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ENHANCING EMBANKMENT STABILITY ASSESSMENT IN MINING OPERATIONS THROUGH FIBER OPTIC INSTRUMENTATIONS: A DMAIC APPROACH

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ABSTRACT

This paper proposes a comprehensive solution to enhance embankment stability assessment in mining company's tailings management operations through the implementation of Fiber Optic instrumentations. The current monitoring solutions lack real-time capabilities, hindering timely assessment and mitigation of embankment stability issues. Fiber Optic cables provide sensing capabilities to detect vibrations and measure temperature variations, enabling early detection of structural issues within embankments. Real-time monitoring allows continuous assessment and immediate identification of potential risks. Implementing fiber optic cable instrumentations enhances embankment stability assessment, ensuring safety and minimizing failures. Data-driven decision-making is empowered through accurate and real-time data, enabling efficient resource allocation. The implementation follows a DMAIC (Define, Measure, Analyze, Improve, Control) approach, ensuring a comprehensive analysis and step-by-step plan. In conclusion, fiber optic cable instrumentations offer valuable enhancement to embankment stability assessment in mining's tailings management operations. Real-time monitoring, accuracy, and precision contribute to proactive measures and improved decision-making. Implementing this solution strengthens embankment stability practices, safeguards surrounding areas, and maintains regulatory compliance, fostering resilience and sustainability in mining operations.

INTRODUCTION

Mining companies play a crucial role in supporting various industries and providing essential commodities that form the building blocks of modern civilization. However, the generation of a substantial amount of non-economic byproduct known as tailings poses significant challenges for the mining process. Proper management of tailings' containment facilities, specifically embankments, is of utmost importance in mitigating environmental risks, ensuring safety, and maintaining regulatory compliance (Freeport-McMoRan, 2022; International Council on Mining and Metals, 2023). However, the assessment of embankment stability in tailings management operations faces limitations with current solutions, such as periodic inspections and manual measurements, which can be time-consuming, resource-intensive, and prone to human error. Real-time monitoring and early detection of potential risks are lacking, leading to safety hazards, environmental risks, and non-compliance with regulatory requirements (K2fly, 2020).

Effective embankment stability assessment in mining's tailings management operations is crucial for ensuring safety, minimizing environmental risks, and complying with regulations. The International Council on Mining and Metals (ICMM) (2023) recognizes the significance of tailings management and emphasizes the need for robust embankment stability assessment to prevent catastrophic incidents). Past tailings dam failures such as the Mount Polley, a Canadian gold and copper mine in British Columbia, tailings dam failure in Canada (2014), the Samarco (A Brazilian mining company) dam failure in Brazil (2015), and the Brumadinho (in Brazil) dam failure, also in Brazil (2019), resulting in loss of life and severe environmental impacts, highlight the urgency to improve embankment stability assessment practices and prevent future disasters (BBC, 2016).

In the context of a representative mine complex in Papua, Indonesia, various methods are currently employed to assess embankment stability in tailings management activities. These methods include Interferometric Synthetic Aperture Radar (InSAR) for deformation monitoring (K2fly, 2020), Vibrating Wire Piezometers (VWP) for measuring excess water pore pressure (RST Instruments, 2023; Sisgeo, 2023), Light Detection and Ranging (LiDAR) for creating accurate topographic maps (National Ocean Service, 2023), and seismic and hydraulic modeling for evaluating seismic and hydraulic loads on the embankment (Remo et al., 2012; Szepesházi et al., 2015). While these solutions have their advantages in longer-term decision making and enhancing embankment design, they have limitations in terms of real-time assessment, data availability, and immediate decision making.

This study aims to address the research question, "How can embankment stability assessment in mining's tailings management operations be enhanced?" The objective is to propose and evaluate the implementation of fiber optic instrumentations as a solution for improving embankment stability assessment. By introducing fiber optic instrumentations, the researchers aimed to provide a novel approach that enhances real-time monitoring, early risk detection, and proactive management of embankment stability. The research contributes to advancing mining practices, aligning with the ICMM's vision of promoting responsible and sustainable mining.

METHOD

The method employed in this study is the DMAIC (Define, Measure, Analyze, Improve, Control) methodology, which is a structured problem-solving approach widely utilized in process improvement initiatives (Six Sigma, 2023c, 2023a). The DMAIC methodology offers a systematic and data-driven framework for addressing challenges related to embankment stability in tailings management activities within the mining industry (Six Sigma, 2023b).

