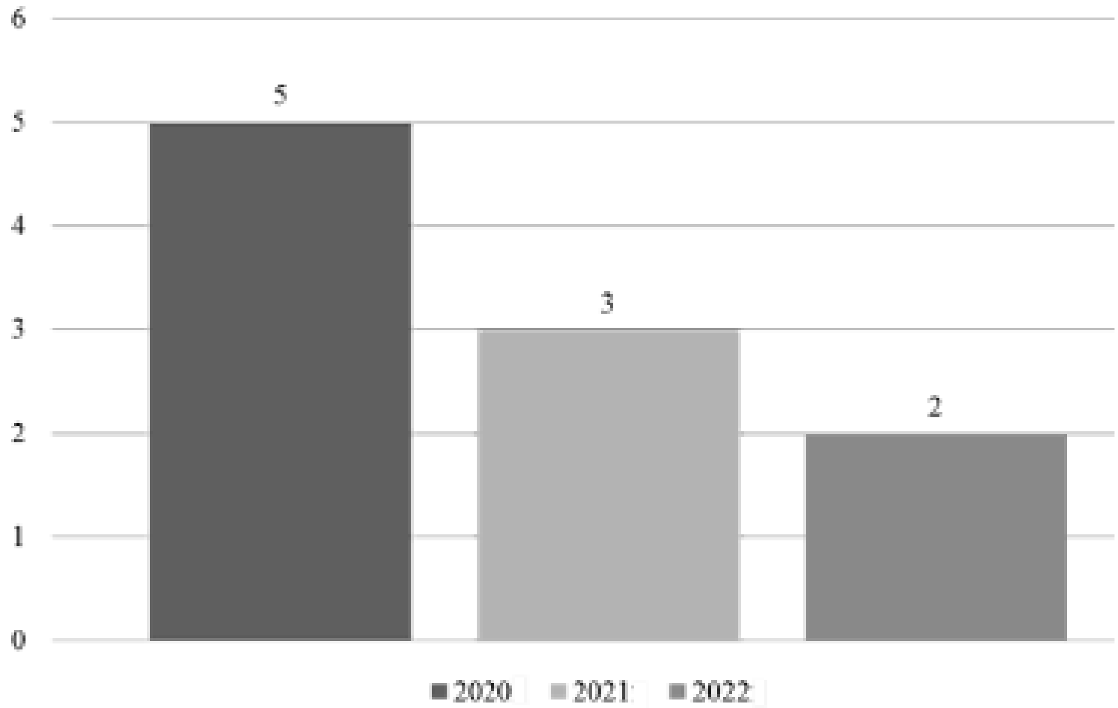


Figure 1. Statistics of major tailings dam accidents for the period 2020-2022

The environmental repercussions are diverse, yet certain patterns of manifestation are commonly observed, including:

1. Mismanagement leading to diminished quality and quantity of natural resources, termed spoilage;
2. Alterations in the physical and chemical properties of air, water, or soil, to any degree, identified as pollution;
3. Diminution of the beneficial natural attributes of resources, referred to as depletion;
4. Compromised utility in terms of both quality and quantity, recognized as damage;
5. Complete loss of functional quality and quantity, defined as destruction.

An analysis of the environmental damage impacting demographic regions in recent years suggests the necessity for:

1. Strengthening legal frameworks;
2. Revising the stipulations of the Environmental Code;
3. Aiming to stabilize pollutant emissions within the Republic of Kazakhstan to 2017 levels by aligning emission standards with the National Standards for Emission Reduction (NSDT);
4. Mandating the application of NSDT for all new enterprises while aiming for a reduction

of air emissions by at least 10-20% in the most polluted Kazakhstani cities.

In addition the legislation should encapsulate the authority to implement specific economic mechanisms within the Republic of Kazakhstan. It is proposed that these economic mechanisms be instituted in alignment with the outlined strategies (Figure 2).

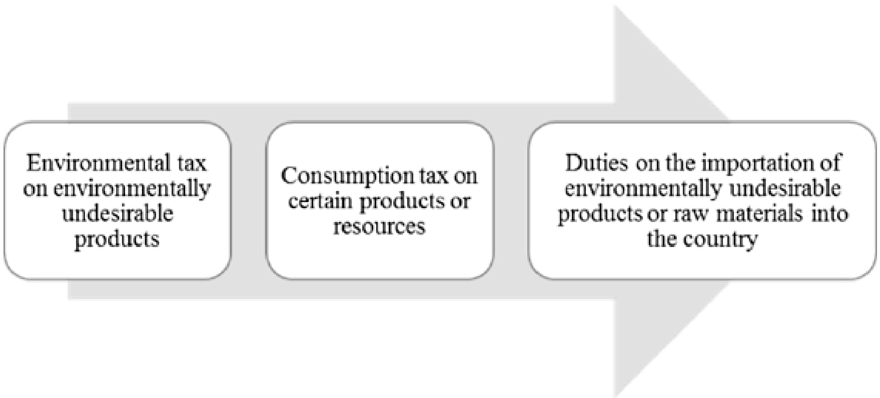


Figure 2. Main economic mechanisms enshrined in the legislation of the RK

The implementation of a provisional tariff augmentation for the settlement period, with the explicit allocation of the supplementary revenue, is advocated. This approach is anticipated to optimize the efficacy of the initiative [15-16]. Preliminary projections suggest that this strategy could facilitate a twofold decrease in the volume of contaminated wastewater discharge, as delineated in Figure 3.

