iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 Issue: VIII Month of publication: August 2025

DOI: https://doi.org/10.22214/ijraset.2025.73747

# To Study the Geotechnical Parameters for Slope Stability in Opencast Mines

Mr. Ravi Singh[1], Dr. Ram Chandra Chaurasia[2]
[1]*Research Scholar, Department of Mining Engineering, LNCT College, Jabalpur*
[2]*Associate Professor & Head of Department, Department of Mining Engineering, LNCT College, Jabalpur*

***Abstract: Slope stability is a critical aspect in the design and operation of opencast mines throughout the entire project lifecycle. Slope failure can lead to significant hazards including equipment damage, production delays, and worker injuries. Therefore, ensuring stable slope design is essential. The failure mechanisms are primarily influenced by geotechnical parameters such as rock mass strength, structural discontinuities, and groundwater conditions. Historically, due to limited technological advancement, slope failures were frequent, and the development of benches posed major challenges. However, modern advancements in rock mechanics, field investigations, and simulation-based software have revolutionized slope design processes. With the integration of advanced software tools and skilled personnel, slope failures can now be effectively predicted and mitigated. This study focuses on understanding and analyzing pit slope design in the context of the Singhori opencast project of Western Coalfields Limited (WCL). The project involves the use of secondary data from earlier research and government agencies, which has been numerically modeled to analyze slope behavior. The findings emphasize that final pit design is not only influenced by ore grade and economics, but also critically by rock mass strength and stability. Thus, slope stability assessments must be integral to every mining plan to ensure safe and efficient operations.***
***Keywords: Slope Stability, Opencast Mining, Geotechnical Parameters, Rock Mass Strength, Pit Slope Design, Numerical Modeling, Slope Failure, Singhori Opencast Project.***

## I. INTRODUCTION

Slope stability analysis is a fundamental pillar of geotechnical engineering and plays a pivotal role in the planning, operation, and closure phases of opencast mining projects. Ensuring the stability of both natural and engineered slopes—such as pit walls, haul roads, waste dumps, and embankments—is crucial not only for the safety of personnel and equipment but also for maintaining operational continuity and economic viability. These slopes are constantly subjected to excavation-induced stress changes, groundwater fluctuations, weathering, and dynamic loads such as blasting and heavy machinery movement, making them inherently vulnerable to failure. In the Indian mining sector, slope design remains largely governed by empirical practices and engineering intuition due to the lack of formal, site-specific regulatory standards. Despite global advancements in slope engineering and risk management, many Indian opencast mines continue to rely on outdated methodologies, often failing to capture the complex interplay of geological, hydrological, and mechanical factors influencing slope behavior. This regulatory and technological gap significantly elevates the risk of slope failures, particularly in deeper and steeper mines. Opencast mining has become increasingly prevalent in India owing to its higher productivity, shorter gestation period, and safer working conditions compared to underground mining. However, this trend brings with it several environmental and technical challenges. The removal of massive overburden volumes generates large quantities of waste that require safe disposal, leading to extensive land degradation and increased susceptibility to slope instability. As mining depths increase, the geotechnical complexity also intensifies, driven by factors such as loss of cohesion in weathered rock masses, groundwater infiltration, and structural discontinuities like joints and faults. Slope failures in opencast mines have far-reaching consequences, including production delays, equipment loss, increased operating costs, and in severe cases, human casualties and abandonment of mine blocks. Groundwater presence within slope materials can exacerbate instability by reducing shear strength and increasing pore pressure. Therefore, a detailed understanding of both geotechnical and hydrogeological conditions is essential for reliable slope design. Economically, steeper pit slopes are desirable as they reduce the stripping ratio and increase ore recovery. However, pushing slope angles without rigorous geotechnical validation significantly raises the risk of failure. Thus, the final pit geometry must carefully balance ore recovery with structural safety. This calls for comprehensive site investigations, including core drilling, geophysical surveys, laboratory testing, and in-situ measurements, to obtain accurate data on rock and soil properties.

