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MONITORING THE INACTIVE LANDFILL STABILITY IN GORJ COUNTY

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Abstract

Monitoring landfill stability is critical in mining operations to prevent failures that could have significant environmental and safety implications. Site characterization is a comprehensive approach to monitoring landfill stability in order to conduct detailed geological assessments to understand the composition, structure, and physical properties of the tailing material, to perform laboratory tests to assess the engineering properties, all these correlated with geodetic repeated measurements. Techniques and instruments used in geodetic monitoring are chosen depending on the type of surveyed displacement and level of accuracy required. Photogrammetric and remote sensing technologies play an essential role in the detection and monitoring displacements and deformations, providing crucial support in the rapid and effective management of these emergencies. These techniques allow for large-scale, continuous monitoring of slope movements without requiring direct contact with the slope. This way, it ensures precise deformation monitoring, validates theoretical models, enhances predictive capabilities, and supports safety, regulatory compliance, and environmental protection efforts. A well-designed monitoring system not only ensures compliance with environmental regulations but also provides valuable insights for designing effective mitigation and rehabilitation strategies.

Key words: *displacement and deformation, environmental protection, geotechnical assessment, monitoring landfill stability, photogrammetric and remote sensing technologies.*

INTRODUCTION

Precise spatial measurement, a surveyor's most traditional and well-known expertise, is crucial not only for monitoring climate change impacts but also for developing adaptation strategies. Detailed topographic mapping, fundamental for land use planning and deformation monitoring, can be achieved through conventional surveying techniques, laser scanning, or digital image analysis. The construction of new engineering infrastructure to support climate change adaptation depends on geodetic measurements - such as levelling, total stations, and GNSS technologies – complemented by visual assessments and geotechnical data (Hannah et al., 2014).

At the 2002 World Summit on Sustainable Development, nine key societal benefits of Earth observations were identified (United Nations publication, 2002): disaster management (minimizing loss of life and property from natural and human-made disasters), health (analysing environmental factors affecting human well-being), energy resources (enhancing energy resource management), climate (assessing, predicting, mitigating, and adapting to climate variability and change), water (improving water resource management by understanding the water cycle), weather (enhancing forecasting and warning systems), ecosystems (better management and protection of terrestrial, coastal, and marine ecosystems), agriculture (promoting sustainable farming and combating desertification), and biodiversity (monitoring, preserving, and understanding biodiversity).

Romania adheres to Decision No. 766 of November 21, 1997, which governs the monitoring of construction behaviour during operation, investment phases, and post-usage. Published in the Official Gazette No. 352 on December 10, 1997, this law applies to all types of constructions and aims to evaluate their technical condition while ensuring their continued suitability for use. In the field of construction and civil engineering, a tailings landfill is a designated site for storing mine tailings, which are the residual materials left after valuable minerals have been extracted from ore. These tailings, typically consisting of fine rock particles, water, and chemicals, are often disposed of in large, controlled piles or ponds.

Monitoring the stability of tailings landfill slopes is essential in mining operations to prevent failures that could lead to severe environmental and safety consequences. Quality in the construction sector is maintained through the following measures (Hannah et al., 2014; Caldera et al., 2016):

- Monitoring construction behaviour during operation to ensure structural stability and enable early detection of potential degradations.
- Interventions involving construction work aimed at maintaining or enhancing operational efficiency.
- Post-usage management, including safe demolition or in-situ abandonment, efficient material recovery, environmental restoration, and sustainability assurance.

The security and sustainability of a tailings landfill are evaluated based on two key engineering and environmental factors (Hannah et al., 2014; Caldera et al., 2016; CRED, 2016; VicRoads, 2021):

- Geotechnical stability: Engineering design must ensure that the tailings landfill remains structurally safe, preventing catastrophic failures such as tailings dam collapses.
- Environmental impact: Effective management of tailings landfills is crucial to prevent pollution of nearby water sources, soil contamination, and harm to wildlife. In some cases, monitoring is necessary to detect the release of hazardous substances like heavy metals or cyanide.