The implementation of a provisional tariff augmentation for the settlement period, with the explicit allocation of the supplementary revenue, is advocated. This approach is anticipated to optimize the efficacy of the initiative [27-28]. Preliminary projections suggest that this strategy could facilitate a twofold decrease in the volume of contaminated wastewater discharge, as delineated in Figure 3.

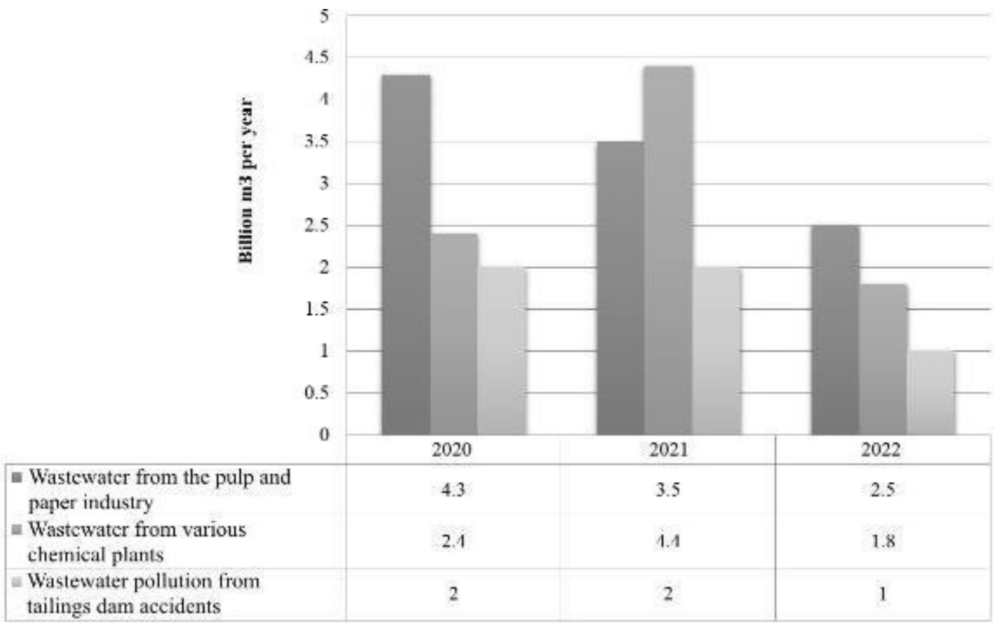


Figure 3. Complete cessation of untreated wastewater discharge into water bodies

From Figure 3, we can observe the following trends:

- The pulp and paper industry shows a consistent decrease in wastewater production over the three years.
- Chemical plants had a spike in wastewater production in 2021 but then a decrease in 2022 that is lower than the 2020 levels.

Pollution from tailings dam accidents reduced significantly in 2022 compared to the previous years.

Current data indicating the levels of pollution entering aquatic ecosystems should not surpass the natural regenerative capacity of these water bodies to maintain or restore their intrinsic water quality. It is imperative to conduct a comprehensive analysis of the principal categories and processes involved in resource planning for the Gas Transmission System (GTS) project. Such an analysis will significantly contribute to enhancing the quality of both the development and execution of technological solutions aimed at mitigating accidents at tailings dams, exemplified by the operations at the Enrichment Plant Zyryanovsky Mining and Processing Complex (EP ZMPC) of LLP "Kazzinc" [29].

Furthermore, the compilation of analytical and reporting summaries will be instrumental in formulating an effective project risk management framework.

Initially, the focus is on the EP ZMPC, strategically located at the eastern periphery of the city of Altai, which predominantly processes polymetallic and copper-zinc ores extracted from the Maleevskoye deposit. The facility encompasses various sections, including heavy slurry ore processing and beneficiation, grinding and flotation, thickening and filtration, reagent handling with an integrated lime plant, a tailings storage facility, a pilot plant, and a copper sulphate production unit (Figure 4).

a b

Figure 4. Disposal area: a) EP ZMPC; b) Location of the enrichment plant and tailings management facilities of Altai Mining and Processing Division

Table 1. Characterisation of the tailings dam

№	Parameters	Unit	Indicators
1	Designation	Storage of flotation tailings	
2	Territory area	м^2	4 444 800
3	Length of borders	м	8 570,80
4	Area of prohibited zones	м^2	4 444 800

5	Sanitary protection zones	м^2	4 850 500
6	Length of zone boundaries	м	13 240
7	Average elevation AMSL	м	466
8	Seismicity	points	8
9	Characterisation of the terrain	Plain, foothill. Right-bank part of the Berezovka River	

Materials and methods of research. Throughout the investigation, it was determined that the Interferometric Synthetic Aperture Radar (InSAR) system, is optimally configured to furnish dependable and precise real-time surveillance of tailings dams. The InSAR methodology, a form of remote sensing, is designed to observe movements presenting potential or immediate hazards to tailings dams. The superior precision offered by this three-dimensional real aperture radar system facilitates the real-time tracking of critical areas, establishing a robust framework for the management of risk-prone zones, which is essential for ensuring safety [30-32].