Modern slope stability analysis has evolved beyond traditional deterministic approaches and now increasingly employs advanced numerical modeling and probabilistic assessments. Techniques such as the Limit Equilibrium Method (LEM), Finite Element Method (FEM), and Discrete Element Method (DEM) allow for simulation of various failure modes—planar, wedge, circular, and toppling—and can be effectively used when calibrated with site-specific data. Moreover, real-time geotechnical monitoring tools such as piezometers, inclinometers, extensometers, and radar-based systems enhance early warning and risk mitigation strategies. Given the growing depth and complexity of Indian opencast mines, there is an urgent need to standardize slope stability practices, enhance the technical capacity of mine personnel, and integrate scientific tools into routine slope design and monitoring. This research aims to investigate the critical geotechnical parameters influencing slope stability in opencast conditions, supported by field data and numerical modeling, with a focus on the Singhori opencast project of Western Coalfields Limited (WCL). The study endeavors to contribute scientifically grounded recommendations for improving slope design reliability and ensuring safer mining operations.

## II. LITERATURE REVIEW

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.

## III. NUMERICAL MODELING

### *A. Numerical Modeling Of Opencast Mine*

In the context of Singhori Opencast Coal Project (OCP), numerical modeling has played a vital role in understanding and analyzing the stability of mine slopes under varying geological and operational conditions. The study area is characterized by the presence of four distinct geological formations—Soil, Weathered Zone, Kamptee Formation, and Barakar Formation—each possessing unique geotechnical properties that significantly influence slope behavior. To assess the slope and dump stability comprehensively, numerical modeling was carried out using both the Finite Element Method (FEM) and the Limit Equilibrium Method (LEM). These advanced computational techniques allow for a detailed understanding of slope deformation mechanisms, failure potential, and stress distribution in complex geological settings. As shown in Figure 4.1, the general layout of Singhori OCP was mapped, and specific cross-sections of interest were selected in coordination with mine officials. These cross-sections, which traverse the critical overburden dump areas and final pit walls, formed the basis for numerical simulation and analysis (refer to Figure 4.1). The models were developed by incorporating accurate stratigraphic data, including layer thickness, slope geometry, bench configuration, and geotechnical parameters derived from field and laboratory investigations. The numerical simulations were carried out for two principal scenarios—current operational stage and the final stage of mining—to compare the factor of safety (FoS) and identify critical slip surfaces under both present and future conditions. The FEM-based software Phase2 was used for these analyses, utilizing the Shear Strength Reduction (SSR) technique to compute FoS without assuming a pre-defined failure surface. In parallel, GEO5 software was employed using the Bishop's method under the LEM framework to validate the results and provide a comparative understanding of stability. By modeling the dynamic and static loading conditions, including potential water infiltration, dump loading, and operational blasting effects, the simulations provided a realistic picture of how various formations behave under stress. These simulations revealed zones of vulnerability where slope failure could initiate due to weak strata like weathered zones or due to geometrical configurations of high and steep benches. The analysis of current mining stages confirmed relative slope stability, while projections for the final stage indicated the need for optimized dump geometry and reinforcement strategies to maintain an acceptable FoS. Overall, the numerical modeling exercise offered crucial insights into the long-term safety and sustainability of the Singhori OCP operations, enabling engineers to design and manage slopes more effectively by integrating data-driven geotechnical evaluations with real-time mining strategies.