A comprehensive approach to assessing landfill slope stability involves site characterization (Hannah et al., 2014; Caldera et al., 2016; CRED, 2016; VicRoads, 2021):

- Geological surveys: Conducting thorough geological assessments to determine the composition, structure, and physical properties of the tailing's material.
- Soil and rock testing: Performing laboratory analyses (e.g., shear strength, consolidation, and permeability tests) to evaluate the engineering properties of the tailings.

MATERIALS AND METHODS

Monitoring tailings landfills – large accumulations of waste materials from mining operations – is essential to ensuring environmental safety, structural stability, and regulatory compliance. Slope stability assessment relies on two complementary approaches: the geotechnical approach (analytical) and the parametric approach (measurable). A comprehensive and realistic evaluation of tailings landfill stability requires considering both perspectives (Caldera et al., 2016; CRED, 2016; Gilbert Gedeon, 2021; VicRoads, 2021). Slope stability and landslide monitoring involve identifying specific parameters and tracking their variations over time. The two primary factors in this process are groundwater levels and displacement. Slope displacement is analysed based on failure plane depth, direction, magnitude, and rate, with one or more of these aspects being continuously monitored.

Traditional slope monitoring employs either a single method or a combination of techniques. Piezometers measure water levels, while tools such as surveyed surface monuments, extensometers, inclinometers, and tiltmeters provide insights into slope movement direction, rate, depth, and failure plane extent. Extensometers specifically help quantify displacement magnitude. For long-term slope monitoring, manually operated probe inclinometers are the most widely used instrument (Caldera et al., 2016; CRED, 2016; Gilbert Gedeon, 2021; VicRoads, 2021). Effective waste landfill management requires a combination of monitoring activities and interventions to ensure both stability and sustainability.

These approaches are divided into invasive and non-invasive methods. Invasive methods involve direct physical interaction with the landfill mass, such as drilling, excavation, or other intrusive processes. Non-invasive methods enhance and assess landfill stability without disturbing the waste mass, using remote sensing, surface-based techniques, and indirect monitoring measures. By integrating both invasive and non-invasive strategies, tailings landfills can be efficiently monitored and stabilized, promoting long-term environmental and structural sustainability (Caldera et al., 2016; CRED, 2016; Gilbert Gedeon, 2021; VicRoads, 2021).

The typical workflow for tailings landfill monitoring focuses on:

1. PLANNING AND PREPARATION

The monitoring of tailings landfills starts with a site assessment, which involves identifying specific risks related to the landfill, such as its composition, size, slope, and proximity to sensitive areas like water bodies or nearby communities. This phase also includes defining the monitoring objectives, which may focus on detecting seepage, evaluating slope stability, tracking dust emissions, or ensuring compliance with safety regulations (Popa, 2012; CRED, 2016).

2. DATA COLLECTION

The data collection process employs a combination of manual and automated techniques to monitor various environmental and structural conditions of the tailings landfill (Figure 1). Routine monitoring is a systematic process focused on assessing the technical condition of the land or structures. Its primary goal is to ensure stability during operation. If certain parameters exceed predefined thresholds, special monitoring must be implemented. This involves conducting regular, periodic investigations on specific parameters to assess deformations in the land, structures, or specific components. Special monitoring activities are typically defined during the project planning phase or determined through technical expertise (UTCB, 2009; Popa, 2012; Buchmayer et al., 2021).

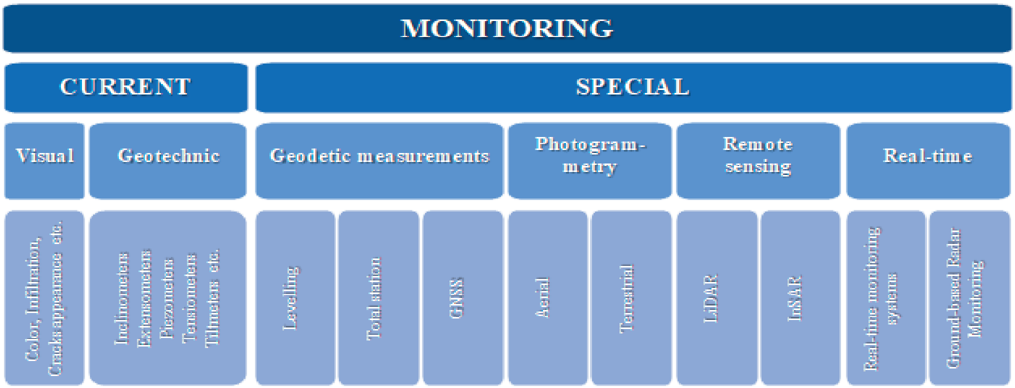

Figure 1. Monitoring methods and instruments - classification by monitoring aspects

