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To Study the Geotechnical Parameters for Slope Stability in Opencast Mines- A Review

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Abstract:
In opencast mining, slope stability is a major safety concern due to the constant excavation of overburden and ore, which disturbs the natural ground equilibrium. Failure of slopes can result in hazardous consequences including loss of life, equipment damage, production delays, and increased operational costs. The evaluation of slope stability is primarily governed by a variety of geotechnical parameters such as cohesion, angle of internal friction, unit weight of the rock or soil mass, water content, and geological discontinuities. This review aims to critically assess various geotechnical factors influencing slope stability in opencast mines and to explore the latest methodologies and instrumentation used for evaluating these parameters. The paper emphasizes the role of site-specific geological conditions, laboratory and in-situ testing techniques, numerical modeling approaches, and monitoring strategies. The review also discusses previous research studies, contemporary challenges, and recommendations for improving slope design and safety management in mining operations.

Keywords: Opencast Mining, Slope Stability, Geotechnical Parameters, Numerical Modelling, Mine Planning, Failure Analysis, Monitoring, Shear Strength.

I. INTRODUCTION

The stability of slopes in opencast mines is one of the most critical aspects in ensuring operational safety, productivity, and environmental sustainability. As surface mining operations expand deeper to access mineral reserves, the design and maintenance of stable slopes become increasingly challenging and complex. In an opencast mining environment, benches are excavated at various levels, creating high vertical or inclined faces in overburden, interburden, and ore zones. These artificially created slopes disturb the natural stress equilibrium of the ground and are continuously subjected to various external and internal forces such as excavation activities, groundwater movement, weathering, dynamic blasting loads, and geological discontinuities. Any failure in these slopes can lead to severe consequences including fatal accidents, equipment loss, operational downtime, environmental degradation, and legal liabilities. Therefore, it becomes imperative to study and evaluate the geotechnical parameters that govern slope behavior. Geotechnical engineering provides tools and methodologies to assess parameters such as cohesion, angle of internal friction, unit weight, shear strength, modulus of elasticity, rock mass rating (RMR), and geological strength index (GSI), which are essential for determining the factor of safety and predicting the potential modes of slope failure. Additionally, slope stability is influenced by geological factors such as lithology, joint sets, fault lines, weathering grade, and groundwater conditions, which must be thoroughly investigated during the site characterization phase. In many cases, slope failures occur not because of lack of design but due to insufficient understanding or underestimation of these parameters. With advances in instrumentation, numerical modeling, remote sensing, and probabilistic analysis, it is now possible to simulate and monitor complex slope behavior under varying stress-strain and hydrogeological conditions. However, despite these technological developments, challenges persist in gathering reliable field data, accounting for material heterogeneity, and incorporating dynamic loading effects into models. This review paper aims to consolidate knowledge from past studies, explore the methodologies used to evaluate geotechnical parameters, and discuss their role in designing stable slopes in opencast mines. The study also highlights the need for an integrated approach that combines empirical, analytical, and numerical techniques, supported by real-time monitoring, to develop safe and economical slope designs that can withstand long-term mining operations. Given the increasing emphasis on mine safety, resource conservation, and environmental protection, understanding the geotechnical behavior of slopes has become more relevant than ever before, and this study serves as a foundational step toward that goal.

II. LITERATURE REVIEW

Over the past several decades, extensive research has been conducted globally to understand the complex interactions of geotechnical parameters that influence slope stability in opencast mines. The evolution of slope stability analysis can be traced from early empirical approaches to more advanced analytical and numerical modeling techniques. Various researchers have contributed significantly to the development of methodologies for identifying and quantifying the key parameters such as cohesion, internal friction angle, unit weight, tensile strength, and shear strength of rock and soil, which directly affect the stability of slopes. One of the most influential contributions in this domain is the Hoek-Brown failure criterion developed by Hoek and Brown in 1980, which is widely used for evaluating the strength of jointed rock masses in slope design and is still considered foundational in modern rock mechanics. Their approach introduced parameters such as the Geological Strength Index (GSI), which accounts for the structural condition and surface characteristics of the rock mass. Wyllie and Mah (2004) further emphasized the importance of using rock mass classification systems like Rock Mass Rating (RMR) and the Q-system in determining slope stability and selecting appropriate support systems. Several studies, such as those by Singh et al. (2011), demonstrated the value of back-analysis techniques to validate design parameters by comparing predicted and actual slope failures, particularly in Indian coal and metal mines. These techniques have proven effective in fine-tuning model inputs and improving the reliability of slope design. Researchers like Maiti et al. (2015) combined geotechnical data with geophysical surveys to assess slope safety in limestone quarries, highlighting the synergistic benefits of multidisciplinary approaches. With the advent of numerical modeling tools such as FLAC3D, PLAXIS, RS2, and SLOPE/W, there has been a significant shift toward simulating real-time conditions, material heterogeneity, and complex geometries under varied loading conditions. Studies have shown that finite element and finite difference methods offer superior insights into stress distribution, deformation patterns, and progressive failure mechanisms compared to traditional limit equilibrium methods, which are more suited for simple planar or circular failures. Jayanthu et al. (2016) reviewed the effectiveness of slope monitoring tools such as Total Stations, Ground Penetrating Radar (GPR), InSAR, LiDAR, and drone photogrammetry in predicting failure zones and facilitating early warning systems. The integration of these technologies into slope management strategies has significantly improved the ability of mine planners to ensure safety and reduce unexpected failures. Moreover, recent literature has shifted toward probabilistic and reliability-based approaches, as proposed by researchers like Read and Stacey (2009), where the inherent uncertainties in geotechnical parameters are acknowledged, and risk-based design decisions are emphasized. The focus is now not only on static slope stability but also on dynamic behavior under blast loading, rainfall infiltration, and seismic forces. Additionally, literature highlights that anthropogenic activities such as over-digging, improper blasting, and inadequate drainage systems contribute to slope destabilization, and these operational factors must be considered alongside geological ones. Case studies from Indian mines, such as those in Singrauli, Neyveli, and Jharia, have provided valuable insights into common failure patterns and remediation techniques, including slope re-profiling, drainage installation, rock bolting, and grouting. Overall, the literature strongly supports an integrated geotechnical approach combining detailed site investigation, rigorous laboratory testing, advanced numerical simulations, and real-time monitoring for effective slope management in opencast mining operations. The reviewed works collectively form a robust knowledge base and demonstrate the progressive evolution of slope stability assessment methods, while also identifying the gaps in current practice, particularly in terms of long-term performance monitoring, data availability, and the need for region-specific design criteria in diverse geological settings.