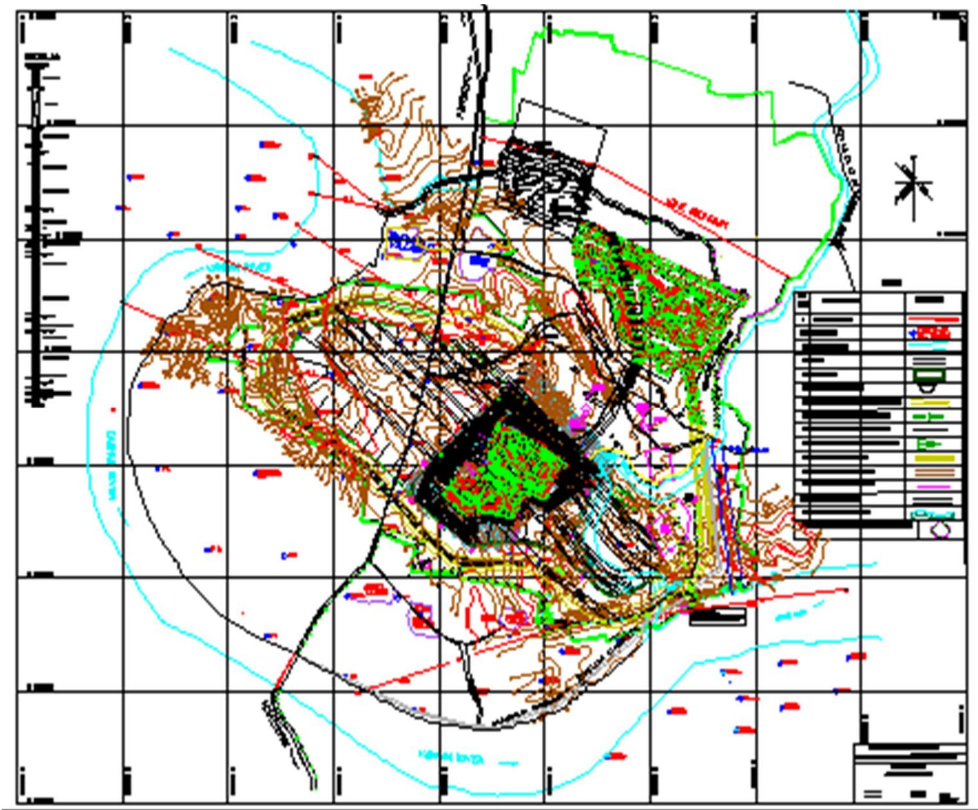


Figure 4.1: Mine Plan of Singhori OCP along with River

*B. Present Condition Of Opencast Mine*

Figure 4.2 illustrates the layout plan of the current working condition of the Singhori Opencast Mine, offering a comprehensive view of the mining geometry and the location of critical slope sections under operation. To analyze the existing slope stability in detail, three key sections—Section 28, Section 30, and Section 34—were selected for simulation based on their operational significance and structural configuration. These sections, depicted in Figures 4.3 to 4.5, provide discretized cross-sectional views of the mine, showing the bench profiles, geological layering, and dump geometry. The numerical simulations for these sections were conducted using both the Finite Element Method (FEM) and the Limit Equilibrium Method (LEM) to evaluate the Factor of Safety (FoS) under present site conditions. The FEM-based simulations, performed using advanced geotechnical software such as Phase2, allowed for detailed visualization of stress distribution, shear strain development, and deformation characteristics across different strata. The Limit Equilibrium Method, executed through GEO5 software using Bishop's Simplified Method, provided comparative FoS values by evaluating the resisting and driving forces acting along potential circular failure surfaces. The critical output from these simulations is summarized in Table 6, which presents the calculated Factor of Safety at various sections using both methods. Furthermore, Figure 6 illustrates the shear strain contours and potential failure surfaces derived from FEM analysis, helping to identify areas of localized stress concentration and potential slip zones. The results of this comprehensive analysis indicate that the Factor of Safety at all analyzed sections exceeds 1.50, which is considered a satisfactory threshold for short-term and operational stability in opencast mining. The high safety margin confirms that the present slope configuration, bench geometry, and dump design are structurally sound and pose minimal risk of failure under existing loading and hydrological conditions. Therefore, it can be concluded that the current design of the Singhori Opencast Mine is geotechnically stable, and no immediate intervention is required from a slope safety perspective. However, continued monitoring and periodic reassessment of slope stability are recommended, especially during the monsoon season and progressive excavation, to ensure long-term structural integrity and safe mining operations.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
*ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538*
*Volume 13 Issue VIII Aug 2025- Available at www.ijraset.com*