Visual Monitoring

Regular field inspections and surveys play a crucial role in supplementing instrument-based monitoring. Visual inspections help identify early warning signs of instability, such as the formation or expansion of surface cracks, changes in vegetation or water drainage patterns (which may indicate subsurface movement or shifts in stability), and surface subsidence or slumping. These issues are particularly common in carbonate deposits due to karst features or weathering (UTCB, 2009).

Geotechnical Monitoring

Geotechnical monitoring utilizes various instruments to continuously or periodically measure ground movements, stresses, and other factors influencing slope stability.

The geotechnical parameters essential for ensuring construction stability and safety can be categorized into two main groups (UTCB, 2009):

- Environmental factors: These include water levels, air temperature, water temperature at various depths, solar radiation, and seismic activity.
- Structural response measurements: These depend on the type of construction. For tailings landfills, key monitored parameters include: absolute and relative displacements of the landfill and geotechnical characteristics, particularly vertical settlements during construction and operation, displacement between structural

elements, temperature variations within the landfill body, deformation and stress conditions, crack development, infiltration rates and the position of the infiltration curve, pore water pressure within earthen sealing elements, effective and total stress conditions, and slope displacements and infiltration through slopes.

Monitoring instruments must be deployed in adequate numbers and at appropriate intervals to detect abnormal behaviour. When irregularities are observed, the data collected – combined with field inspections – should enable the identification of underlying causes. In some cases, additional monitoring tools may be required (UTCB, 2009).

Advancements in technology, particularly the Internet of Things (IoT), have significantly enhanced traditional monitoring methods, overcoming challenges such as low measurement frequency and time-intensive data collection. IoT-based systems enable real-time and precise tracking of changes in enclosure structures, allowing for dynamic adjustments to construction parameters and techniques (Figure 2). This adaptive monitoring approach provides critical technical support by assessing the stability of surrounding rock formations, evaluating the reliability of primary supports and secondary linings, refining support system designs based on real-time data, determining optimal timing for secondary lining installation, and adjusting construction methods to enhance overall structural safety and efficiency. By integrating modern monitoring technologies, construction teams can proactively address stability concerns, ensuring the long-term safety and sustainability of tailings landfills (Buchmayer et al., 2021).

Global investigations focus on determining the geophysical structure and geotechnical characteristics of a tailings landfill, as well as detecting water circulation within the landfill and its surrounding environment. Piezometers are used to measure pore water pressure within weak soil layers, particularly inside slopes. Installed in boreholes within the landfill or slope, these instruments monitor fluctuations in water pressure within carbonate rock formations. Elevated pore pressure can reduce effective stress, potentially leading to slope instability. In carbonate deposits, water infiltration through fractures or karst formations can further contribute to slope failures. Piezometer data is essential for tracking groundwater conditions and assessing stability risks (UTCB, 2009; Buchmayer et al., 2021.

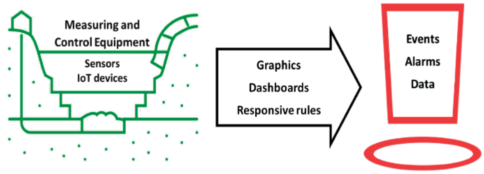

Figure 2. The use of modern technologies in monitoring activities

In addition to geotechnical monitoring instruments, seismic activity monitoring is critical for tailings landfills. Seismometers record ground movement, measuring velocity and acceleration, while seismographs track acceleration over time. For comprehensive seismic monitoring, devices should have three measurement components and be installed at three levels at least: the crest elevation of the tailings landfill, the foundation level, and the open field reference point. The interpretation of seismic data and application of results must be conducted by qualified specialists to ensure accurate risk assessments and effective mitigation strategies (UTCB, 2009; Buchmayer et al., 2021).