[1] Slope Stability Analysis of Open-Pit Mine Considering Weathering Effects by Wei Liu et al. (2024)- In the research study conducted by Wei Liu, Gang Sheng, Xin Kang, Min Yang, Danqi Li, and Saisai Wu (2024), titled Slope Stability Analysis of Open-Pit Mine Considering Weathering Effects, the authors explored the critical influence of weathering on the structural behavior and safety of open-pit mine slopes. Published in Applied Sciences, the paper underscores how progressive weathering alters the mechanical and physical characteristics of slope materials, particularly focusing on black shale, and how such transformations significantly affect slope stability. Through a rigorous approach combining in-situ field observations, controlled laboratory experiments, and numerical modeling techniques, the researchers established a correlation between weathering intensity and the deterioration of geotechnical properties. It was observed that uniaxial compressive strength, shear strength, and elastic modulus of black shale showed a marked decrease as weathering progressed, thereby increasing the likelihood of slope failures such as landslides and collapses. The study developed a functional relationship between weathering time and mechanical degradation, offering a valuable predictive tool for assessing slope vulnerability in operational mines. The authors emphasized the necessity of integrating weathering parameters into slope stability models to enhance the precision of stability predictions. Additionally, the research presented actionable slope reinforcement and risk mitigation strategies tailored for weathered rock masses, thereby contributing to the formulation of more resilient and adaptive slope management practices. This study is part of a special issue focusing on stability control in underground openings under high stress and deep mining environments, reflecting its relevance in current geotechnical and mining engineering discourse. The insights offered are instrumental for mine planners and geotechnical engineers aiming to optimize safety protocols and operational efficiency in weather-affected mining terrains.

[2] Assessment of Slope Stability in Opencast Coal Mines Using Software by Tavitinaidu P. et al. (2019)- The authors examined the critical aspects of slope stability in opencast coal mining operations through numerical modeling techniques. The study emphasized the potential hazards and economic setbacks associated with slope failures in open-pit mining, where geological variability and rock mass conditions are highly site-specific and influence the overall slope behavior. Utilizing the FLAC/Slope software, a robust numerical tool for geotechnical analysis, the research aimed to simulate and analyze the slope conditions under different parametric inputs, primarily focusing on failure modes and their triggers. Through a series of simulations, the authors explored how changes in slope geometry, particularly the slope angle, significantly impact the factor of safety and the likelihood of slope failure. The ease of use and user-friendly interface of FLAC/Slope was also highlighted, indicating its practical applicability for engineering students and professionals alike. The study concluded that numerical modeling, especially with adaptable software like FLAC/Slope, is an essential approach to evaluate the stability of mine slopes accurately. Moreover, the findings reinforced the importance of maintaining optimal slope angles to minimize failure risks, thereby enhancing both the safety and efficiency of mining operations. This research contributes valuable insights into the application of advanced modeling tools in geotechnical engineering, supporting the design and monitoring of safer open-pit mining environments.

[3] Factors Affecting Slope Stability of an Opencast Mine: A Brief Study by M. Sathish Kumar et al. (2022)- The authors present a comprehensive discussion on the various elements that influence slope stability in opencast mining environments. The study underscores the growing relevance of slope stability and monitoring in ensuring operational safety and reducing economic losses in mining activities. The authors highlight the rapid advancement and integration of wireless sensor networks (WSNs) and Internet of Things (IoT)-based technologies into slope monitoring systems, emphasizing how these innovations have significantly elevated slope management standards. Particularly notable is their contribution to reducing costs, thereby encouraging adoption even by small-scale mining operations. Despite these technological strides, the paper points out persisting gaps in monitoring accuracy, especially in addressing complex slope failures triggered by multiple, interrelated factors. To mitigate such issues, the authors advocate for the deployment of multi-sensor systems capable of capturing diverse aspects of slope movement simultaneously. The study thoroughly explores the various physical, geological, environmental, and structural components affecting slope stability, aiming to improve the predictive capability and reliability of monitoring systems. The authors argue that a deep understanding of these factors is essential for designing more robust slope stabilization measures. Ultimately, this paper serves as a valuable resource for engineers and researchers looking to enhance mine safety through the integration of advanced monitoring techniques and informed slope design practices in opencast mining scenarios.