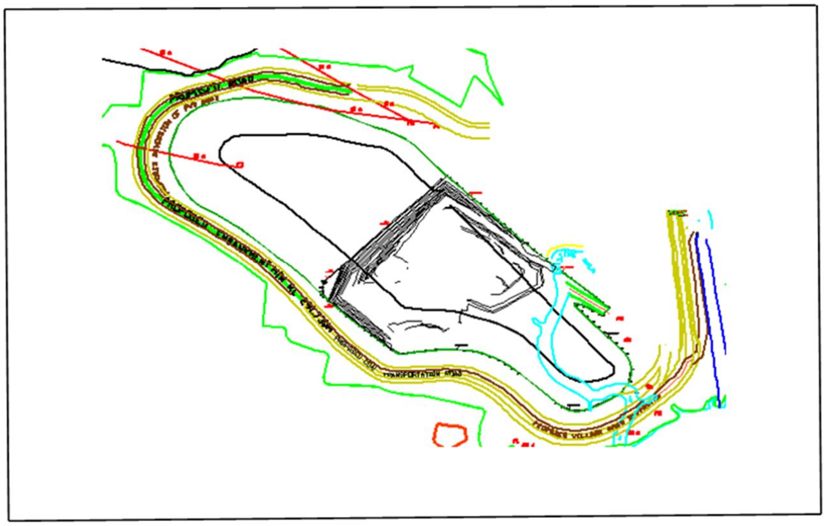


Figure 4.2: Mine Plan of Singhori OCP and section details

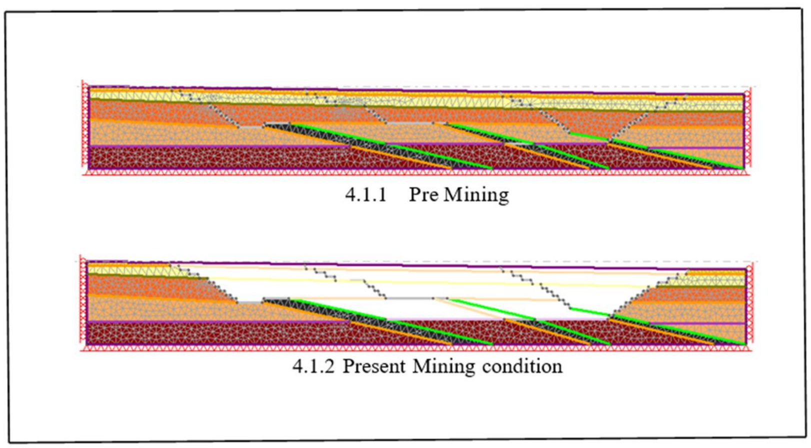



Figure 4.3: Discretized view of mine slope at sections 28

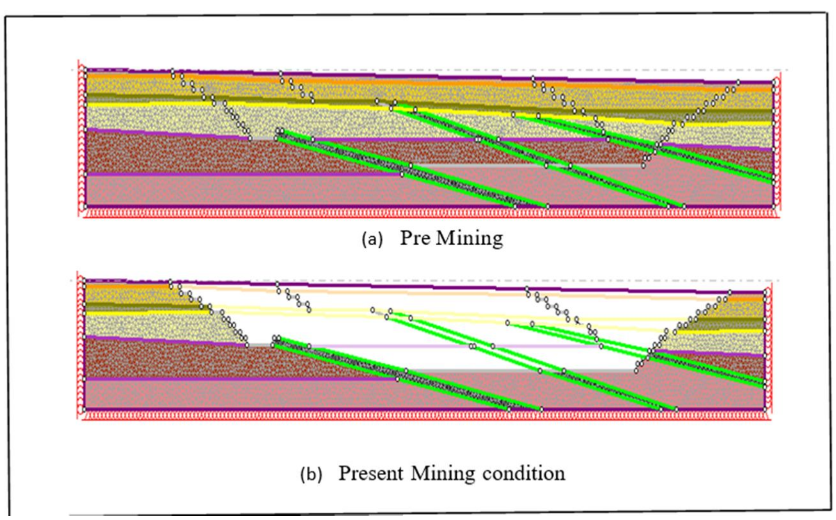



Figure 4.4: Discretized view of sections 30

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
*ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538*
*Volume 13 Issue VIII Aug 2025- Available at www.ijraset.com*

