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A Review of the Issues and Challenges of Slope Stability in the Opencast Coal Mines of India

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Abstract

Slope stability in opencast mines is a critical aspect of mining operations, particularly in India, where extensive mineral extraction occurs under diverse geological and climatic conditions. Ensuring stable slopes is essential for worker safety, the sustainability of mining operations, and environmental protection. This review highlights the importance of addressing slope stability challenges posed by weathering, geological complexities, and human activities in Indian opencast mines. The study synthesises existing research to identify slope stability factors, including lithology, hydrogeological influences, and mining-induced stresses. The methodology involves a comprehensive review of slope stability analysis techniques, such as numerical modelling, geotechnical investigations, and remote sensing-based monitoring systems. Additionally, the paper evaluates case studies from Indian mines to illustrate common failure mechanisms and mitigation strategies. The results reveal that slope instability often arises from inadequate design practices, insufficient drainage systems, and the interplay of geological discontinuities. Advanced monitoring systems, coupled with geotechnical modelling, are effective in predicting potential failures. The discussion underscores the significance of integrating traditional and modern approaches to enhance stability. The review concludes with actionable recommendations, including adopting real-time monitoring systems, enhancing slope design protocols, and implementing region-specific stabilization techniques. These measures can significantly mitigate risks and improve operational safety in Indian opencast mines, ensuring both economic and environmental sustainability.

Keywords: *Case Studies, Geotechnical Analysis, Opencast Mines, Recommendations*

1.0 Slope Stability

The major findings are as follows:

1. Slope stability in Indian opencast mines is affected by geological, hydrogeological, and human-induced factors, with common issues including inadequate drainage and geological discontinuities.
2. Advanced techniques like numerical modelling, geotechnical investigations, and remote sensing are effective for analysing and monitoring slope stability.
3. Challenges such as poor design practices and limited integration of modern monitoring systems contribute to slope instability.
4. Effective strategies include the adoption of real-time monitoring systems, enhanced slope design protocols, and region-specific stabilization measures.
5. A combined approach utilizing both traditional and modern methods is essential for improving slope stability, ensuring safety, and promoting sustainability in mining operations.

1.1 Introduction

Opencast mining is a widely used method for extracting minerals and ores in India, but it comes with inherent risks related to slope stability. The stability of slopes in opencast mines is crucial for ensuring the safety of workers, protecting the environment, and maintaining the productivity of mining operations. This paper will review

the existing literature on slope stability in opencast mines in India to provide insights into the current challenges and potential solutions for improving slope stability in these mining environments.

2.0 Literature Review

Slope stability analysis is a critical aspect in the assessment and management of opencast mines in India. It is important to ensure the stability of slopes in these mining operations to prevent accidents, protect infrastructure, and optimize production[1].

The literature on slope stability of opencast coal mines in India is vast and multifaceted, reflecting the complex nature of this geological and engineering challenge. Numerous studies have explored the various factors influencing slope stability, including geological conditions, mining methods, water table fluctuations, and external environmental impacts. Additionally, researchers have investigated the effectiveness of different slope stabilization techniques such as benching, terracing, and revegetation. These studies have provided valuable insights into the unique considerations and best practices for ensuring the stability and safety of opencast coal mine slopes in the Indian context. Some key findings from the literature include:

- The geological conditions in India, characterized by diverse rock types and structural complexities, play a crucial role in determining the stability of opencast coal mine slopes. Studies have highlighted the significance of thorough geological assessments in understanding the potential failure mechanisms and designing appropriate slope stabilization measures[2].
- The choice of mining methods, whether it's highwall mining, contour mining, or area mining, has been found to have varying impacts on slope stability. Understanding these impacts is essential for implementing effective slope management strategies and minimizing the risk of slope failures[3,4].
- Water table fluctuations in opencast coal mines have been identified as a major factor influencing slope stability. Research has emphasized the need for comprehensive hydrogeological investigations to assess the interactions between groundwater and slope stability, ultimately guiding the implementation of appropriate dewatering and drainage measures[5].
- External environmental impacts, such as rainfall, seismic activity, and anthropogenic disturbances, have been studied for their effects on slope stability. These studies have underscored the significance of incorporating these dynamic environmental factors into slope stability analyses and adopting adaptive slope management practices[6].
- The effectiveness of various slope stabilization techniques, including benching, terracing, and revegetation, has been evaluated in the Indian context. Findings emphasize the need for site-specific considerations and the integration of multiple stabilization measures to ensure long-term slope stability and environmental sustainability in opencast coal mines[7].