[4] Slope Stability Analysis Under a Complex Geotechnical Condition – A Case Study by G. S. Utami et al. (2019)- This case study centers around a mining site located in Tanjung Enim, South Sumatera, Indonesia, which is characterized by intricate subsurface conditions. The study employs the limit equilibrium method through the GeoSlope-Slope/W software to evaluate the safety and reliability of the proposed mine slope design. Results indicate that the slope, in its current configuration, is unstable due to the shear force exceeding the shear strength—an outcome largely attributed to complex geological structures like faults and discontinuities. These subsurface anomalies compromise the structural integrity of the slope, highlighting the inadequacy of traditional slope designs under such geologically variable conditions. Recognizing this, the authors propose an alternative slope design that addresses the identified weaknesses and improves the safety margins for future mining operations. This research emphasizes the necessity of incorporating site-specific geotechnical complexities into slope analysis to prevent failures and ensure sustainable mining. The approach detailed in this paper offers a practical framework for engineers dealing with similar geotechnical uncertainties in mining environments, showcasing how adaptive slope design can mitigate risks and support safer mining practices.

[5] Study of Slope Stability of the Mining Wall in an Open-Pit Coal Mine by the Paste Cut-and-Backfill Method by Chano Simao Francisco et al. (2024)- In the recent study titled Study of Slope Stability of the Mining Wall in an Open-Pit Coal Mine by the Paste Cut-and-Backfill Method, authored by Chano Simao Francisco, Meng Li, Baiyi Li, and Makavelo Germain Deon (2024), and published in Applied Sciences, the researchers delve into the innovative application of the paste cut-and-backfill mining method as a strategic approach to enhance slope stability and prevent wall collapses in open-pit coal mining operations. The study was conducted under the auspices of the State Key Laboratory for Fine Exploration and Intelligent Development of Coal Resources and the School of Mines at China University of Mining and Technology, with collaboration from Púnguè University in Mozambique. The researchers first investigated the geotechnical, physical, and mechanical characteristics of the stope and surrounding waste rock materials, finding them suitable for slope stability analysis. The core focus of the study was the development and optimization of Cemented Paste Backfill (CPB) using combinations of mine waste rock, fly ash, and varying cement contents. A comprehensive series of laboratory tests were conducted using cement content of 6%, 8%, and 10% alongside fly ash content of 25%, 30%, 35%, and 40% to determine the most effective mix for artificial support of mining walls, balancing both economic efficiency and structural performance. The study employed the FLAC-Slope 8.1 software to model slope stability through limit equilibrium methods under various CPB compositions and curing durations (1, 3, 7, and 28 days). The results demonstrated how increased cement content and curing time significantly improved compressive and shear strength, thus elevating the safety factor of the slope. This research provides crucial insights into how backfill strategies, when properly engineered, can serve as a reliable method for stabilizing pit walls, protecting infrastructure, and reducing the likelihood of catastrophic slope failures in open-pit coal mines. The study's findings serve as a foundation for integrating backfill-based reinforcement into slope design protocols in contemporary mining engineering practice.

[6] Slope Stability Analysis of an Open Pit Mine with Considering the Weathering Agent: Field, Laboratory and Numerical Studies by Mohammad Rezaei et al. (2024)- In the detailed study Slope Stability Analysis of an Open Pit Mine with Considering the Weathering Agent: Field, Laboratory and Numerical Studies by Mohammad Rezaei and Seyed Zanyar Seyed Mousavi (2024), published in Engineering Geology, the authors investigate the significant impact of weathering agents—specifically the freezing-thawing (F-T) cycles—on slope stability in open-pit mining operations, especially in cold mountainous regions. The research is centered on the Angouran open-pit mine, where both in-situ field measurements and laboratory experiments were integrated with numerical modeling to evaluate and predict slope behavior under weathering stress. Initially, the study quantified changes in physico-mechanical properties of schist rock, including dry density and both uniaxial and triaxial compressive strengths, as these properties were subjected to repeated F-T cycles to simulate natural weathering conditions. The Hoek-Brown failure criterion was then applied to determine the weathered rock mass properties. A numerical model of the pit slope was constructed incorporating these degraded parameters, and slope displacements were analyzed accordingly. The modeling revealed displacements ranging from 0 to 14.6 meters, especially within highly weathered zones, highlighting localized instability with low risk of large-scale collapse. For validation, a comprehensive field monitoring program was conducted, wherein 30 displacement prisms were installed on the mine's north-west wall, and displacements were recorded thrice weekly over a year. The comparison between observed field data and the simulation results showed strong correlation, with an R^2 value of 0.80, confirming the model's reliability. This research highlights the necessity of integrating weathering effects, particularly freeze-thaw cycles, into geomechanical modeling and mine design, offering a valuable framework for improving safety and cost efficiency in cold-climate mining operations.