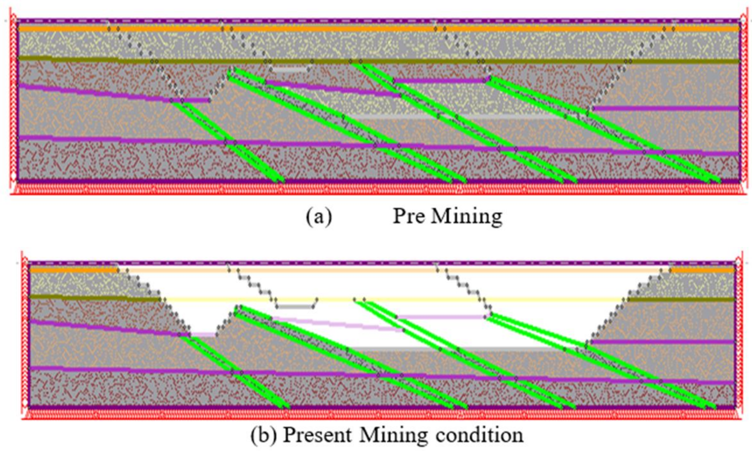



Figure 4.5: Discretized view of sections 34

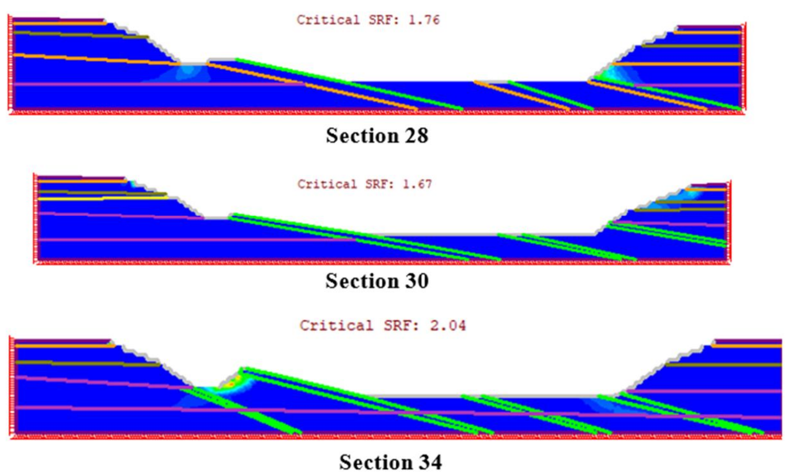



Figure 4.6: Maximum Shear strain at various sections of Open Cast Coal Mines in present condition of mining

Table 4.1: Factor of safety by finite element and limit equilibrium method

| SN | Section details | Factor of safety by (FEM) | Factor of safety by (LEM) |
|---|---|---|---|
| 1 | Section 28 | 1.76 | 1.60 |
| 2 | Section 30 | 1.67 | 1.41 |
| 3 | Section 34 | 2.04 | 2.20 |

### *C. Final Design Of Opencast*

The final design of the Singhori Opencast Coal Mine was analyzed using advanced numerical simulation techniques to ensure long-term slope stability at the ultimate pit depth of approximately 200 meters. The discretized model of the final pit slope geometry, shown in Figure 4.7, includes detailed cross-sectional profiles along critical lines—Section AA’, BB’, and GG’—representing different parts of the final pit configuration. These sections were carefully chosen based on their geological variability, slope height, and potential risk zones to offer a representative understanding of the overall pit stability at full excavation depth. The numerical simulations were carried out using both the Finite Element Method (FEM) and the Limit Equilibrium Method (LEM). Figure 8 displays the complete simulation setup and input parameters utilized for these analyses. FEM simulations were conducted to assess the distribution of stress, displacement, and shear strain within the slope, while LEM, implemented via GEO5 software using Bishop's Method, was used to estimate the Factor of Safety (FoS) for different potential slip surfaces. The results derived from these models were compared and validated across the selected sections. Figure 4.12 presents the visual output of these simulations, highlighting the zones of maximum shear strain and indicating the likely failure mechanisms in terms of critical circular slip surfaces. The results reveal that in all three cross-sections—AA’, BB’, and GG’—the Factor of Safety exceeds 1.50, both in FEM and LEM analyses, which is within the acceptable safety margin for long-term open-pit slope design. This robust FoS confirms the structural soundness and geotechnical reliability of the final mine design. Thus, based on the numerical modeling and comparative analysis, it is evident that the final slope design of the Singhori Opencast Mine is geotechnically stable. The consistent performance across different simulation approaches strengthens confidence in the design's ability to withstand operational stresses, hydrological variations, and other site-specific conditions. Continued geotechnical monitoring and adaptive slope management strategies, however, are recommended to ensure ongoing stability throughout the mine's lifecycle.