Geodetic Measurements

Field surveys are commonly conducted using geodetic methods and instruments such as levelling, total stations, and GNSS systems, which enable the detection of surface movements over time. The Monitoring Geodetic Network (MGN) consists of two main categories of points (Figure 3) (Popa, 2012):

- Reference points: These are further classified into three types: survey points – directly used for monitoring the targeted structure, control points – assess the stability of survey points, and orientation points – provide geodetic network alignment. Reference points must meet several essential criteria: ensure long-term stability and reliability, be strategically positioned to enable precise and accurate data collection, be placed on solid, stable geological formations to prevent movement-related distortions, and be located in areas

where groundwater levels do not compromise stability.
- Object points: These points must also fulfil specific requirements: they should be embedded within the load-bearing components of the structure, and their placement should align with the foundation's geometry and load distribution to ensure accurate monitoring.

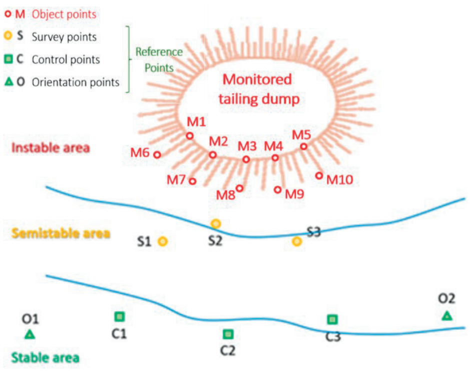

Figure 3. The monitoring geodetic network

Techniques and instruments used in geodetic monitoring are chosen depending on the type of surveyed displacements and deformations, and level of accuracy required.

Photogrammetry

Photogrammetry plays a significant role in slope stability monitoring by providing accurate, detailed, and often real-time measurements of changes in the surface geometry of slopes, being preferred over traditional methods. Photogrammetry contributes to surface change detection (comparing models over time, deformations, cracks, subsidence, or bulging can be revealed – key signs of instability). Photogrammetry allows the surveying of extensive or dangerous terrains without needing physical access, ensuring safety while capturing critical data. The outputs of repeated surveys can be integrated into Geographic Information Systems (GIS) for more advanced geotechnical analyses and risk mapping. Photogrammetry is an effective method for monitoring terrain displacement, particularly useful for generating 3D models of slopes through photographic imagery. Multiple aerial or ground-based photos are combined to create detailed models of the landfill slope. By comparing models taken at different times, any changes in the slope can be identified. This technique is particularly useful for detecting surface cracks, erosion, and slumping in carbonate deposits (Hannah et al., 2014; Dimen et al., 2024).

Photogrammetry combines precise visual data with geospatial analysis, making it ideal for both large-scale and localized environmental monitoring projects (Hannah et al., 2014; Dimen et al., 2024).

Photogrammetry and unmanned aerial vehicles (UAVs) are closely linked, with UAVs enhancing photogrammetry by providing a versatile and efficient platform for capturing aerial imagery, which serves as the foundation for photogrammetric analysis (Hannah et al., 2014).

A UAV (drone) can operate autonomously or be controlled remotely. Equipped with technologies like GNSS, cameras, sensors, and specialized software for tasks such as collecting data from hard-to-reach areas, UAVs are increasingly utilized in monitoring (Hannah et al., 2014).

The imagery captured by UAVs is processed using photogrammetry software to create 3D models, orthomosaics, and contour maps. Advanced algorithms use overlapping images to triangulate points and generate accurate spatial data, which is then correlated with other field-collected information (Hannah et al., 2014).

Though, there are a few challenges which should be kept in mind. Photogrammetry requires good lighting and clear views (vegetation can be a problem), while accuracy depends heavily on ground control points and the camera quality and processing software. Photogrammetry mostly tracks surface movement, not internal slope deformations (for subsurface issues, photogrammetric surveys still need to be correlated with geotechnical measurements).

Remote Sensing

Modern remote sensing technologies play a crucial role in detecting and monitoring displacements and deformations in tailings landfills. These technologies support rapid and effective management, enabling large-scale, continuous monitoring of slope movements without direct contact. This is especially valuable for monitoring expansive landfill slopes in mining operations (Hannah et al., 2014; Dimen et al., 2024).