[7] Stability Analysis of Dump Slope in Open Cast Mines by B. Shruthi et al. (2019)- In the research article Stability Analysis of Dump Slope in Open Cast Mines, authored by B. Shruthi, Vaishali J. Rajurkar, and Sumit S. Geete (2019), and published in Helix, Vol. 9(6), the authors present a detailed case study of slope stability evaluation at the Makardhokra – II opencast mine operated by Western Coalfields Limited. The study focuses on the geotechnical challenges posed by dump slope instability, particularly due to the presence of expansive black cotton soil extending up to 20 meters deep. The research employed the GEO5 software, which utilizes the Limit Equilibrium Method (LEM), to model and analyze the stability of the Over Burden Dump (OBD) slopes using Bishop's Method, Fellenius Method, and Spencer Method. Soil samples were collected from OBD benches, and geotechnical parameters such as cohesion, internal friction angle, and unit weight were assessed for both black cotton soil and white soil. The analysis revealed that the Factor of Safety (FoS) significantly decreases with increasing slope angle, indicating higher instability risks. To enhance stability, engineering interventions such as the construction of cantilever retaining walls and gabion walls were explored. Various wall heights and backfill distances were modeled to evaluate their effectiveness. Although cantilever walls provided a higher FoS, their construction was deemed economically less viable, with costs around 70% higher than that of gabion walls. Additionally, due to land constraints, the feasibility of conventional retaining walls was ruled out. The study concluded that gabion walls, in conjunction with partial replacement of black cotton soil with more stable white soil, offer a cost-effective, sustainable, and practical solution for improving dump slope stability. The findings provide actionable insights for mine planners and engineers managing slope stability in similar soil and terrain conditions, and emphasize the importance of tailored geotechnical interventions for OBD slope management.

[8] Advancement in Bench Slope Stability in Open Cast Mines by Raj Ashish (2022)- In the paper Advancement in Bench Slope Stability in Open Cast Mines, authored by Raj Ashish (2022) and published in NeuroQuantology, Vol. 20, Issue 21, the study provides an insightful review of the recent advancements in maintaining and improving the stability of bench slopes in open cast mining operations. Recognizing that bench slope failures can pose severe safety hazards and operational setbacks, the paper outlines how modern mining practices are increasingly integrating advanced technologies to address these geotechnical challenges. The author highlights the evolution of numerical modeling tools used for simulating slope behavior under varying geological and operational conditions, enabling more accurate and predictive slope stability analyses. In addition, the paper discusses the significant role of instrumentation and real-time monitoring systems—including sensors, inclinometers, and remote sensing tools—which allow for continuous observation of slope movement and early detection of potential failure zones. A noteworthy aspect of the study is its exploration of cutting-edge innovations such as machine learning, artificial intelligence (AI), and autonomous systems in slope stability management. These technologies offer adaptive learning capabilities, allowing systems to analyze complex datasets from various slope conditions and optimize response strategies. The paper also points to the future of geotechnical engineering in mining, where automated decision-making and real-time hazard assessments may drastically improve mine safety and operational efficiency. Raj Ashish concludes that while traditional engineering principles remain foundational, the integration of emerging digital technologies is reshaping the approach to slope stability in open cast mines, ushering in a new era of intelligent, proactive, and safer mining practices.

[9] Stability Analysis of Open Pit Slope by Finite Difference Method by K. Soren et al. (2014)- In the paper titled Stability Analysis of Open Pit Slope by Finite Difference Method, authored by K. Soren, G. Budi, and P. Sen (2014), and published in IJRET: International Journal of Research in Engineering and Technology, the authors present a rigorous numerical modeling approach for analyzing the stability of slopes in open-pit mines. The study, conducted at the Indian School of Mines, utilizes the Finite Difference Method (FDM) via the FLAC (Fast Lagrangian Analysis of Continua) software to evaluate stress distribution, displacement behavior, and factor of safety in pit slopes. The primary aim of this work is not only to generate quantitative outputs such as stress and strain values but also to deepen the understanding of failure processes in jointed rock masses. The research emphasizes the critical role of geological discontinuities, including joints, faults, and bedding planes, in controlling the mechanical behavior of rock slopes. For this purpose, the study employs the Ubiquitous Joint Model (an anisotropic plasticity model) integrated with the Mohr-Coulomb failure criterion, which allows for the inclusion of weak planes at specified orientations within the rock mass. The simulations performed identify zones of instability and likely failure mechanisms, facilitating optimized slope design from both safety and economic standpoints. The results of the modeling—particularly the distribution of stress, strain, and displacement fields—provide essential insights into slope behavior under excavation stresses, making the study a valuable resource for geotechnical engineers involved in the design and stabilization of open-pit mine slopes. The authors conclude with recommendations for practical slope designs and remedial measures tailored to jointed and weathered rock conditions.