Overall, the literature review underscores the complexity of slope stability in opencast coal mines in India and highlights the multidisciplinary approach required for effective slope management. These findings serve as a valuable foundation for further research and the development of comprehensive guidelines for ensuring the stability and safety of opencast coal mine slopes in the Indian context.

3.0 Factors Affecting Slope Stability

Various factors influence the stability of slopes in opencast mines, and it is essential to consider these factors during slope stability analysis. Some of the key factors affecting slope stability include:

3.1 Geological Conditions

- **Rock Type**: The type of rock or soil present in the slope can significantly impact its stability. Some rocks are more prone to weathering and erosion, leading to instability[8].
- **Geological Structures**: Faults, joints, bedding planes, and other geological structures can create planes of weakness that may influence slope stability[9].

3.2 Hydrological Conditions

- **Water Content**: High water content in the soil can increase pore water pressure, reduce soil strength, and lead to slope instability[10].
- **Seepage**: Seepage of water into the slope can increase pore water pressure and reduce effective stress, affecting slope stability.

3.3 Slope Geometry[11]

- **Slope Angle**: Steeper slopes are generally more prone to instability than gentler slopes due to increased gravitational forces.
- **Slope Height**: Taller slopes may experience higher stresses and deformations, potentially leading to instability.

3.4 Soil Properties[12]

- **Soil Type**: Different soil types have varying strengths and properties that can affect slope stability.
- **Soil Composition**: The presence of clay minerals, sand, silt, and other components can influence the shear strength and stability of the slope.

3.5 External Factors

- **Loading Conditions**: Additional surcharge loads from freshly shovel-dumper dumps over dragline dump, vehicles can impact slope stability.
- **Reclamation of dumps**: The presence or absence of vegetation can affect slope stability by influencing soil cohesion and erosion control.
- **Seismic Activity**[4]**- Earthquakes**: Seismic events can induce ground shaking and trigger slope failures, especially in areas prone to seismic activity.

3.6 Human Activities

- **Excavation**: Man-made excavations can alter the natural slope geometry and stability.
- **Construction**: The construction of structures on or near slopes can change the loading conditions and affect slope stability.

Considering these factors and conducting a comprehensive slope stability analysis using appropriate methods can help in assessing the stability of slopes and implementing necessary measures to mitigate potential risks.

4.0 Methods for Slope Stability Analysis

Slope stability analysis is a crucial aspect of geotechnical engineering to ensure the safety and stability of slopes. There are several methods used for slope stability analysis, each with its advantages and limitations. Some of the commonly used methods include:

4.1 Limit Equilibrium Methods

4.1.1 Bishop's Method

This method is based on the limit equilibrium theory and accounts for the interslice forces and moments to determine the factor of safety.

Assumptions:

- Failure occurs along a circular slip surface.
- Shear and normal forces at interslice boundaries do not generate moments.
- The soil is homogeneous and isotropic.

Limitations:

- Cannot handle non-circular failure surfaces effectively.
- Accuracy decreases for slopes with significant pore water pressure or complex soil conditions.

Applications:

- Appropriate for slopes with simple geometry and circular failure mechanisms, such as homogeneous embankments.

4.1.2 Janbu's Method

It is an extension of Bishop's method and considers the non-circular failure surface shapes.

Assumptions:

- Interslice shear forces can be significant but are simplified for computational purposes.
- Pore water pressure is accounted for but requires input values.

Limitations:

- Results are less precise compared to Spencer's or Morgenstern-Price methods for steep slopes.
- Can overestimate or underestimate the factor of safety due to simplifications.

Applications:

- Useful for slopes with non-circular failure surfaces, such as those in heterogeneous or stratified soils.

4.1.3 Spencer's Method

This method considers the non-circular failure surfaces and includes the effect of pore water pressure.

Assumptions:

- Interslice forces are assumed to act at a constant angle throughout the slip surface.
- Requires iterative calculations to converge on a solution.

Limitations:

- Computationally intensive compared to Bishop's or Janbu's methods.
- Requires more detailed input parameters.

Applications:

- Suitable for slopes with complex geometries, varying pore water pressures, or mixed soil conditions.
- Commonly used for engineering designs requiring high accuracy.