When satellite data is combined with aerial imagery and field measurements, it provides an accurate and comprehensive view of the monitored area. This data is crucial for coordinating adaptation strategies, responding to emergencies, and optimizing resource allocation. It also aids in planning operational measures and predicting future behaviour (Dimen et al., 2024).

Real-time Monitoring

A real-time monitoring system continuously collects data and provides alerts for any significant changes. The goal of such systems, especially for mining waste landfills, is to ensure safety, environmental compliance, and operational efficiency. Real-time data helps detect even small, progressive slope movements before they escalate into major failures, allowing for prompt mitigation actions in cases of structural instability, excessive seepage, or environmental contamination (UTCB, 2009; Buchmayer et al., 2021).

In addition to geotechnical, hydrological, and environmental sensors, real-time monitoring systems should include GNSS and total stations for precise surface movement monitoring.

These sensors continually collect data on various parameters, with wireless communication networks (e.g., 4G/5G, LoRaWAN, or satellite links) transmitting the information in real-time to central monitoring stations or cloud-based platforms. Specialized software analyses incoming data to identify anomalies and trends. Machine learning algorithms or predefined thresholds can trigger automated alarms when critical conditions are detected (Buchmayer et al., 2021).

The data is displayed on user-friendly dashboards featuring charts, maps, and 3D visualizations. Stakeholders are notified via SMS, email, or other notification systems when thresholds are exceeded. Real-time data is also integrated with weather monitoring, geological models, and remote sensing data (such as from drones or satellites) for a comprehensive analysis (UTCB, 2009; Buchmayer et al., 2021).

Interpretative algorithms are absolutely crucial when it comes to predicting landfill slope failures, especially when working with large, complex datasets. Modern monitoring methods produce huge datasets (e.g. point clouds, images, displacement maps). Algorithms process, analyse, and filter this data efficiently, identifying meaningful patterns or anomalies that humans would miss. There could be early warning signs, like subtle slope movements (millimetres of displacement), that can be an early indicator of impending failure. Algorithms can detect these small changes over time, often earlier and more accurately than manual inspections. By learning historical deformation patterns, algorithms can predict future behaviour, recognizing acceleration trends that precede a collapse. Moreover, algorithms can combine various factors (e.g. displacement rates, rainfall data, soil type, slope angle) to quantify failure probabilities, turning subjective assessments into objective risk metrics, aiding decision-making. Interpretative algorithms interpret incoming data in real time. If critical thresholds are crossed (e.g. displacement rate suddenly doubles), the system can trigger alarms immediately (Buchmayer et al., 2021).

By continuously monitoring the landfill, real-time systems enable proactive risk management, providing ongoing insights into structural, environmental, and operational conditions. This technology supports sustainable, safe management practices, reduces risks to human life and the environment, and improves decision-making (Caldera et al., 2016; CRED, 2016).

3. DATA TRANSMISSION AND MANAGEMENT

Data from different type of sensors and monitoring devices are consolidated within a centralized system, often referred to as a Supervisory Control and Data Acquisition (SCADA) system or a similar platform. This system enables real-time monitoring and triggers alerts in response to abnormal readings, such as unusual seepage or deformation (Figure 4) (Buchmayer et al., 2021).