[10] Optimizing Design and Stability of Open Pit Slopes in Tolay Coal Mine, Ethiopia by Eyerusalem Alemayehu et al. (2025)- In the open-access article Optimizing Design and Stability of Open Pit Slopes in Tolay Coal Mine, Ethiopia, authored by Eyerusalem Alemayehu, Endalu Tadele Chala, Nagessa Zerihun Jilo, Tiyasha Tiyasha, and Belachew Moges (2025), and published in Scientific Reports, the authors investigate the geotechnical and structural stability of slopes in the Tolay open-pit coal mine located in the Jimma zone of Ethiopia. With coal being a vital energy source for global industries, the study emphasizes the need for safe and efficient extraction methods, particularly in geologically sensitive regions. The site comprises basalt, mudstone, siltstone, claystone, and weathered soils, which significantly influence slope behavior. To assess the slope stability, a combination of geological mapping, discontinuity analysis, Schmidt hammer testing for uniaxial compressive strength (UCS), and soil laboratory testing was undertaken. The stability analysis incorporated both Limit Equilibrium Methods (LEM) using Slide software and Finite Element Methods (FEM) via Phase2 software. Results revealed that most slope benches were unstable, with low Factor of Safety (FOS) values ranging from 0.220 to 0.430—well below acceptable thresholds. Only Bench 4 exhibited moderate stability with FOS between 1.228 and 1.487. The study demonstrated that a significant improvement in slope stability could be achieved by optimizing slope geometry; notably, reducing the slope angle from 70° to 26° improved the FOS from 0.322 to 1.373. These findings highlight the importance of considering slope angle, bench height, and local geotechnical characteristics in slope design. The study concludes with recommendations for design optimization strategies to ensure the structural integrity of mine slopes, reinforcing the crucial role of geotechnical analysis in the safety and sustainability of coal mining operations.

[11] Slope Stability Study of External Dump of Sonepur-Bazari Opencast Coal Mine, India — A Case Study by Indrajit Roy (2008)- In the paper Slope Stability Study of External Dump of Sonepur-Bazari Opencast Coal Mine, India — A Case Study, presented by Dr. Indrajit Roy at the 6th International Conference on Case Histories in Geotechnical Engineering (2008), the author addresses the pressing geotechnical challenge posed by external dump instability in India's rapidly expanding opencast coal mining sector. With India ranking among the top global coal producers, the demand for land to accommodate both mining operations and overburden disposal has intensified, particularly in densely populated regions. The study centers on the Sonepur-Bazari opencast coal mine in eastern India, where a 75-meter-high external overburden dump was constructed above a 15-meter-thick, fully saturated clay stratum. This configuration led to significant geotechnical distress in the form of floor heaving near the dump toe, raising serious concerns about slope stability, environmental safety, and operational sustainability. Dr. Roy undertook a comprehensive slope stability assessment, analyzing the geotechnical behavior of the dump material and the underlying saturated clay layer to identify the causes and extent of instability. The study employed standard analytical and empirical techniques to evaluate slope performance, and proposed design and remediation strategies to mitigate the risk of failure. Key recommendations included revising the dump geometry, improving drainage, and reducing the load intensity to stabilize the foundation clay layer. This case study underscores the critical need for detailed geotechnical investigation and slope design optimization in external dumping practices, especially in regions with weak subsoil and high groundwater conditions. The findings serve as an essential reference for mine planners and geotechnical engineers in managing overburden dumps safely and efficiently in similar geological and hydrological settings.

[12] Slope Stability Analysis of Open Pit Mine by Using Finite Element Method by Abdul Nabi Umrani et al. (2023)- In the research article Slope Stability Analysis of Open Pit Mine by Using Finite Element Method, authored by Abdul Nabi Umrani, Muhammad Burhan Memon, and Muhammad Rehan Hakro (2023), and published in the International Research Journal of Modernization in Engineering, Technology and Science, the authors investigate the application of Finite Element Method (FEM) for assessing the stability of slopes in open-pit mining operations. The study, conducted by scholars from the Mehran University of Engineering and Technology, Jamshoro, Pakistan, focuses on the advantages of FEM over traditional Limit Equilibrium Methods (LEM) in analyzing complex slope geometries and heterogeneous soil and rock properties. FEM offers a more realistic simulation of stress distribution, deformation behavior, and failure zones under varying loading and geological conditions. The authors utilize numerical modeling tools to construct 2D models of the mine slope and perform simulations that reveal critical information such as displacement patterns, potential failure surfaces, and stress concentration zones. The research finds that the Factor of Safety (FoS) calculated using FEM is sensitive to changes in slope angle, material strength, pore water pressure, and boundary conditions. The study also emphasizes the role of FEM in identifying subtle signs of slope failure and enhancing the reliability of slope designs. This work contributes to the growing body of knowledge advocating for advanced numerical modeling techniques in geotechnical and mining engineering, and it underscores FEM's ability to support safer, more economical slope management strategies in open-pit mining environments.

[13] Study on the Stability of Open Pit Slopes Based on Geotechnical and Safety Aspects at the PT. Integra Mining Nusantara Indonesia Nickel Mine in Pagimana District, Banggai Regency, Central Sulawesi by Ireyndra Yusuf et al. (2024)- In the comprehensive research study Study on the Stability of Open Pit Slopes Based on Geotechnical and Safety Aspects at the PT. Integra Mining Nusantara Indonesia Nickel Mine in Pagimana District, Banggai Regency, Central Sulawesi, authored by Ireyndra Yusuf, Sriyati Ramdhani, and Sukardan Tawil (2024), and published in International Journal of Research in Engineering and Science (IJRES), the authors investigate slope stability conditions and safety aspects in an active nickel mining operation. The research is anchored in regulatory compliance, particularly following the Indonesian Ministerial Decree No. 1827 K/30/MEM/2018, which underscores the integration of geotechnical and occupational safety parameters in mining activities. Focusing on the Pit B area of the mine, the study evaluates geological formations such as serpentinite and peridotite, noting that laterization occurs only in about 27% of the region due to the prevalence of serpentinite, thereby affecting slope behavior. Stability assessments were conducted using the Limit Equilibrium Method (LEM) augmented with the probabilistic Monte Carlo simulation, processed via Slide 2D software. The initial findings indicate that existing slopes were unsafe, with safety factor (SF) values falling below the 1.3 threshold and a landslide probability reaching 29.4%, indicating a high-risk scenario under both static and dynamic conditions. A redesigned slope geometry was proposed, modifying slope angles to 31°, and bench configurations to 4–6 m in height and 5 m in width. This reconfiguration significantly improved the SF values above 1.3, and reduced the probability of failure to just 10%, thereby achieving compliance with safe mining design principles. The study not only highlights the critical role of localized geological characteristics in slope behavior but also reinforces the importance of integrating probabilistic risk analysis in mine slope design. This paper contributes to a broader understanding of how tailored slope design and safety monitoring can mitigate geotechnical hazards in nickel mining operations within complex tropical geological settings.