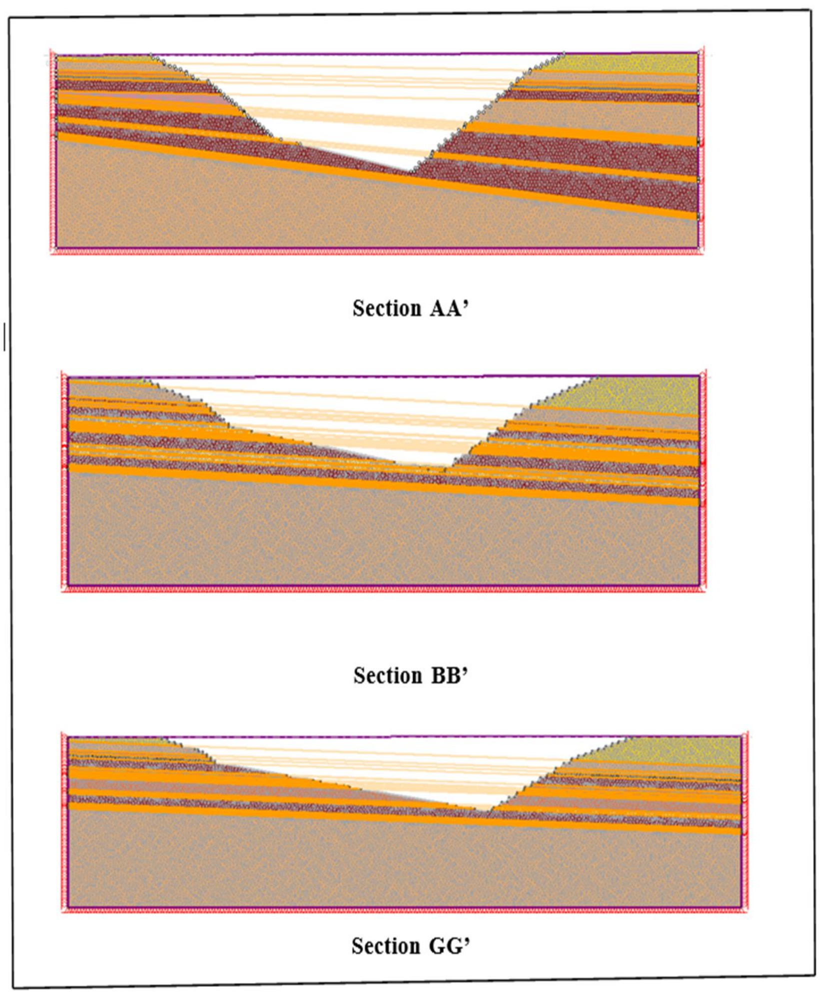



Figure 4.7: Discretized view of various sections of Open Cast Coal Mine

ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VIII Aug 2025- Available at www.ijraset.com