The remote sensing technique offers measurements of terrestrial deformation, employing radar satellite imagery and sophisticated algorithms frequently without the necessity for terrestrial instruments. Such targeted surveillance methodologies are imperative for safety, as they are principally aimed at quantifying the variation between sequential spatial positions. Moreover, this approach is marked by its efficacy, particularly in acquiring data concerning the topography of tailings dams and their temporal alterations. Referring to Figure 5, it is observable that the Total Station computes the three-dimensional distance from each prism, with the deviation being recorded as a chronological series of prism locations.

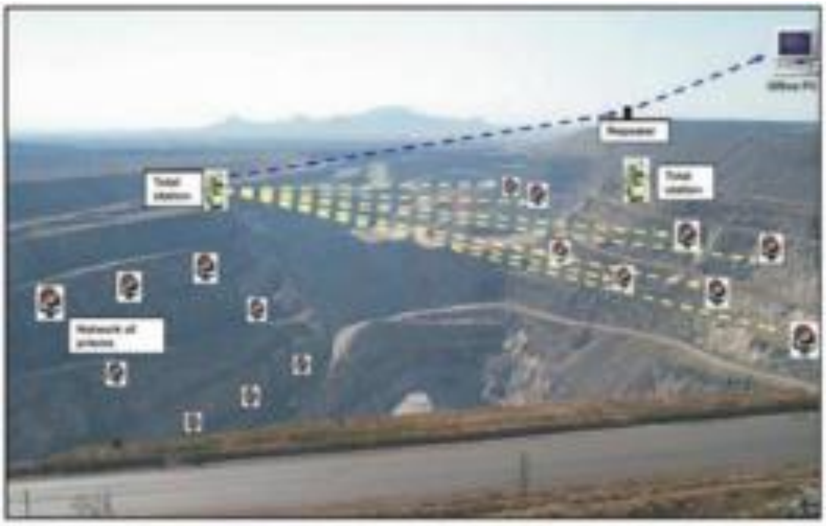


Figure 5. Monitoring with Tacheometer

The Total Station, equipped with precise measurement capabilities, represents an exemplary instrument for the surveillance of volumetric alterations within spoil heaps. It enables the accurate detection and quantification of changes in the volume of materials accumulated in these areas. This attribute is particularly beneficial for managing and mitigating potential environmental impacts associated with spoil dumps, allowing for informed decision-making regarding their maintenance and remediation.

In contrast, within the existing satellite landscape, as depicted in Figure 6, the Interferometric Synthetic Aperture Radar (InSAR) system faces limitations in its ability to monitor volumetric changes at such sites. Although InSAR is renowned for its proficiency in detecting ground deformation and movement with high precision, its current application in satellite-based monitoring does not extend effectively to assessing volumetric variations within spoil dumps. This limitation underscores the necessity for integrating various monitoring technologies, like the Total Station, to comprehensively address the diverse aspects of environmental monitoring and management of spoil dumps.

The integration of these technologies enhances the ability to conduct thorough assessments, providing a multidimensional perspective on the dynamics of spoil dumps. It facilitates a deeper understanding of the volumetric changes occurring over time, contributing significantly to the development of sustainable management practices for these environmental liabilities.

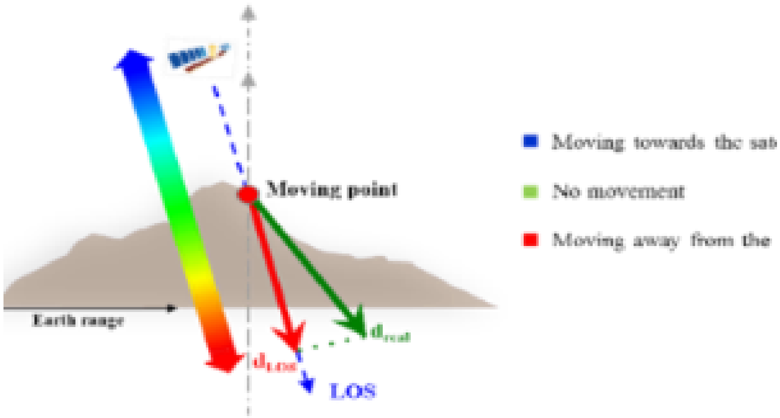


Figure 6. Line-of-sight measurements

Synthetic Aperture Radar (SAR) satellites observe the Earth's surface from an oblique perspective, a methodology referred to as the line of sight (LOS). This observational approach enables the detection of surface changes by comparing the phase difference of radar signals reflected back to the satellite from the Earth's surface at different times. The Interferometric Synthetic Aperture Radar (InSAR) technique, building on this principle, quantifies the component of the actual ground displacement that is projected onto the LOS, as illustrated in Figure 7.