4.1.4 Morgenstern-Price Method

It considers the mobilization of shear strength along the potential failure surface.

Assumptions:

- Shear strength is mobilized along the entire failure surface.
- The shape of the failure surface can be user-defined.
- Interslice forces follow a defined function (e.g., linear, exponential).

Limitations:

- Highly computationally intensive.
- Requires detailed input data, which might not always be available.

Applications:

- Best suited for slopes with highly irregular geometries or where precise modelling of interslice forces is critical.
- Often used in research or high-stakes engineering projects requiring sophisticated analysis.

It provides a clear understanding of which method to choose based on the complexity of the slope stability problem and the required level of accuracy.

- *Bishop's Method* is best for quick, approximate analyses of homogeneous slopes with circular failures.
- *Janbu's Method* is more suitable for stratified or heterogeneous slopes with non-circular failure patterns.
- *Spencer's Method* provides a balance between accuracy and computational effort, making it ideal for practical engineering applications.
- *The Morgenstern-Price Method* is the most accurate but should be reserved for cases where precision outweighs computational complexity, such as high-risk slopes.

4.2 Numerical Methods

4.2.1 Finite Element Method (FEM)

FEM can be used to analyse slope stability by considering the soil behaviour as a continuum and incorporating probabilistic analysis.

Assumptions:

- Soil and rock properties are defined for each element and are assumed constant within the element.
- Appropriate boundary conditions must be applied for realistic results.

Limitations:

- Computationally intensive, especially for large or highly refined meshes.
- Requires expertise to define input parameters accurately (e.g., constitutive models, boundary conditions).
- Results depend heavily on mesh quality; poorly defined meshes can lead to errors.

Best Applications:

- Slope stability problems involving complex geometries or loading conditions.
- Cases requiring detailed stress-strain analysis, such as slopes with non-linear soil behaviour.
- Useful for projects with heterogeneous materials, such as layered or fractured rock masses.

4.2.2 Finite Difference Method (FDM)

FDM discretizes the slope into grid points and solves the equilibrium equations iteratively.

Assumptions:

- The slope is discretized into a uniform grid, and each grid point represents the soil or rock properties at that location.
- The time-stepping or iteration process converges to a solution.

Limitations:

- Less flexible than FEM in handling irregular geometries or complex material properties.
- Requires high grid density for accurate results, which can increase computational demand.
- May not handle anisotropic or non-linear material behaviours as effectively as FEM.

Best Applications:

- Suitable for simpler geometries and soil conditions.
- Useful for dynamic analysis, such as seismic loading or rapid slope failures.
- Appropriate for preliminary slope stability assessments or when computational resources are limited.

Both FEM and FDM are valuable tools for slope stability analysis, but their applicability depends on the complexity of the problem, the required level of accuracy, and the available computational resources. FEM offers greater flexibility and precision for complex problems, while FDM is ideal for simpler, time-dependent analyses.

4.3 Numerical Limit Analysis

4.3.1 Nonlinear Programming

This method formulates the slope stability problem as an optimization problem to find the critical slip surface.

Assumptions:

- The slope is treated as a continuum.
- Failure occurs along a well-defined slip surface, often pre-defined as circular or non-circular.
- Material properties are represented by deterministic or probabilistic values.

Limitations:

- Highly dependent on the accuracy of the optimization algorithm and the initial guess for the slip surface.
- Computationally intensive for slopes with irregular geometries or highly variable material properties.
- Simplifies interactions within the slope, such as discontinuities or particle-level behaviours.

Best Applications:

- Determining the critical slip surface for slopes with varying material properties.
- Cases where optimization can efficiently identify failure mechanisms, especially in homogeneous or layered soils.
- Useful in preliminary slope stability analyses and conjunction with other methods for validation.

4.3.2 Discrete Element Method (DEM)

DEM models the individual interactions between particles to simulate the behaviour of the slope.

Assumptions:

- The slope is composed of discrete particles or blocks.
- Particle properties (e.g., size, shape, density) are predefined.
- Contact forces between particles follow specific constitutive laws (e.g., Coulomb friction).

Limitations:

- Requires significant computational power, especially for large-scale problems.
- Input data for particle properties may not always be available or accurate.
- Less effective for continuum behaviours or slopes dominated by large-scale deformation rather than particle interactions.