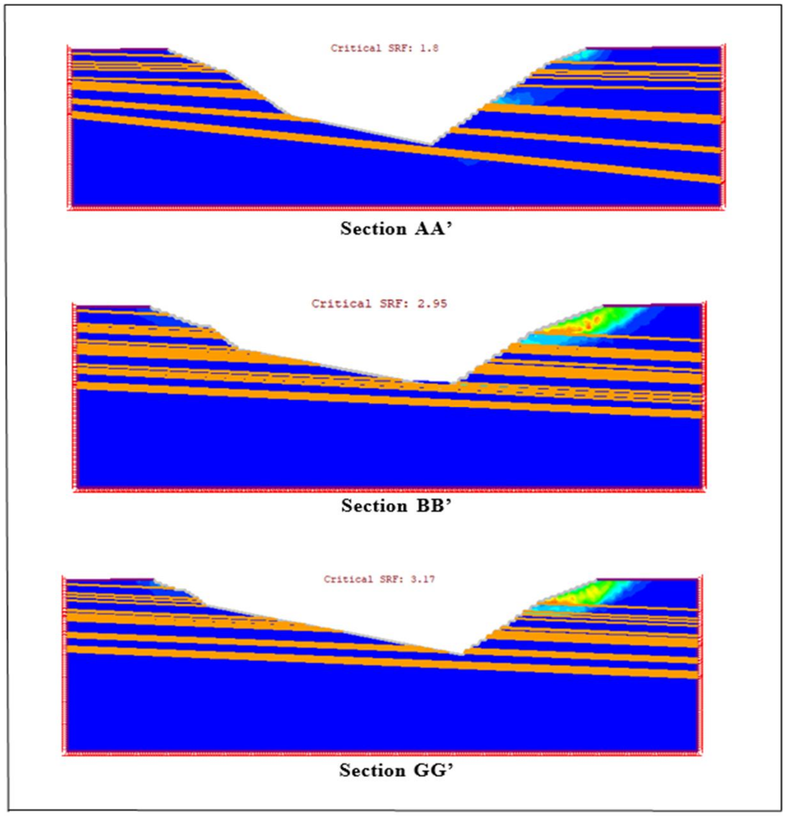



Figure 4.8: Maximum Shear strain at sections BB' of Open Cast Coal Mine

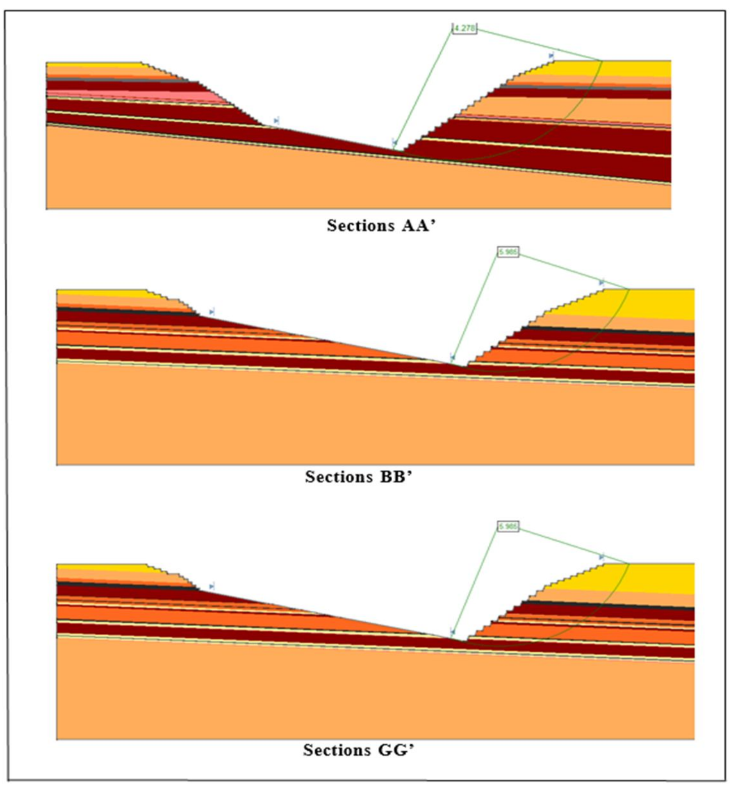



Figure 4.9: Factor of safety and probable failure circle by Limit Equilibrium method

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VIII Aug 2025- Available at www.ijraset.com