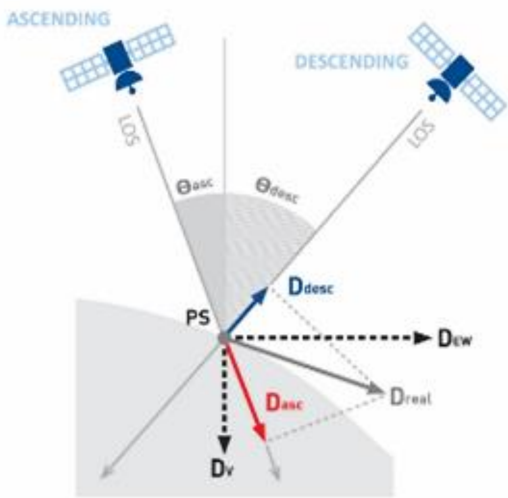


Figure 7. One-dimensional measurements (2D)

This measurement is crucial for understanding the dynamics of the Earth's surface, including deformations due to seismic activities, volcanic eruptions, and anthropogenic factors such as mining and urban development. By measuring the phase shift in the radar signals caused by changes in the distance between the satellite and the ground surface, InSAR provides precise data on the rate and direction of ground movement. The projection of real-world displacements onto the LOS allows for the interpretation of these movements in three dimensions, albeit constrained by the sensitivity of the radar to the component of motion in the direction of the LOS.

The InSAR's capability to discern subtle changes over large areas with high precision makes it an invaluable tool in geoscience research, land use planning, and monitoring of critical infrastructure. Its application is pivotal in the early detection of potential geological hazards, contributing to the mitigation of risks associated with natural and human-induced ground movements.

The acquisition of two-dimensional (2D) motion components, specifically in the vertical and east-west directions, is facilitated through the synthesis of line of sight (LOS) measurements from both ascending and descending satellite passes. This methodological approach integrates these readings onto a unified, regularly spaced grid, adhering to the following principles:

The 2D measurement points are conceptualized not as discrete radar targets but rather as grid cells, representing averaged values over specified areas.

These 2D points are derived exclusively at locations where data from both ascending (uplink) and descending (downlink) satellite paths are available, ensuring a comprehensive coverage that permits the derivation of motion components.

This integrated analysis allows for the detection of displacement components along the east-west axis and the vertical axis. However, due to the geometric constraints of the satellite observation angles and the processing methodology, movements in the north-south direction remain undetectable with this technique.

By amalgamating data from both the uplink and downlink satellite trajectories, researchers can accurately discern displacement patterns in the east-west and vertical planes. This capability is instrumental in a wide range of geoscientific and engineering applications, including the monitoring of land subsidence, infrastructure deformation, and the dynamics of natural hazards such as landslides and earthquakes.

Despite the sophistication of this approach, it is important to note the inherent limitation regarding the detection of north-south displacement. This constraint stems from the geometric properties of the satellite observation system and the specific characteristics of radar signal interaction with the Earth's surface, which do not favor the resolution of movements along the north-south axis with the same level of precision as those detected in the east-west and vertical directions (Figure 8, 9).

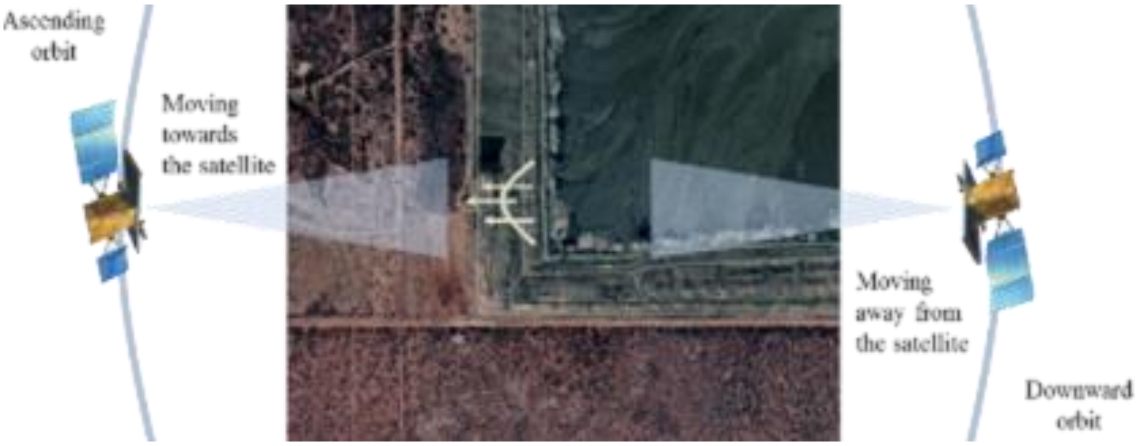


Figure 8. Vertical and East-West

Figure 9. North-South vertical

The orbital orientation of Synthetic Aperture Radar (SAR) satellites inherently restricts their ability to capture the north-south component of displacement on the Earth's surface. This limitation arises from the specific trajectory and angle at which these satellites orbit the Earth, which primarily allows them to measure displacement components that are parallel or oblique to their line of sight (LOS), but not perpendicular to it.

When considering the one-dimensional (1D) LOS measurements provided by SAR satellites, it is essential to analyze the displacement factor, expressed in millimeters per year (mm/yr). These measurements reflect the velocity at which a point on the Earth's surface is moving towards or away from the satellite. The LOS displacement is a projection of the actual three-dimensional (3D) motion onto the sensor's LOS, encapsulating both the magnitude and direction of movement in a single value.