The DMAIC methodology is derived from the Six Sigma framework and provides a structured approach to problem-solving and process improvement. It consists of five distinct phases: Define, Measure, Analyze, Improve, and Control.

Define Phase

The Define Phase establishes the foundation for the DMAIC process. It involves the identification of the problem, definition of project requirements, and establishment of goals for success. The 5W2H tool (What, Why, Where, When, Who, How, and How much) is utilized to define the problem and promote a culture of continuous improvement (Cancian, 2021).

Measure Phase

The Measure Phase focuses on creating a baseline metric for the process and collecting data to analyze the current state of the process. Relevant process metrics are identified, and data collection is initiated. The Failure Modes and Effect Analysis (FMEA) tool is used during this phase to identify potential failures in the process and their causes.

Analyze Phase

The Analyze Phase involves developing hypotheses about causal relationships between inputs and outputs. Statistical analysis and data are employed to identify patterns, trends, and sources of variation in the process. Tools such as process mapping, cause and effect diagrams, and FMEA are used to analyze the data and assess potential failures and their impact on the process.

Improve Phase

The Improve Phase focuses on addressing the root causes of process inefficiencies or problems identified during the Analyze Phase. Solutions are brainstormed, evaluated, and selected for implementation. The solutions selection matrix, an analytical tool, is used to propose and rank solutions based on their effectiveness, feasibility, and cost-benefit rating. Experiments may be conducted to test the effectiveness of proposed changes.

Control Phase

The Control Phase ensures the sustained effectiveness of the improved process. Monitors, control plans, and other mechanisms are established to maintain the successful functioning of the process after implementing changes. The FMEA method is revisited to determine the effectiveness of the recommended changes and actions in reducing the risk of failure.

By employing the DMAIC methodology in the context of tailings management, mining companies can systematically identify and address gaps in embankment stability assessment. This method provides a structured approach to problem-solving and continuous improvement, promoting enhanced tailings management practices, environmental sustainability, and operational safety.

RESULT AND DISCUSSION

Define Phase

In the Define phase, the problem statement is identified and articulated using the 5W2H method.

What is the problem?

The existing methods employed for embankment stability assessment in tailings management at the company exhibit a significant time gap between potential triggering events such as earthquakes and floods, and the subsequent data gathering activities involving InSAR, VWP, LiDAR, Seismic & Hydraulic Modeling. Furthermore, there is a notable delay in data processing, analysis, and decision-making. In essence, the primary challenges revolve around the lack of real-time monitoring capabilities and the absence of a 24/7 early warning system (Please see **“Current Solution Implemented to Assess Tailings’ Embankment”** for further details of the limitations of each actual tailings’ embankment stability assessment).

Why is it the problem?

It was identified as the problem because currently the company does not have sufficient real-time monitoring (continuous), whereby 24/7 early warning systems can assist in conducting assessment of tailings’ embanking facility.

Who is affected by the problem?

Inadequate real-time monitoring and assessment pose potential risk of failure, which can lead to severe environmental and safety consequences. The existing methods may not provide timely and reliable information to mitigate these risks.

When does the problem occur?

The problem arises throughout the life cycle of tailings management, from initial deposition to closure and post-closure as well. Continuous monitoring and assessment are required to ensure long-term embankment stability.

Where does the problem occur?

The problem occurs specifically in the tailings management activities at mining sites where embankments are utilized to contain and manage the tailings.

How does the problem manifest?

The lack of real-time monitoring of embankment stability hinders the ability to proactively detect and mitigate potential risks.

How much of an impact does the problem have?

Embankment failures in terms of general tailings management can result in significant environmental damage, threats to human safety, and financial losses for the mining companies. The consequences of such failures can be catastrophic and long-lasting.

According to the 5W2H above, the problem is defined as follows: The existing tailings' embankment assessment process lacks efficient real-time monitoring and 24/7 early warning systems in terms of embankment condition, resulting in delays in detecting and responding to potential risks to embankment stability.