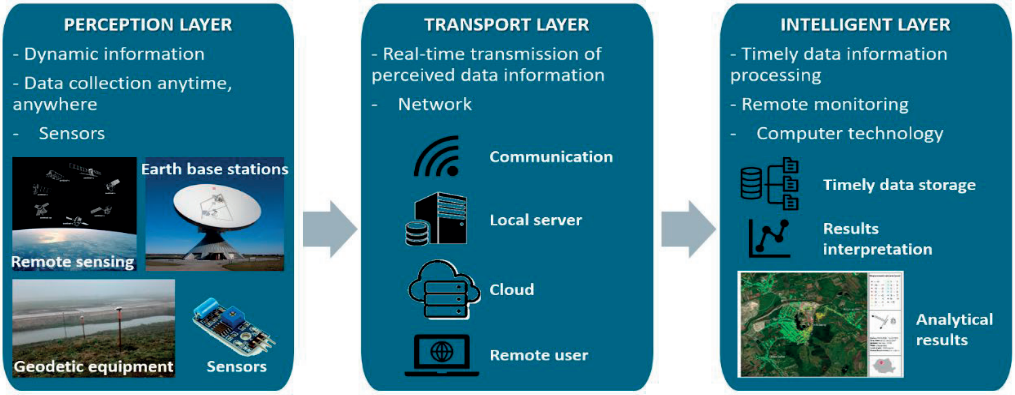

Figure 4. Layers of a real-time monitoring system

4. DATA ANALYSIS

For thorough analysis and interpretation, field-collected data is integrated by combining outputs from various instruments using specialized software designed for analysis and stability assessments. The data is then processed and interpreted to uncover patterns, trends, and potential issues. To create a 3D model of the tailings landfill for further analysis, the collected data must be processed using specific modelling software. Interpolation techniques are often required due to challenges in data acquisition and the limited number of measurement points. Most modelling software provides users with various interpolation methods to choose from. Before selecting the most suitable spatial interpolation technique, it is essential to evaluate the assumptions and characteristics of each approach, along with the spatial properties and analysis of the data (Herban & Alionescu, 2012).

Several factors influence the accuracy of Digital Elevation Models (DEMs), including sampling density for contour derivation, the vertical spacing of contours, the grid cell size of the DEM, field complexity, and spatial filtering. Advances in terrestrial measurement technology have significantly improved accuracy, enabling the development of models that can be utilized in deformation analysis and predicting the future behaviour of the tailings landfill (Figure 5) (Herban & Alionescu, 2012).

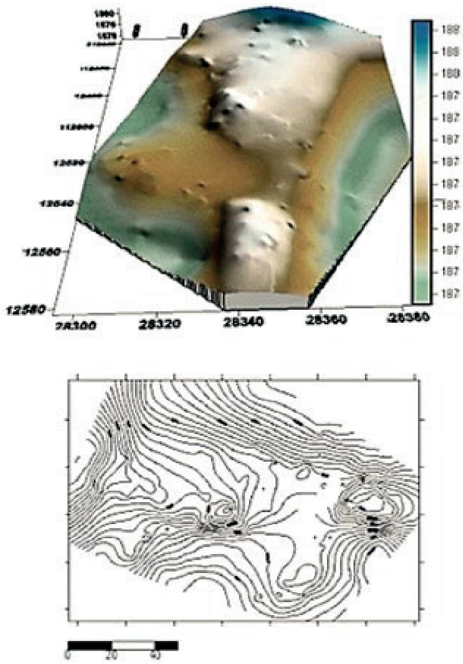

Figure 5. Digital elevation model and contour lines (Herban & Alionescu, 2012)

Data Quality Control

Data cleaning is essential to eliminate outliers or erroneous values, often caused by sensor malfunctions. The validated data must align with known benchmarks and expected ranges for parameters like pH, temperature, and deformation (Welsch & Heunecke, 2005; Popa, 2012).

The relation between geotechnical parameters (e.g., pH, temperature) and landfill slope stability is indirect but significant, because they influence the geotechnical behaviour of the waste material, leachate chemistry, and biological activity, all of which affect how stable the landfill slope is. Low pH accelerates the breakdown of organic materials leads to weaker waste material, and, therefore, higher risk of slope failures. On the other side, a neutral or high pH leads to more chemically stable environment and more stable slopes. High temperatures are more often met in case of waste weakening and could be an early sign for slope instability.

Statistical and Geospatial Analysis

Statistical methods, such as regression and trend analysis, are applied to detect significant changes in tailings behaviour, including gradual slope shifts or sudden seepage spikes. Environmental conditions, like rainfall or temperature, are correlated with variations in tailings characteristics, such as water chemistry and seepage rates. Geographic Information System (GIS) software enables mapping of monitoring points to visualize spatial patterns, like areas of excessive settling or deformation. By overlaying environmental data—groundwater and surface water quality—onto topographical maps, risks of contamination can be assessed (Welsch & Heunecke, 2005; Popa, 2012).

During analysis, the tailings landfill is treated as a unified system, fully monitored to identify displacements and deformations over time. Repeated measurements relative to the surrounding environment form the basis for determining absolute displacements (Welsch & Heunecke, 2005; Popa, 2012).