[15] Stability Investigation of Open-Pit Slopes During Blasting Activities by Maral Malekian et al. (2022)- In the research article Stability Investigation of Open-Pit Slopes During Blasting Activities, authored by Maral Malekian, Moe Momayez, Pat Bellett, Stefania Mancino, and Fernanda Carrea (2022), and published in International Journal of Engineering Research & Technology (IJERT), Vol. 11, Issue 08, the authors explore the significant influence of blasting activities on the stability of open-pit mine slopes. Blasting is a fundamental operation in mining but can generate energy that disrupts slope integrity, causing responses that range from minor deformations and rockfalls to catastrophic slope failures. This paper presents findings from 15 real-world case studies across various global mine sites, examining the diversity of slope reactions to blast-induced vibrations and stresses. A key innovation in the study is the deployment of BlastVision®, a cutting-edge monitoring tool developed by GroundProbe, which uses high-resolution drone imagery and visual data to detect subtle ground luminance changes—a novel method for identifying micro-movements in the slope. The study categorizes slope responses based on their proximity to blast zones and evaluates how blasting patterns and designs influence wall stability. The research shows that slopes closest to blast epicenters experience the highest deformation magnitudes, while strategic blast orientation and controlled energy distribution can mitigate risks. Overall, the paper emphasizes the need for precise blast design, continuous slope monitoring, and integration of advanced technologies like BlastVision® to enhance predictive capabilities and ensure safer blasting operations in open-pit mines. These insights contribute to a more nuanced understanding of the dynamic interaction between blasting practices and slope behavior, offering valuable guidelines for improving operational safety and geotechnical performance.

[16] Numerical Analysis of Dump Slope Stability Using Material Properties Obtained by Parallel Gradation Method by Eeswara Sai Chaitanya Kumar Rudra et al. (2023)- In the article Numerical Analysis of Dump Slope Stability Using Material Properties Obtained by Parallel Gradation Method by Eeswara Sai Chaitanya Kumar Rudra, Prudhvi Raju Gadepaka, Ashok Jaiswal, and others (2023), the authors address the complex challenge of evaluating dump slope stability where dump materials contain a wide range of particle sizes, sometimes up to 1000 mm. Traditional laboratory methods fall short in replicating the mechanical behavior of such heterogeneous materials due to equipment limitations. To overcome this, the study employs the parallel gradation method, which allows researchers to scale down particle sizes while maintaining the geometric similarity of the particle size distribution (PSD). The scaled samples are then used to derive shear strength properties, particularly the angle of internal friction, which is extrapolated to represent the full-scale material. The study validates this method by comparing the predicted values with those obtained from empirical relationships, showing a high degree of correlation. Using these derived parameters, numerical modeling is performed using the RS2 V9.0 finite element software to simulate dump slope conditions. The analysis reveals that the Factor of Safety (FoS) of the dump slope increases with larger maximum particle sizes, assuming the shape of the PSD curve remains constant. This indicates that particle size distribution plays a crucial role in dump stability, and accurate modeling of this parameter can significantly enhance prediction accuracy. The proposed methodology introduces a refined approach to slope stability analysis, especially for conditions involving large, heterogeneous waste dumps where standard lab testing proves inadequate. This study advances the field of geotechnical engineering by providing a practical and reliable solution for analyzing and ensuring the safety of dump slopes in mining and large-scale earthwork operations.

[17] Shear Strength Parameters for Assessing Geotechnical Slope Stability of Open Pit Coal Mine Spoil Based on Laboratory Tests by Kho, A. K., Williams, D. J., Kaneko, N., and Smith, N. J. W. (2013)- Presented at the Slope Stability 2013 symposium in Brisbane, Australia, the paper by Kho et al. (2013) focuses on evaluating the shear strength parameters of open pit coal mine spoil through laboratory testing, with a goal of improving geotechnical slope stability assessments of increasingly deep and high spoil piles. The study acknowledges the difficulty in accurately characterizing spoil materials that consist of highly variable particle sizes and compositions. Samples were collected from four different coal mine sites across Queensland and New South Wales, representing a broad range of spoil types—from fresh, well-cemented sandstone to weakly cemented and weathered clay-rich materials. To investigate the effects of particle size and scalping on shear strength behavior, direct shear tests were conducted using both small-scale (60 mm) and large-scale (300 mm) shear boxes. Testing was performed on loose specimens at in-situ moisture content, and further examined under saturated conditions to simulate post-rainfall slope behavior. The research reveals notable variations in strength properties depending on the spoil type, particle size distribution, and saturation condition. The study critically assesses whether laboratory-obtained values from scalped samples can be reliably extrapolated to full-scale mine spoil piles, given the discrepancy in particle size representation. Results from the shear testing are compared against recommended shear strength parameters found in literature, providing insights into the adequacy of commonly used geotechnical assumptions. The study highlights the limitations of current lab testing methods for coarse spoil materials, and stresses the need for site-specific calibration and cautious application of lab-derived parameters for slope design and stability evaluations. This work is especially valuable for geotechnical engineers involved in mine planning and design, as it underscores the importance of representative testing procedures and data interpretation for safe and efficient spoil dump construction in large-scale open pit coal mining operations.