Measure Phase

During the Measure phase, a baseline metric is established for the process, and the Failure Modes and Effect Analysis (FMEA) tool is employed to identify potential failures and their causes. The FMEA is completed as follows:

Table 1. Failure Modes and Effect Analysis (FMEA) on Tailings' Embankment Stability Assessment

Process Step	Potential Failure	Potential Failure Effect	SEV*	Potential Cause of Failure	OCC**	Current Monitor / Control	DET***
Data Acquisition	Inadequate data due to acquisition frequency	Inadequate embankment stability assessment	5	Limited monitoring data	8	Manual data acquisition (visual field documentation)	5
Data Processing and Analysis	Delayed processing	Inefficient embankment stability analysis	5	Long duration to process the data	8	Manual data processing & analysis to identify potential embankment instability	5
Tailings' Embankment Assessment	Not a real-time assessment	Inadequate embankment stability real-time control	9	Insufficient real-time data input	8	Manual assessment on-site by Engineer	5
Early Warning System (EWS)	Absence	Delayed response	9	Lack of real-time data	9	No early warning system	9
Decision Making	Informed decisions	Misinformed decisions	9	Limited real-time data availability	8	Technical expert judgement	4

*Severity → 1 = No effect; 2 = Very minor effect on product or system performance; 3 =Minor effect on product or system performance; 4 = Small effect on product performance. The product does not require repair; 5 = Moderate effect on product performance. The product requires repair; 6 = Product performance is degraded. Comfort or convenience functions may not operate; 7 = Product performance is severely affected but functions. The system may not be operable; 8 = Product is inoperable with loss of primary function. The system is inoperable; 9 = Failure involves hazardous outcomes and/or noncompliance with govt. regulations or standards; 10 = Failure is hazardous and occurs without warning.

**Occurrence → 1 = Nearly impossible; 2 = Remote; 3 = Low; 4 = Relatively low; 5 = Moderate; 6 = Moderately high; 7 = High; 8 = Repeated Failures; 9 = Very High; 10 = Extremely High Failure Almost Inevitable.

[1] Detection → 1 = Almost certain detection; 2 = Very high chance of detection; 3 = High probability of detection; 4 = Moderately high chance of detection; 5 = Moderate chance of detection; 6 = Low probability of detection; 7 = Very low probability of detection; 8 = Remote chance of detection; 9 = Very remote chance of detection; 10 = Absolute uncertainty.

*** Detection → 1 = Almost certain detection; 2 = Very high chance of detection; 3 = High probability of detection; 4 = Moderately high chance of detection; 5 = Moderate chance of detection; 6 = Low probability of detection; 7 = Very low probability of detection; 8 = Remote chance of detection; 9 = Very remote chance of detection; 10 = Absolute uncertainty.

The FMEA identifies potential failures, their effects, severity (SEV), causes (OCC), current monitoring/control, and detection (DET) ratings for each process step. The severity (SEV) rating ranges from 1 to 10, where 1 indicates minimal impact, and 10 indicates severe consequences. The occurrence (OCC) and detection (DET) ratings also range from 1 to 10, representing the likelihood/frequency of failures occurring and the effectiveness of current controls in detecting failures, respectively. This Measure phase provides insights into the current state of the process and sets the stage for data-driven decision-making and improvement actions.

Analyze Phase

In the Analyze Phase of the DMAIC methodology, the collected data from the Measure Phase is carefully examined to identify the root causes of potential failures and their impact on embankment stability in tailings management. The objective is to gain a deep understanding of the underlying factors contributing to the challenges and limitations in the current assessment process.

The analysis begins by reviewing the data gathered in the Failure Modes and Effect Analysis (FMEA) spreadsheet, which includes information on potential causes of failure, occurrence ratings, current monitoring/control measures, and detection ratings. This data is analyzed to identify trends, patterns, and correlations that can provide insights into the critical areas requiring improvement.

After a thorough analysis, the Risk Priority Number (RPN) is calculated using the formula RPN = SEV × OCC × DET. The RPN serves as a quantitative measure of risk, considering the severity (SEV), occurrence (OCC), and detection (DET) ratings. Based on the FMEA results presented in Table 2, the RPN values for all identified process setups exceed 100, indicating significant areas for improvement.