Applications:

- Analysing granular materials, rock masses, or slopes with discontinuities and blocky structures.
- Simulating dynamic events like rockfalls, landslides, or slope failures triggered by seismic activity.
- Ideal for research and scenarios requiring a detailed understanding of micro-mechanical behaviours.

Each method has its applicability based on the complexity of the slope geometry, soil properties, and required level of accuracy. It is common practice to use a combination of methods to verify the stability of slopes and ensure the safety of internal as well as external overburden dumps.

5.0 Case Studies

The paper will present case studies of slope stability issues in opencast mines in India to illustrate the real-world challenges faced by mining operators. These case studies will highlight the causes of slope failures, the consequences of mining operations, and the lessons learned from these incidents.

Case studies of dragline dump failures of Jayant and Khadia (Northern Coalfields Limited, Singrauli) and Sasti (Western Coalfields Limited, Nagpur) are presented here.

5.1 Dragline Dump Failure in Sasti Opencast Mine, WCL Nagpur (Roy, 2011)

5.1.1 Introduction of the Dragline Dump Failure Zone

Coal India produced 576.40, 572.101 and 569.766 million tonnes of coal in the years 2019, 2020 and 2021 from opencast mining. It is essential to know that 576.40, 572.101, and 569.766 million tonnes of coal were mined from opencast mining; 1161.99, 1154.33 and 1344.68 M Cum. of waste soil and rock (OBR) was taken out in the last three financial years[13]. In the 2009-10 financial year, Coal India (World's and India's largest coal Production Company) produced 431.27 million tonnes from opencast coal mines. It's worth noting that in 2009-10, 695.29 million cubic meters of waste soil and rock were removed to mine 431.27 million tonnes from opencast coal mines. However, the amount of land required to maintain existing coal productivity levels from open-cast coal mining is a major hurdle. According to estimations, by 2025, the total area affected by opencast coal mining would be 2925 sq. km (including 730 sq. km of forest land), up from the current 1470 sq. km.

The Sasti opencast mine is covered by a thick layer of black-cotton soil that ranges in thickness from 0.5 to 20.0 meters. This layer sits on top of strata that are 10.10 to 14.25 meters thick and is composed of red-brown, yellow-coloured, fine to coarse-grained sandstone with clay beds. The next layer is 46 to 130 meters thick and is composed of grey to white, fine to medium-grained sandstone with shale intercalation. Its greatest depth is 150 meters, and its surface and floor quarry areas are each 167 and 143 hectares (one hectare is equal to 104 square meters). The mine's longest possible strike is 1525 meters.

Dragline dump failures have occurred often in the mine in recent years, including one that resulted in the deaths of two mine workers and the displacement of 0.2 million cubic meters of dragline-dumped waste rock.

5.1.2 The Conclusion of the Study

After considering all the safety factors advised by various authorities for surface mining slope design, a safety factor of higher than 1.10 was essential for the development which considered maximum seismic acceleration. A site-specific FORTRAN-language computer software had performed stability analysis (developed for this purpose)[14].

5.1.3 Major Findings of this Case Study

a. Seismic-resistant design: Incorporate seismic acceleration factors into all slope stability models and design criteria.
b. Strengthening slope monitoring: Utilize real-time monitoring systems to track changes in seepage patterns, shear strength, and slope movement.
c. Geotechnical site assessment: Conduct detailed site-specific investigations to better characterize soil properties and stratigraphy to inform design strategies.
d. Safety factor standards: Ensure that designs and slope stability analyses consistently aim for a safety factor greater than 1.10 to account for both static and dynamic forces.
e. Risk management and emergency preparedness: Given the risk of fatalities and displacement, establish clear mine safety protocols and emergency response plans.

5.2 Dragline Dump Failure, Khadia Opencast Mine, Singrauli Coalfields (Roy, 2015)

5.2.1 Location of the Dump Failure Site

The mining operation of the Khadia project is based on the dragline cum shovel dumper combination method. Mine floor inclination and average stripping ratio of the project are 20-40 and 4.23 m^3/tonne respectively[15]. In June 2015, a dragline dump slid into the Khadia opencast mine due to the heavy seepage force inside the dump mass. The main reason for the dump slide was the accumulation of

rainwater inside the dump up to 15m. The seepage force of accumulated water came into strength with a moment of vibration due to an earthquake. This disturbing force was towards the high wall side against the resistive force of the coal rib and threw the coal rib about 75m far from the initial position up to the high wall. One standby machine on the coal floor was also buried under the slid material and one was pushed up to a high wall and damaged by the force of sliding mass.