[18] Dump Slope Stability Analysis – A Case Study by Prasanta Kumar Behera, Kripamoy Sarkar, Ashok Kumar Singh, A. K. Verma, and T. N. Singh (2016)- In their 2016 research article Dump Slope Stability Analysis – A Case Study, Behera et al. focus on assessing the slope stability of overburden (OB) dumps in the Talcher Coalfield, located in Angul district, Odisha, India. Given the critical role of dump slope stability in ensuring operational safety and minimizing economic losses in open-cast coal mining, the authors highlight the urgent need for systematic stability assessments. The study is rooted in a tragic real-world context—a major dump failure in 2013 at the Basundhara mines under Mahanadi Coalfields Limited (MCL), which resulted in the loss of 14 lives and raised serious concerns about dump management in the region. The authors undertook a detailed geotechnical evaluation using laboratory and field investigations, analyzing the dump material for its physical, mechanical, and mineralogical characteristics. A significant finding is the impact of prolonged and heavy rainfall in increasing pore water pressures within the dump material, which severely compromises slope stability. Through the application of the Limit Equilibrium Method (LEM), the team modeled potential failure scenarios and determined the Factor of Safety (FoS) under various moisture conditions. Their results confirm that the presence of clayey materials and water infiltration due to inadequate drainage systems are key contributors to dump failures in the Talcher Coalfield. The study emphasizes the importance of integrating hydrological data with geotechnical modeling to develop more robust slope designs. Practical recommendations include improving drainage management, adjusting dump geometries, and considering mineralogical content during site planning. This case study serves as an important reference for mine planners and geotechnical engineers aiming to adopt sustainable and safe practices for overburden disposal in monsoon-prone regions.

[19] A Review on Fly Ash Slope Stability by Prajwala S. Chachadi and Prasanna Patil (2021)- In the article A Review on Fly Ash Slope Stability (2021), Chachadi and Patil explore the geotechnical potential of fly ash—a byproduct from coal-based thermal power plants—for use in slope construction and stabilization, addressing its problematic environmental disposal in India. The review highlights fly ash as a promising backfill material, especially for low-lying terrain, owing to its lightweight properties and ease of compaction. However, its inherent lack of cohesion and shear strength presents challenges for standalone slope stability. To overcome these drawbacks, the authors examine reinforcement strategies involving plastic scraps and various geosynthetics. Through laboratory model tests, both reinforced and unreinforced fly ash slopes were evaluated under different footing types and slope angles. The outcomes demonstrated that the load-carrying capacity, settlement resistance, and overall deformation characteristics significantly improve with reinforcement, validating the applicability of recycled materials like plastic waste in geotechnical engineering. Furthermore, numerical analysis using PLAXIS 2D software substantiated the experimental findings, offering a detailed understanding of stress-strain behavior and stability patterns in fly ash slopes under various loading and reinforcement configurations. The study concludes that reinforced fly ash slopes show higher factors of safety and lower settlement values compared to their unreinforced counterparts, underscoring the material's viable reuse in sustainable slope engineering.This review is particularly valuable for civil and geotechnical engineers seeking eco-friendly solutions in slope construction, promoting the dual objective of waste material utilization and geotechnical performance enhancement.

[20] Stability Evaluation of Highwall Slope in an Opencast Coal Mine – A Case Study" by I. Satyanarayana, G. Budi, Phalguni Sen, and A.K. Sinha (2018)- Focuses on assessing the stability of pit slopes at the Medapalli Opencast Project (MOCP) of Singareni Collieries Company Ltd. (SCCL), India. With the growing depth of opencast mines due to increased coal demand and mechanization, slope stability has become a significant safety concern. The study investigates a 170-meter-high highwall inclined at 45°, where slope instability was observed, indicated by cracks widening up to 90 cm before failure. Visual monitoring and the use of Cyclops instruments were employed to track slope deformations. Numerical modeling using FLAC/Slope software was carried out, incorporating laboratory-determined shear strength parameters of the rock mass. The analysis revealed that groundwater had a critical impact on slope stability, reducing shear strength under undrained conditions and leading to slope failure. The failure zone was identified to extend 10 meters from the pit crest and 20 meters deep. To mitigate the issue, a proper drainage system was implemented, which significantly improved the Factor of Safety (FoS) and allowed safe resumption of mining operations. The modeled results, including the failure surface and FoS, were successfully validated with field observations, highlighting the importance of combining geotechnical investigation, monitoring, and numerical analysis for ensuring safe and sustainable opencast mine operations.