To forecast future evolution with maximum accuracy, displacement and deformation models are developed by analysing changes over time and space. These models incorporate causal forces, such as internal or external stresses, which drive the displacements and deformations (Nikolić, 2009).

A practical method involves integrating observation-based analyses to study displacements and deformations. This includes geometric state analysis and physical interpretations that identify dynamic processes. "Integrated analysis" refers to merging geometric evaluations with predictive models (Welsch & Heunecke, 2005).

The synergy between geodetic repeated measurements and parametric modelling is pivotal for effective tailings landfill monitoring and management. Geodetic measurements yield high-resolution spatial data on deformations, while parametric models contextualize these measurements, integrating geotechnical and environmental factors. By combining these approaches, deformation trends can be precisely analysed, risks predicted, and future behaviours simulated under varying conditions (Welsch & Heunecke, 2005; Popa, 2012).

This integrated framework validates theoretical models while enhancing safety compliance and environmental stewardship. It enables proactive identification of hazards - like seepage or slope failures - that may lead to contamination or ecological damage. Ultimately, the correlation fosters a robust risk assessment strategy, supporting informed decision-making and resource optimization to protect human lives, infrastructure, and the surrounding ecosystem (Welsch & Heunecke, 2005; Popa, 2012).

Predictive Modelling, Alarm Systems and Thresholds

Historical data is utilized to develop predictive models that can anticipate issues such as tailings dam failure, seepage migration, or structural shifts. These models support proactive management and the establishment of early warning systems. Key parameters, such as maximum allowable pore pressure or ground displacement, are assigned thresholds. If these thresholds are exceeded, alarms are triggered to alert the management team to potential risks (Welsch & Heunecke., 2005).

5. REPORTING AND DECISION MAKING

Reporting involves generating regular summaries of monitoring data and analysis. These reports typically include visual representations, such as graphs, charts, and maps, alongside an assessment of trends and anomalies. Recommendations for mitigation measures or further monitoring are also provided. Ensuring regulatory compliance involves meeting environmental regulations, standards, and submitting the necessary reports to local authorities or regulatory bodies (Welsch & Heunecke, 2005; Caldera et al., 2016; CRED, 2016).

Based on these analyses, the management team may implement actions such as modifying the operation of the tailing's facility, strengthening the structure, or initiating deeper investigations. After each monitoring cycle, it is crucial to review the system's effectiveness. This review assesses whether the data collected is sufficient and accurate, prompting adjustments to the monitoring strategy where needed—for example, adding sensors or altering data collection intervals (Welsch & Heunecke, 2005; Caldera et al., 2016; CRED, 2016).

As technologies advance, adopting new monitoring tools and analytical techniques should be considered to enhance accuracy and efficiency in the monitoring process.

RESULTS AND DISCUSSIONS

Ensuring the stability of landfill slopes in carbonate deposits requires a combination of instrumentation, remote sensing, and geotechnical modelling. The unique characteristics of carbonate formations - such as fractures, karst features, and susceptibility to water infiltration - necessitate a comprehensive monitoring approach to maintain safety and stability. Continuous data collection from these methods enables the early detection of potential failures, allowing for proactive mitigation (Welsch & Heunecke, 2005; Caldera et al., 2016; CRED, 2016).

A multi-faceted approach is essential for monitoring tailings landfill slope stability, integrating traditional geotechnical techniques with modern technology. By implementing a robust monitoring program, mining operations can significantly reduce risks associated with tailings storage, enhancing both safety and environmental protection (Welsch & Heunecke, 2005; Caldera et al., 2016; CRED, 2016).