This projection enables the detection and quantification of vertical and horizontal (east-west) displacements with a high degree of accuracy. However, due to the geometric constraints imposed by the satellite's orbit, movements along the north-south axis are not directly measurable. This is a significant consideration in the analysis and interpretation of SAR data, as it necessitates the use of additional methodologies or assumptions to infer north-south movements indirectly.

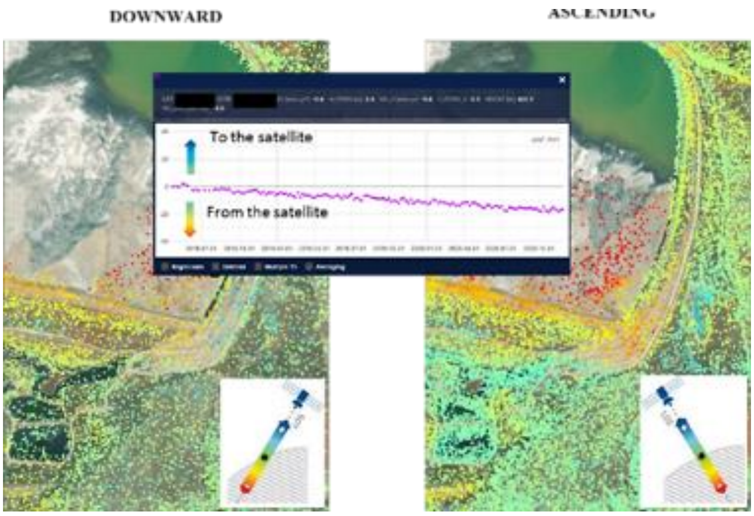


Figure 10. 1D line-of-sight (LOS) measurements and displacement factor (velocity) [mm/year]

Two-dimensional (2D) line of sight (LOS) measurements, along with the displacement factor, quantified as velocity in millimeters per year (mm/year), are pivotal metrics in the field of remote sensing, particularly when utilizing Synthetic Aperture Radar (SAR) technology. These measurements provide a nuanced view of the Earth's surface dynamics by encapsulating both the rate and direction of displacement within the plane defined by the satellite's LOS.

The 2D LOS approach integrates information on the movement of the Earth's surface along the satellite's LOS, combining both vertical and horizontal (east-west) components of displacement. This integration is critical for accurately assessing the behavior of natural and anthropogenic features over time. The velocity component, expressed in mm/year, offers a precise measurement of the speed at which these features are moving towards or away from the satellite, providing invaluable data for monitoring geological phenomena, infrastructure stability, and the effects of climate change on the environment.

By analyzing 2D LOS measurements and displacement velocities, scientists and engineers can detect subtle ground deformations, assess risks associated with landslides and earthquakes, monitor subsidence, and evaluate the structural health of buildings and other infrastructure. This data is essential for informed decision-making in urban planning, disaster management, and environmental conservation.

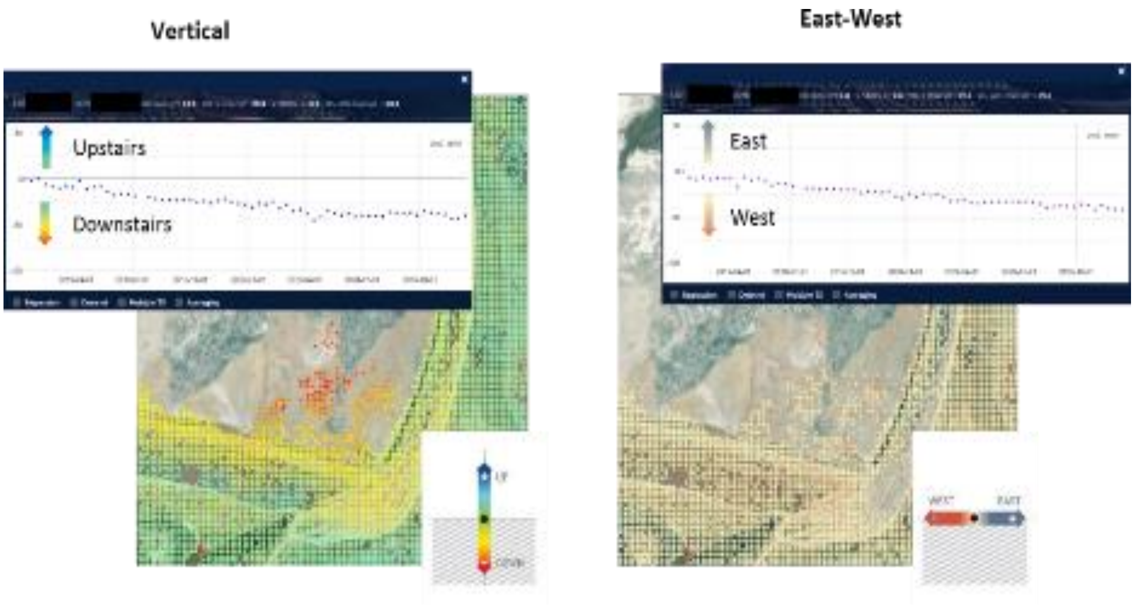


Figure 11. 2D line of sight (LOS) measurements and displacement factor (velocity) [mm/year]

Results and discussion. To guarantee a foundational level of operational security for tailings dams, the preliminary requirement is the early detection of any movements within these structures. Interferometric Synthetic Aperture Radar (InSAR) stands out as a pivotal technology in this context, as it possesses the capability to discern variations in movement patterns of the dams. InSAR technology enables the monitoring of these critical infrastructures by detecting slight displacements that may indicate potential instability or failure risks, thereby facilitating timely intervention measures (Figure 12).