Table 2. Failure Modes and Effect Analysis (FMEA) on Tailings' Embankment Stability Assessment – The Risk Priority Number and Recommended Change / Actions

Process Step	RPN*	Recommended Changes / Actions
Data Acquisition	200	Implement automated and continuous data collection system
Data Processing and Analysis	200	Introduce automated and continuous data processing and analysis tools
Tailings' Embankment Assessment	360	Implement automated and continuous stability assessment tools
Early Warning System (EWS)	729	Establish 24/7 early warning system

Decision Making	288	Implement real-time data-driven decision-making process

*Risk Priority Number (RPN) → A 1,000 rating implies a certain failure that is hazardous and harmful; A 1 rating is failure that is highly unlikely and unimportant; Rating above 100 will occur; Rating below 30 are reasonable for typical applications.

These recommended changes and actions are aimed at overcoming the limitations identified during the analysis phase and improving the overall tailings' embankment stability assessment process. By conducting a thorough root cause analysis and proposing targeted actions, the Analyze Phase provides valuable insights and a roadmap for enhancing the current assessment methods and addressing the identified challenges in tailings management.

Improve Phase

In the Improve phase of the DMAIC methodology, mining companies focus on addressing the root causes identified during the Analyze phase to improve tailings' embankment stability assessment. This phase involves developing and implementing targeted solutions to drive measurable improvements. The key activities in the Improve phase are as follows:

Solution Development

Mining companies engage in collaborative brainstorming sessions to generate potential solutions for the identified issues. These solutions are evaluated based on their feasibility, impact, and alignment with the desired objectives. The Solutions Selection Matrix, as shown in Table 3, is used to evaluate the recommended changes and prioritize actions.

Table 3. Solutions Selection Matrix

Problem Statement	Validated Root Cause	Potential Solutions	Practical Method	Effectiveness*	Feasibility**	Cost-Benefit***	Overall****	Take Action?
The existing tailings' embankment assessment process lacks efficient real-time monitoring and 24/7 early warning systems in terms of embankment condition, resulting in delays in detecting and responding to	Limited monitoring data	Implement automated and continuous data collection system	Tool / instrument that can download, process, and analyze the data automatically and transmit to the system	9	10	8	720	Yes
	Long duration to process the data	Introduce automated and continuous data processing and analysis tools						
	Insufficient real-time data input	Implement automated and continuous						

potential risks to embankment stability		stability assessment tools						
	Lack of real-time data	Establish 24/7 early warning system	Utilize the data transmitted by a tool / instrument to create early warning system that will notify certain responsible person	9	9	8	648	Yes
	Limited real-time data availability	Implement real-time data-driven decision-making process						

*Effectiveness is the measure of how well a solution will eliminate a root cause for a problem, with 1 being not effective and 10 being highly effective

**Feasibility is the measure of effort required to implement the improvement, with 1 being not feasible because of the effort or resources required and 10 being highly feasible.

***Feasibility is the measure of effort required to implement the improvement, with 1 being not feasible because of the effort or resources required and 10 being highly feasible.

****Overall score comes from multiplying score of effectiveness, feasibility, and cost-benefit. The overall score can be used to prioritize solutions and select the solution that features the best overall effectiveness, feasibility, and cost-benefit rating.

Based on the Solutions Selection Matrix, the mining company should prioritize finding a tool or instrument with the capability to continuously collect data on tailings' embankment movement and excessive water in the embankment body. Additionally, utilizing the continuous data transmitted by the instrument to establish a 24/7 early warning system is crucial.

Pilot Testing

Prior to full-scale implementation, mining companies can conduct a controlled pilot test of the selected solution. This allows for performance assessment, issue identification, and necessary adjustments. The pilot test also confirms the system's ability to continuously monitor tailings' embankment movement and excessive water. Insights gained during this phase contribute to refining the implementation approach and validating the chosen instrument's suitability.

Installation and Integration

Upon successful pilot testing, the selected tool or instrument with real-time data monitoring capability is installed and integrated into the existing monitoring infrastructure. This involves hardware deployment, setting up data acquisition and transmission systems, integrating with monitoring and analysis platforms, and calibration and validation of the system.

Training and Education

Upon successful pilot testing, the selected tool or instrument with real-time data monitoring capability is installed and integrated into the existing monitoring infrastructure. This involves hardware deployment, setting up data acquisition and transmission systems, integrating with monitoring and analysis platforms, and calibration and validation of the system.