5.2.2 Major Causes of Failure

It has been observed from the failure site that there was a heavy flow of water from the dump side which indicated the development of groundwater or strata water table within the dump mass. Hence there was a reduction of shear strength parameters at the base of the dump and there was heavy seepage of water pushing the dump mass.

a. The dump mass under water was also experiencing an upward thrust of water which reduced the weight of the dump mass.
b. It was also noted that the base of the dump mass was fully saturated or soaked with water as the 18th cut was abandoned for quite some time.
c. Observed that a slushy layer of coal dust mixed with water and crushed rock was accumulated at the floor of the mine, over which the dragline dump was formed. This slushy layer is termed here as interface material which acts as slippery material at the base of the dump.
d. An earthquake tremor was also reported from the surrounding area of the mine twice before the failure of the dump. This earth-shaking reduced the compactness of the dump material, thereby causing a reduction of shear strength parameters.

5.2.3 Key Findings of this Case Study

a. Hydro-mechanical factors: The interplay of water seepage, saturation, and hydrostatic forces played a critical role in reducing the shear strength and stability of the dump.
b. Interface material: The slushy layer at the base acted as a lubricant, facilitating the movement of the dump mass.
c. Seismic contribution: Earthquake tremors exacerbated the instability by reducing compaction and shear strength.
d. Operational challenges: Lack of proper drainage systems to manage water accumulation within the dump was a major contributing factor.
e. Combined failure mechanisms: The failure was a result of combined hydrological, geological, and dynamic factors, highlighting the importance of integrated stability analysis in mine design and operations.

5.2.4 Recommendations Based on Findings

a. Drainage Management: Develop and implement robust drainage systems to prevent water accumulation within dump masses.
b. Monitoring and early warning: Utilize real-time monitoring systems to detect water seepage, ground vibrations, and shear strength changes.
c. Design improvements: Ensure proper compaction of dump materials and address potential seismic impacts in slope stability designs.
d. Interface treatment: Treat or replace slushy layers with more stable materials to enhance the frictional resistance at the dump base.
e. Seismic considerations: Incorporate seismic stability assessments and reinforce dumps in seismically active regions.

5.3 Study of Slope Failure at Jayant Opencast Mine[2,16]

a. Because of its high population density, India is in a difficult situation when it comes to procuring large amounts of land for opencast coal mining. Draglines are employed in opencast coal mines with flat coal deposits because of their operational advantage in simultaneous excavation and back-filling over shovel-dumper combinations. However, the dragline operating method, which involves the free fall of dump material and simultaneous backfilling, is linked to slope stability issues in dragline-formed waste rock dumps.
b. India has witnessed fatal accidents in two dragline-operated opencast mines in the years 2008 and 2009. This case study discusses the stability problems of the Jayant opencast mine which experienced a fatal accident on 17th December 2008.

c. Internal dump failure is a complicated issue. It has a direct impact on resource recovery, mine safety, and mining costs, in addition to environmental factors (Kainthola *et al.,* 2011). Opencast project of Jayant, India is a prominent coal mine that was founded in 1976-77. It generates 10 million tonnes of coal per year and 27 million cubic meters of waste rock per year[17].

d. The production of such a significant amount of coal and waste rock production is concurrent with the safety aspects of the mine, particularly the stability of the waste rock dump formed by the dragline. This mine has been experiencing frequent dragline dump failures the recent one being in December, 2008[18,19]. This case study presents the causes of accidents, methodology for stability analysis, recommendation dragline profile and suggestions for preventive measures.

5.3.1 Key Findings from the Case Study

1. Frequent Dragline-Induced Slope Failures:
   - Dragline operations, especially free-fall dumping, were identified as a significant cause of slope instability.
2. Hydrological factors contributed to failure:
   - Water seepage and heavy rainfall reduced the shear strength of waste rock dumps, leading to instability.
3. Operational methods and poor drainage:
   - Uneven stress caused by the dragline dumping process and inadequate drainage exacerbated slope failure risks.
4. Internal dump failure as a complex issue:
   - Internal failures impacted resource recovery, mine safety, and environmental stability.
5. Stability analysis *via* computational modelling:
   - Advanced geotechnical modelling showed the interactive effects of hydrology and shear strength reductions in triggering the failure.