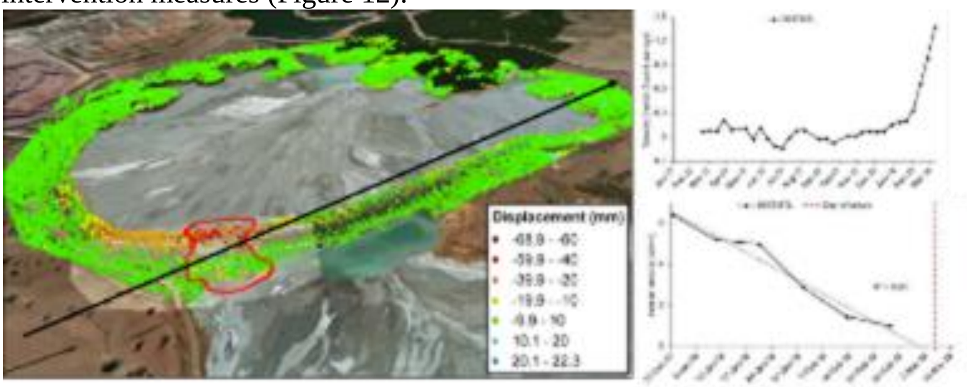


Figure 12. Early motion detection with InSAR

It is critical to acknowledge that InSAR technology extends its utility beyond mere detection of surface movements; it is adept at analyzing multiple stratifications within a tailings management facility. This multi-layered insight allows for a comprehensive assessment of the dam's condition, encompassing both surface and subsurface anomalies. By leveraging InSAR's capacity to provide detailed observations across various layers of the tailings dams, stakeholders can implement more informed and effective management strategies (Figure 13, 14).

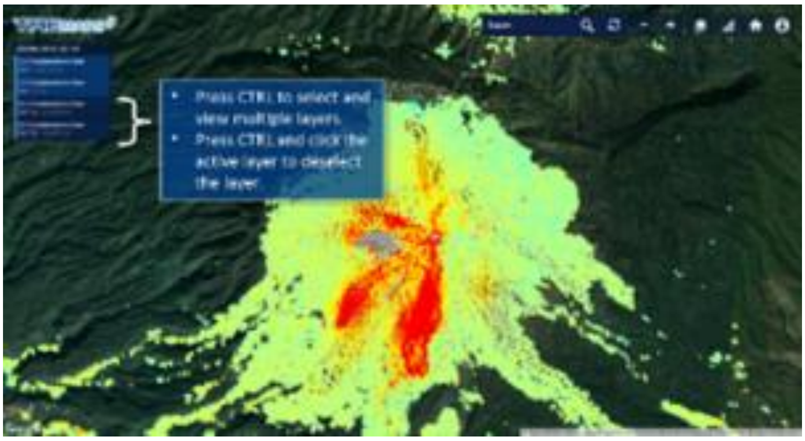
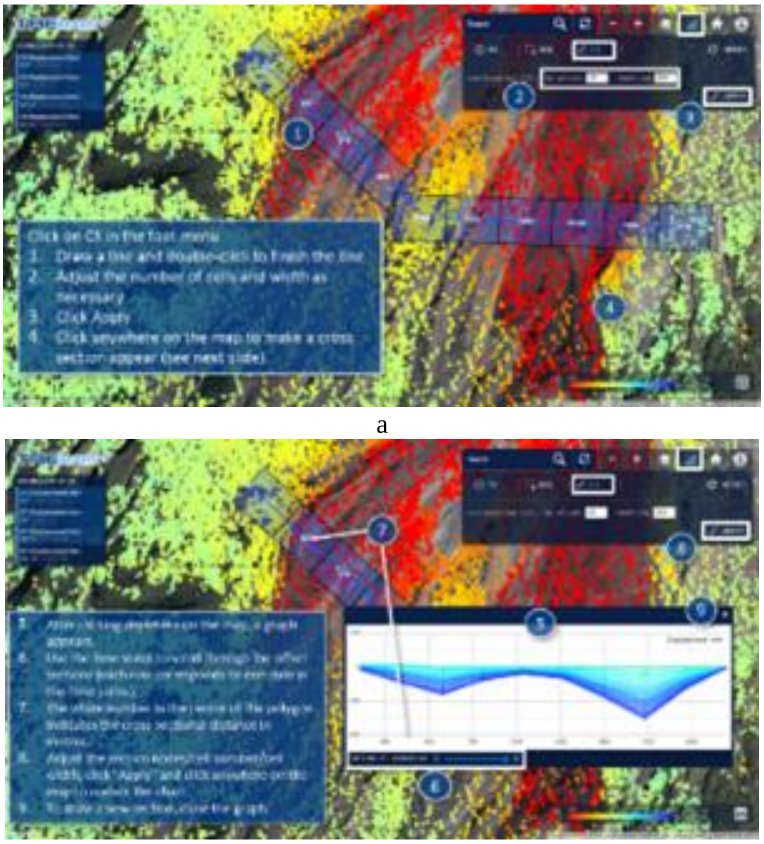