Revisiting the FMEA

As part of the continuous improvement process, mining companies revisit the Failure Modes and Effects Analysis (FMEA) to evaluate the effectiveness of the implemented solutions. By comparing FMEA findings from previous phases with the current state, companies assess the impact of the solutions on identified failure modes and associated risk factors. This helps determine if further refinements are necessary. See below the table that represents of revisiting the FMEA.

Table 6. Failure Modes and Effect Analysis (FMEA) on Tailings' Embankment Stability Assessment – The Risk Priority Number and Recommended Change / Actions

Recommended Changes	Potential Failure and Effect	SEV	Potential Cause of Failure	OCC	Proposed Control	DET	RPN
Tool / instrument that can download, process, and analyze the data automatically and transmit to the system	Instrument error, resulting to data cannot be downloaded and transmitted	2	IT problem due to power outage, etc.	3	Periodic maintenance and install UPS	2	12
Utilization of data transmitted from instrument to create 24/7 Early Warning System	System error, resulting Early Warning System becomes offline	2	IT problem due to power outage, etc.	3	Periodic maintenance and install UPS	2	12

Since the RPN results of these two recommended changes are 12 or less than 100, it means that these two failures are highly unlikely to occur. However, the proposed control needs to be applied and will be furtherly explain in the Control phase.

The Improve phase basically focuses on developing targeted solutions, conducting pilot testing, implementing the selected solution, providing comprehensive training, and continuously evaluating the effectiveness of the implemented changes. By following this phase, mining companies can drive improvements in tailings' embankment stability assessment and mitigate potential risks.

Control Phase

In the Control phase of the DMAIC process, mining companies focus on sustaining the improvements achieved and ensuring long-term effectiveness in tailings' embankment stability assessment (Rochman & Agustin, 2017). The Control phase involves the following steps.

Establishing Control Measure

Define specific measures to track and monitor the performance of the implemented improvements, such as embankment stability assessment accuracy and early warning system responsiveness.

Implementing Monitoring Systems

Deploy monitoring systems, including tools/instruments with real-time data monitoring capability, to collect data regularly. Analyze the collected data and compare it against established targets and thresholds.

Conducting Regular Assessment

Analyze the collected data and review control measures to evaluate the effectiveness of the improvements. Promptly address any identified deviations or issues and initiate corrective actions.

Establishing Corrective and Preventive Action

Take corrective actions when assessments reveal signs of embankment instability. This may involve reinforcement measures or additional drainage systems. Implement preventive actions, such as enhancing embankment design guidelines or adding monitoring measures in high-risk areas.

Documentation and Reporting

Maintain detailed documentation of control measures, monitoring data, assessments, and actions taken. Generate regular reports to communicate performance to stakeholders and ensure transparency (Yuliyono et al., 2019).

Continuous Monitoring

Establish a feedback loop for ongoing evaluation and adjustment of control measures and processes. Continuously monitor and review the effectiveness of control measures to identify areas for improvement.

By implementing a robust control plan, mining companies can sustain the improvements achieved in the previous phases and ensure the long-term effectiveness of their tailings' embankment stability assessment. The Control phase establishes a systematic framework for ongoing monitoring, evaluation, and adjustment, leading to a culture of continuous improvement and enhanced risk management practices in tailings management.

DMAIC Approach Result

The result of implementing the DMAIC methodology and utilizing supporting tools is the establishment of a tool/instrument with continuous monitoring capabilities for embankment movement and excess water condition inside it, accompanied by an early warning system (Smętkowska & Mrugalska, 2018). This enables mining companies to ensure sustainable operations and effectively mitigate risks associated with embankment failures (Bhargava & Gaur, 2021). The systematic approach provided by DMAIC and the use of tools like 5W2H, FMEA, and Solutions Selection Matrix allow for the identification of objectives, data gathering, root cause analysis, solution implementation, and the establishment of a robust control plan for ongoing monitoring and adjustment. This result enhances safety, protects the environment, and maintains operational continuity.