Integrating geodetic repeated measurements with parametric modelling plays a critical role in monitoring tailings landfills, which serve as storage areas for mining waste. This integration delivers precise, timely, and actionable insights into the structural stability, integrity, and environmental impact of the landfill. Key advantages of this correlation include (Welsch & Heunecke, 2005; Caldera et al., 2016; CRED, 2016; Gilbert Gedeon, 2021; VicRoads, 2021):

- Geodetic measurements provide high-precision spatial data on geometric displacements, while parametric modelling aids in understanding the behaviour of the landfill. Together, they enable the detection of deformation trends and early identification of anomalies signalling potential instability. Combining high-precision geodetic tools (e.g. GNSS, LiDAR) with robust modelling and uncertainty analysis is crucial in early warning systems. Thus, minor inaccuracies in measurement or modelling can mask critical pre-failure displacements, especially in systems like landfills where early deformations may be subtle but significant. Small but persistent inaccuracies can lead to misinterpretation of long-term trends, such as poor resolution or incorrect model calibration that may suggest stability even when precursors to failure exist.
- Discrepancies between observed measurements and model predictions can highlight areas for model improvement or uncover hidden risk factors. Geodetic deformation analysis helps validate parametric models, while tailings landfill conditions and responses are simulated based on their characteristics.
- Localized geodetic displacements may indicate risks, such as slope failures or seepage. By considering material properties, loading conditions, and environmental factors, this approach develops a complete risk profile, combining empirical observations with theoretical assessments for more informed decision-making.
- Regular monitoring and reporting are often required to meet regulatory standards. Incorporating geodetic monitoring within parametric models enhances communication with regulators and stakeholders by providing evidence-based assurances of safety and stability. This practice minimizes the risk of overdesigning stabilization measures or underestimating risks, ensuring optimized resource allocation.
- A general monitoring strategy for tailings landfills should support sustainable mining by addressing environmental hazards proactively. Monitoring displacement

patterns can reveal potential pathways for seepage or contamination. Simulating environmental impacts enables the development of effective containment strategies, further reinforcing environmental stewardship.

CONCLUSIONS

Romania complies with legislation regarding the monitoring of construction behaviour throughout all phases of its life cycle – pre-usage, exploitation, and end-of-life. In case of inactive landfills, as construction in the third life cycle phase, a long-term stability assessment is still required, in order to ensure residual waste continuity to settle safely without causing surface deformation or failure, while environmental monitoring involves continuous tracking of groundwater, air quality, and leachate for decades.

Therefore, monitoring through all life cycle phases ensures the landfill does not become a long-term environmental or structural hazard. It protects ecosystems, human health, and investments while enabling informed decision-making.

Monitoring a landfill using both geodetic methods and geotechnical parameter measurements is essential because each approach provides complementary information crucial for understanding and managing stability risks. This approach brings more benefits, such as a comprehensive understanding of landfill stability, early warning and risk mitigation, improvement in data reliability and confidence in decision-making, more accurate predictive modelling for stability assessments, and ensuring compliance and enhancing public and environmental safety.

A range of sensors, including vibrating wire piezometers, electrolytic bubble inclinometers, and tiltmeters, are commonly used to monitor groundwater levels and ground movement for slope stability assessments. Recent advances in electronic technology, coupled with reduced costs, have made remote monitoring a highly efficient and cost-effective tool for evaluating slope stability.

The workflow for monitoring tailings landfills is a multi-step process involving meticulous planning, the use of advanced monitoring equipment, systematic data collection, comprehensive analysis, and ongoing reporting. This structured approach helps identify risks early, enabling prompt action to prevent environmental damage and ensure community safety.

In summary, the integration of geodetic repeated measurements with parametric modelling establishes a synergistic framework for tailings landfill monitoring. This integration provides accurate deformation assessments, validates theoretical models, improves predictive capabilities, and bolsters efforts in safety, regulatory compliance, and environmental protection.

Environmental monitoring for water, air, and soil should follow an integrated approach rather than operating separately. This ensures a holistic management strategy through:

- Identifying relationships between pollutants across water, air, and soil systems.
- Utilizing real-time data to detect contamination at an early stage and prevent its spread.
- Implementing actions like containment barriers for water and soil, dust suppression systems for air, water treatment methods such as filtration, reverse osmosis, or chemical neutralization, and soil rehabilitation through phytoremediation or amendments.

Monitoring tailings landfills is crucial for minimizing environmental and public health risks. A thoughtfully designed monitoring system not only ensures compliance with environmental regulations but also provides valuable insights to develop effective mitigation and rehabilitation strategies. Continuous evaluation of environmental conditions allows stakeholders to preserve ecological balance and promote sustainable mining practices.

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