Figure 13. View multiple layers



a

b

Figure 14. View offset cross-section: a) Define cross-section; b) Construct cross-section

The employment of InSAR technology in monitoring tailings dams embodies best practices aimed at preempting incidents at these facilities. By proactively identifying and addressing potential threats, the likelihood and severity of accidents can be significantly reduced, thereby mitigating their impact on both the environment and human communities. The adoption of InSAR in ensuring the operational safety of tailings dams thus contributes vitally to the environmental conservation efforts and the safeguarding of public health and safety. Through the strategic application of InSAR, we enhance our commitment to protecting the ecosystem and ensuring the welfare of the population in the surrounding areas (Table 2, Figure 15).

Table 2. Data types and frequency

№	Zone type	Product	Update frequency
1	Tailings	SqueeSAR (time series points)	Every 11 days
2	Whole mine	SqueeSAR (time series points)	Every 6 months
3	Tailings pond / whole mine	Optical orthoimage	Annually / as requested

Table 3. Downloading a report from TREmaps software

Date	Picket № (Displacement in m)										Rates		
	P-274	P-275	P-276	P-277	P-278	P-279	P-280	P-281	P-282	P-283	AVG	Positiv	Negativ
01.06.2023	-0.012	-0.025	0.014	-0.004	0.009	-0.013	-0.022	-0.008	0.005	-0.016	-0.007	0.028	-0.100
01.07.2023	0.007	0.011	-0.011	-0.014	0.001	-0.027	-0.012	0	-0.012	-0.010	-0.007	0.019	-0.086
01.08.2023	-0.004	0.004	0.012	-0.027	-0.020	-0.015	-0.013	0.012	-0.018	-0.019	-0.009	0.028	-0.116
01.09.2023	-0.022	-0.007	-0.017	-0.016	-0.001	-0.017	-0.002	0.005	-0.006	-0.026	-0.011	0.005	-0.114
01.10.2023	-0.027	-0.011	-0.021	-0.024	0.007	-0.017	-0.003	0.003	-0.012	0.007	-0.010	0.017	-0.115
01.11.2023	-0.011	-0.024	-0.021	-0.006	-0.001	-0.013	-0.007	-0.015	-0.003	-0.006	-0.011	0.000	-0.107
01.12.2023	0.01	-0.023	-0.018	-0.009	0.012	-0.002	-0.023	-0.011	-0.012	-0.024	-0.010	0.022	-0.122
01.01.2024	-0.011	0.006	-0.017	-0.006	-0.008	0.009	-0.009	0.006	-0.008	0.009	-0.003	0.030	-0.059
01.02.2024	-0.021	-0.018	-0.016	-0.020	0.009	-0.004	0.001	0.011	0.002	-0.010	-0.007	0.023	-0.089
AVG	-0.010	-0.010	-0.011	-0.014	0.001	-0.011	-0.010	0.000	-0.007	-0.011			
Positiv	0.017	0.021	0.026	0.000	0.038	0.009	0.001	0.037	0.007	0.016			
Negativ	-0.108	-0.108	-0.121	-0.126	-0.030	-0.108	-0.091	-0.034	-0.071	-0.111			

№	Tolerance	
	Min	Max
1	-68.9	-60
2	-59.9	-40
3	-39.9	-20
4	-19.9	-10
5	-9.9	10
6	10.1	20
7	20.1	22.3

Figure 15. Offset cross-section pickets and tolerances

Table 3 presents a detailed dataset chronicling the displacement measurements, in millimeters, of designated points – referred to as pickets, labeled P-274 through P-283 – recorded on the first day of each month from June 2023 to February 2024. The dataset includes both positive and negative displacement values, indicating that the observed movements or adjustments have occurred in various directions or have been subject to correction over time

A nuanced analysis of the displacement data across these pickets over the specified dates reveals distinct patterns; certain pickets, such as P-274 and P-275, exhibit consistently negative displacements, while others, for instance, P-276 and P-281, show a combination of positive and negative movements.

The column labeled "AVG" computes the average displacement for all monitored pickets on each respective date, with the resultant mean values predominantly negative. This trend suggests a general movement or adjustment in that direction across the observed points.

Furthermore, the data are categorized under "Rates," delineated into "Positive" and "Negative" segments, presumably to highlight the maximum rates of displacement observed in either direction across the pickets. This stratification may serve as an indicator of the extremities of movement rates that the pickets have undergone.

The compilation of this dataset likely serves as part of an ongoing monitoring effort aimed at assessing structural integrity, evaluating earth settlement, or detecting other precise physical changes within the monitored environment.