Fiber Optic Cable Instrumentation

Based on the results of the DMAIC methodology, supported by tools like 5W2H, FMEA, and the Solutions Selection Matrix, it is clear that mining companies using tailings embankments need a real-time monitoring tool for continuous monitoring of embankment movement and water condition inside the embankment. Fiber optic cables offer significant advantages for real-time monitoring and stability assessment of embankments (Klar et al., 2014; Voet et al., 2005). Their benefits include:

1) Real-Time Monitoring: Fiber optic cables allow continuous, real-time monitoring of critical parameters, enabling proactive risk detection and immediate response.
2) High-Frequency Data Acquisition: Fiber optic cables can collect data at high frequencies, providing detailed information for precise monitoring and risk identification.
3) Long-Distance Coverage: Fiber optic cables can cover long distances, ensuring comprehensive monitoring across the entire embankment area.

The integration of fiber optic instrumentations into tailings management operations in Mining Company in Papua, Indonesia offers the following benefits:

1) Early Warning and Risk Mitigation: Real-time monitoring provides early warnings of potential risks, enabling prompt mitigation measures and reducing the likelihood of embankment failures.
2) Enhanced Safety and Environmental Protection: Fiber optic cables can detect indicators of instability, ensuring the safety of personnel and minimizing environmental impact.
3) Data-Driven Decision Making: High-resolution data obtained from fiber optic instrumentations enables better stability assessments and targeted remedial actions.
4) Cost Savings in the Long Run: While there are initial investment costs, the long-term benefits of avoiding embankment failures lead to substantial cost savings.

However, it is important to consider potential risks associated with implementing fiber optic instrumentations, such as implementation challenges, cost allocation, technical limitations, data management, maintenance, data security, and stakeholder acceptance. Mitigation strategies should be in place to address these risks effectively.

To overcome the potential risks associated with implementing fiber optic for tailings embankment monitoring, it is essential to develop a comprehensive implementation plan that includes conducting a thorough assessment, allocating sufficient resources, engaging technical experts, establishing a robust data management system, implementing regular maintenance and system upgrades, addressing stakeholder concerns, providing comprehensive training to personnel, and continuously reviewing and improving the monitoring system. By addressing these factors, mining companies can effectively mitigate risks and ensure the successful implementation and utilization of fiber optic instrumentations for tailings embankment monitoring.

CONCLUSION

In conclusion, this study proposed the implementation of fiber optic instrumentations as a solution to enhance embankment stability assessment in mining's tailings management operations. The adoption of a systematic approach based on the DMAIC methodology and the utilization of tools such as 5W2H, FMEA, and the Solutions Selection Matrix resulted in the development of a comprehensive framework. By integrating fiber optic instrumentations, real-time monitoring, high-frequency data acquisition, and long-distance coverage capabilities were achieved, enabling early risk detection and data-driven decision making. This approach contributes to responsible and sustainable mining practices by improving risk management, safety, and environmental protection.

However, it is important to acknowledge the limitations of this research. The sample size and context were specific, potentially limiting the generalizability of the findings. The reliance on data from a single or limited number of sources may introduce biases or limitations in the interpretation of the results. Future research should aim to include a more diverse range of mining operations and tailings management scenarios, as well as explore opportunities for data triangulation and validation.

Furthermore, the implementation of fiber optic instrumentations may face challenges related to implementation, resource allocation, technical limitations, and data security. These risks should be addressed with appropriate mitigation strategies to ensure successful implementation and maximize the benefits. Future research could delve into the specific implementation challenges, organizational resistance, and potential strategies for overcoming these barriers.

To advance the field, future research directions should include comparative studies to evaluate the effectiveness of fiber optic instrumentations against alternative monitoring technologies or approaches. Long-term monitoring and performance assessment studies can provide insights into the durability, reliability, and sustainability of fiber optic instrumentations in different mining environments. Additionally, integrating fiber optic data with other risk management strategies and technologies and conducting comprehensive cost-benefit analyses would contribute to a deeper understanding of their potential and economic viability.

Finally, understanding stakeholder perspectives and addressing their concerns regarding the implementation of fiber optic instrumentations is crucial. Future research should explore stakeholder acceptance, concerns, and the social implications of deploying this technology, enabling the development of strategies that align with stakeholder needs and ensure successful implementation.

In summary, the implementation of fiber optic instrumentations represents a significant advancement in enhancing embankment stability assessment and achieving sustainable mining operations. Acknowledging the research limitations and addressing future research directions will contribute to the continuous improvement and application of fiber optic instrumentations in the mining industry.

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