5.3.2 Recommendations for Improving Slope Stability

Based on the review of existing research and best practices, the paper will provide recommendations for improving slope stability in opencast mines in India.

1. Improved dragline dump practices
   - Separate dumping of topsoil:
     a. Avoid mixing topsoil with waste rock to reduce the risk of shear strength reduction and unstable conditions at the base.
   - Form a foundation for dragline dumps without surface soil:
     a. Establish solid foundations for dragline dumps by removing loose surface soil to reduce instability.
   - Allow sufficient time for settling:
     a. Ensure that dragline dumps are given adequate time to settle and stabilize under natural gravitational effects before further dumping.
2. Addressing hydrological and seepage issues
   - Maintain normal gravitational seepage of water:
     a. Ensure that seepage follows natural pathways and does not accumulate within the waste rock dumps, weakening slope stability.
   - Monitor seepage at regular intervals:
     a. Special attention should be given to monitoring the seepage of water from the dragline dump faces.
3. Regular monitoring and early warning systems
   - Adopt non-contact laser monitoring techniques:
     a. Use laser profilers or scanners to monitor dump face displacement and detect early signs of instability.
   - Conduct frequent monitoring during high-risk periods:
     a. Monsoon and post-monsoon seasons: Monitor every 7 days.
     b. Dry seasons: Monitor every 15 days.
   - Declare hazard zones:
     a. Areas like the de-coaled floor near the toe of the dragline dump should be identified as potential hazard zones for any movement or instability.
4. Geotechnical stabilization techniques
   - Consolidation using dozers:
     a. Use dozers to fill and consolidate voids in and around the waste rock dumps to improve their overall shear strength.
   - Clean interface layers:
     a. Before dumping waste material, remove any slushy or weak interface layers (e.g., coal dust

and water mixtures) that can act as slipping planes and compromise slope stability.

5. Risk management strategies
   - Regular inspections and assessments:
     a. Many slope failures are linked to the lack of regular engineering assessments. Implement periodic inspections to identify early warning signs of instability.
   - Implement better slope design:
     a. Improve design practices with an emphasis on engineering principles to ensure safe dumping angles and better load distribution.
   - Adopt advanced monitoring and technology:
     a. Utilize technologies like advanced laser-based surveying and real-time data analysis to maintain proactive slope stability monitoring.
6. Long-term strategic measures
   - Education and engineering understanding:
     a. Lack of engineering comprehension contributes to many failures. Therefore, continuous training programs should be introduced for mine managers and engineers.
   - Collaboration with risk management frameworks:
     a. Integrate technological advancements, engineering strategies, and risk preparedness into a cohesive risk management system to identify and mitigate potential slope failure scenarios.

6.0 Conclusion

This research review paper will provide directions to address the challenges in this field. By improving slope stability in opencast mines, the mining industry in India can enhance safety, environmental protection, and operational efficiency.

The slope stability of open-cast mines in India is a critical aspect of ensuring the safety of mining operations and personnel working in or around the mines. Given the diverse geological conditions, varying terrain, and operational complexities in India, slope stability analysis plays a vital role in mitigating the risks associated with slope failures in opencast mines.

Several factors must be considered to assess the slope stability of open-cast mines in India effectively. These include geological conditions, hydrological factors, slope geometry, soil properties, external influences, seismic activity, and human activities. Understanding the interplay of these factors is essential for conducting a thorough slope stability analysis and implementing appropriate risk management strategies.

Various slope stability analysis methods, such as deterministic methods (e.g., Bishop's Method, Janbu's Method), numerical methods (e.g., Finite Difference Method, Finite Element Method), and limit equilibrium methods, can be employed to evaluate the stability of slopes in opencast mines. It is often beneficial to use a combination of these methods to account for the complexities of the mining environment and provide a comprehensive assessment of slope stability[20].

Ensuring the slope stability of open-cast mines in India requires a multidisciplinary approach that integrates geological, geotechnical, hydrological, and engineering principles. By conducting rigorous slope stability analyses, implementing appropriate monitoring systems, and adopting proactive risk mitigation measures, mining operators can enhance safety standards, minimize potential hazards, and sustain efficient mining operations in the dynamic landscape of Indian mines.

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