An overarching trend towards negative displacement is discernible, with negative rates often surpassing positive ones, particularly notable in the data from December 2023 and January 2024. The maximum positive displacement recorded within this period is 0.030 meters, and the most substantial negative displacement observed is -0.122 meters.

The presence of positive displacements in some pickets may suggest the implementation of corrective actions or the influence of opposing forces or conditions.

The underlying objective of monitoring these displacements is paramount, as it underlines the significance of the observed values. In contexts such as structural health monitoring, even minor displacements can have critical implications. Conversely, within geological or broader scale observations, these displacements might be considered within expected norms. Hence, this monitoring exercise is structured to systematically oversee and analyze the progression of these physical changes, ensuring the continual assessment of the condition or stability of the monitored system or structure (Table 4).

Table 4. Monitoring procedure

Reasons	Warning controls	Mitigating controls	Consequences
Breach of integrity of the tailings dam barrier	Control of the seepage strength of the dam body	Stopping the tailings slurry feed to the tailings pond (according to the emergency response plan)	Significant environmental damage
	Visual inspection of the dam	Discharge of water from the tailings pond by removing shandors at well No. 3 (according to the emergency response plan)	
	Instrumental surveying of the dam	Operational rehabilitation of the tailings dam at the point of breach (scour)	
	Monitoring the condition of the dam using video cameras	Stopping the tailings slurry feed to the tailings pond (according to the emergency response plan)	Land littering with solid phase of tailings, blocking of the Beryozovka River bed and motorway
	Monitoring of the water level in the tailings pond using a measuring rod and a control and measuring device (ultrasonic level gauge)	Discharge of water from the tailings pond by removing shandors at well No. 3 (according to the emergency response plan)	
	Stopping the tailings slurry feed to the tailings pond (according to the emergency response	Operational rehabilitation of the tailings dam at the point of breach (scour)	
	Monitoring of the water level depression curve in the dam body using piezometers and	Stopping the tailings slurry feed to the tailings pond (according to the emergency response plan)	Significant economic costs of liquidation activities, material compensation
	Increase in the volume of water discharged from the tailings dam	Discharge of water from the tailings pond by removing shandors at well No. 3 (according to the emergency response plan)	
Intense flooding	Stopping the tailings slurry feed to the tailings pond (according to the emergency response	Operational rehabilitation of the tailings dam at the point of breach (scour)	
	Monitoring of the water level depression curve in the dam body using piezometers and gauges	Prompt and effective measures to eliminate and minimise the consequences of the accident	Damage to the company's image
	Monitoring of the water level in the tailings pond using a measuring rod and a control and measuring device (ultrasonic level gauge)	Correct and well-tested presentation of information to the media and the public	
	Increase in the volume of water discharged from the tailings dam	Highly skilled legal Litigation support for the case	Legal proceedings
	Monitoring the water cut-off in the tailings dam using video cameras	Stopping the tailings slurry feed to the tailings pond (according to the emergency response plan)	Complete shutdown of the concentration plant
Disruption of the functionality of the operation Water Pumping Station 4/2 (WPS 4/2)	Control over technological parameters of wastewater disposal	Discharge of water from the tailings pond by removing shandors at well No. 3 (according to the emergency response plan)	
	Visual inspection of the integrity of manhole No.3 and the collector	Operational rehabilitation of the tailings dam at the point of breach (scour)	
	Monitoring the water cut-off in the tailings dam using video cameras		
	Stopping the tailings slurry feed to the tailings pond (according to the emergency response plan)		
	Monitoring of the water level depression curve in the dam body using piezometers and instrumentation		
	Monitoring of the water level in the tailings pond using a measuring rod and a control and measuring device (ultrasonic level		
Violation of reclamation technology beach tailings dump	Control of tailings dam beach reclamation parameters		
	Monitoring the reclamation of the tailings dam beach using video cameras		
	Stopping the tailings slurry feed to the tailings pond (according to the emergency response plan)		
	Monitoring of the water level in the tailings pond using a measuring rod and a control and measuring device (ultrasonic level		
	Monitoring of the water level depression curve in the dam body using piezometers and instrumentation		
	Increase in the volume of water discharged from the tailings dam		
Incorrect design decisions	Author's supervision by Mekhanobr Engineering specialists		
	All deviations from the project should be coordinated with the design supervising organisation Mekhanobr Engineering.		
Seismic activity (earthquake)	Control of slope gradients of the dam slopes relative to the root mark of the bench marks		
	Construction of the dam embankment to the 470 metre level		
Sabotage	Organisation of a set of security measures by the security service		
	Stopping the tailings slurry feed to the tailings pond (according to the emergency response plan)		

Conclusions. The effective and safe disposal of mining waste is a complex technical and environmental challenge. Each site has unique characteristics, and a sensible, site-specific approach is required to ensure safety, environmental sustainability and economic viability. Despite increased caution in many countries with respect to tailings management facilities, the safety of tailings management facilities, both during operation and after decommissioning, requires further improvement. This issue should also be considered in the context of climate change, which may increase the risk of industrial accidents due to natural disasters such as earthquakes and floods, posing serious threats to tailings management facilities.

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