III. PROPOSED METHODOLOGY

The proposed methodology for evaluating geotechnical parameters relevant to slope stability in opencast mines involves a systematic, multidisciplinary approach that integrates field investigations, laboratory testing, numerical modeling, and real-time monitoring. The initial phase begins with an in-depth geological and geotechnical site investigation, which includes detailed surface and subsurface mapping to document lithology, rock mass structures, joint patterns, fault zones, bedding planes, groundwater seepage zones, and weathering profiles. This mapping process provides critical baseline data to assess the geological framework and potential failure mechanisms. Simultaneously, borehole drilling is conducted at strategic locations throughout the mine to collect undisturbed core samples, which are logged and analyzed to determine stratigraphy and geomechanical characteristics. Field tests such as Standard Penetration Test (SPT), Cone Penetration Test (CPT), Pressuremeter Test, and Vane Shear Test are employed to assess soil strength and deformation behavior in situ, while rock mass quality is evaluated using Rock Quality Designation (RQD), Point Load Test, and Schmidt Hammer Rebound Test. The next phase involves comprehensive laboratory testing of collected samples, where soil and rock specimens are subjected to direct shear tests, triaxial compression tests (both consolidated drained and undrained), unconfined compressive strength (UCS) tests, and slake durability tests to derive values of cohesion (c), angle of internal friction (φ), Young's modulus, Poisson's ratio, porosity, unit weight, and permeability. These parameters are essential for calculating the shear strength of slope-forming materials and for input into analytical and numerical stability models. Once the physical and mechanical properties of the slope materials are defined, advanced slope stability analysis is performed using numerical modeling tools such as FLAC3D, RS2, PLAXIS, and SLOPE/W. These models simulate slope geometries, bench configurations, loading conditions, groundwater influence, and dynamic factors such as seismic and blasting effects. Both two-dimensional (2D) and three-dimensional (3D) analyses are conducted to visualize the stress-strain behavior, identify potential slip surfaces, evaluate the factor of safety, and perform sensitivity analysis to assess the effect of parameter variability. Back-analysis of past slope failures, where applicable, is conducted to calibrate and validate the model outputs. In parallel, hydrogeological studies are undertaken to evaluate pore water pressure build-up and seepage patterns, which are crucial for long-term slope stability. The methodology also incorporates the use of geophysical methods such as Electrical Resistivity Tomography (ERT) and Ground Penetrating Radar (GPR) for subsurface profiling and anomaly detection without excavation. In the operational phase, slope monitoring systems are deployed for real-time surveillance. These include installation of inclinometers, extensometers, piezometers, and tiltmeters, along with prism targets and Total Station surveys to monitor deformation trends. Satellite-based remote sensing techniques such as Interferometric Synthetic Aperture Radar (InSAR), LiDAR scanning, and drone photogrammetry are increasingly integrated to detect minute movements across wide mine areas. All collected data is regularly analyzed to assess slope performance and predict potential failures. Risk mapping is performed by combining geotechnical, geological, and hydrological data to categorize slope sections into high, medium, or low-risk zones. Based on the outcomes, mitigation strategies such as slope flattening, installation of drainage galleries, use of geosynthetics, rock bolting, retaining structures, and controlled blasting patterns are recommended to enhance slope stability. The proposed methodology, thus, emphasizes a holistic and iterative approach that blends empirical observations with cutting-edge technology, allowing mine operators to optimize slope angles, ensure operational safety, reduce economic losses, and comply with regulatory standards. This framework not only serves to improve the immediate stability of mining slopes but also contributes toward the long-term geotechnical sustainability of the mine.

CONCLUSION

The stability of slopes in opencast mining operations is a subject of paramount importance, not only from the perspective of worker safety and operational continuity but also from the standpoint of environmental sustainability and economic viability. This review has highlighted that slope stability is a multifaceted geotechnical challenge influenced by a wide array of factors, including but not limited to the physical and mechanical properties of soil and rock, geological structures such as joints and faults, groundwater movement, slope geometry, excavation methods, and dynamic influences like blasting and seismic activity. Through a detailed examination of past research, it is evident that accurate determination and interpretation of geotechnical parameters such as cohesion, angle of internal friction, unit weight, permeability, shear strength, modulus of elasticity, and rock mass classification indices like RMR and GSI form the backbone of any reliable slope stability analysis. Traditional empirical and analytical approaches, while still relevant, are increasingly being complemented and even replaced by advanced numerical modeling techniques that simulate complex geological and stress conditions in both two and three dimensions. These models offer the ability to visualize potential failure surfaces, conduct sensitivity analysis, and evaluate safety factors under variable loading and hydrogeological conditions. Furthermore, the role of modern remote sensing technologies and real-time monitoring systems has been underscored in enhancing the predictive capabilities of slope behavior, thus enabling timely interventions before catastrophic failures occur. It has also been observed that integrating hydrogeological assessments, field instrumentation, laboratory test data, and geophysical surveys leads to more robust and comprehensive slope design strategies. Despite these advancements, significant challenges remain, particularly in the areas of data collection from inaccessible terrain, modeling material anisotropy and heterogeneity, and the practical implementation of mitigation measures in operating mines. The review also reveals a pressing need for region-specific studies, especially in diverse geological conditions such as those found in Indian mines, where lithological variations, intense weathering, and unregulated excavation practices often complicate slope behavior. In light of these findings, it becomes clear that a well-planned, multidisciplinary, and dynamic approach is required to ensure slope stability throughout the life cycle of a mine.

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