Table 4.2: Factor of safety by finite element and limit equilibrium method

| SN | Section details | Factor of safety by (FEM) | Factor of safety by (LEM) |
|---|---|---|---|
| 1 | Sections AA' | 1.80 | 2.278 |
| 2 | Sections BB' | 2.95 | 3.985 |
| 3 | Sections CC' | 3.17 | 4.318 |

*D. Design Of Benches For Opencast*

A comprehensive study has been conducted to determine the optimum bench design parameters including slope angle, height, and width for the Singhori Opencast Mine. The goal of the study was to ensure slope stability and operational efficiency under varying geological and geotechnical conditions. To achieve this, a series of numerical models were developed simulating benches composed of different types of soils including black cotton soil, sandy soil, clayey soil, and alluvial soil. Each simulation was run by varying bench heights and slope angles, while using the geotechnical properties listed in Table 4. These simulations employed finite element and limit equilibrium methods to assess the Factor of Safety (FoS) under different conditions. Figures 4.10 to 4.16 graphically represent the relationship between bench height and slope angle with respect to the FoS for various soil types. The aim was to determine the maximum stable bench height that corresponds to an acceptable FoS (typically ≥ 1.3) for each material type. The results indicate that black cotton soil, due to its expansive nature and strength loss upon saturation, performs better at lower slope angles. For instance, at a bench height of 5 m, the FoS is 1.33 for a 70° slope and improves to 1.51 at a reduced slope angle of 60°, indicating that flatter slopes are more favorable for this soil type. In sandy soils, a bench height of 10 m and slope angle of 37° yields a FoS of 1.28, showing moderate stability due to the frictional resistance provided by sand grains. However, in clayey soils, which are more cohesive and prone to failure under saturation, the simulations show a FoS of 1.20 at 4 m bench height and 70° slope, and a slightly higher FoS of 1.35 at 3 m bench height and 80°, suggesting better stability when bench heights are minimized. For alluvial soil, known for its heterogeneity, the FoS was found to be 1.20 at a 4 m bench height and 60° slope, and improved to 1.40 at a 3 m bench height and 80° slope. This reveals that while alluvial soil can support steeper slopes, reducing bench height significantly enhances overall safety. The analysis concludes that each soil type requires a tailored bench configuration to ensure stability. While flatter slopes generally provide higher safety margins, operational efficiency must also be balanced. Therefore, the study recommends the adoption of material-specific slope angles and bench heights as a critical input for mine design to optimize both safety and productivity in opencast operations.

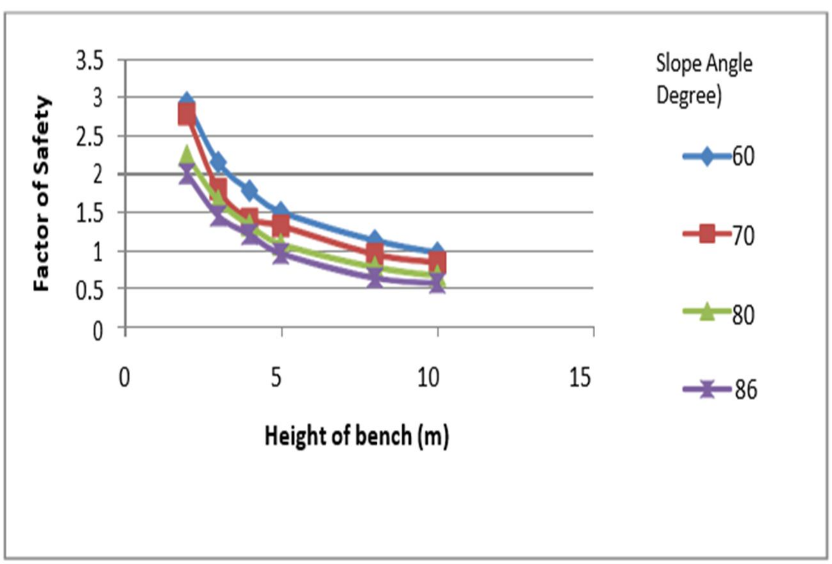



Figure 4.10: Effect of height of slope on factor of safety at different slope angle (black Cotton)

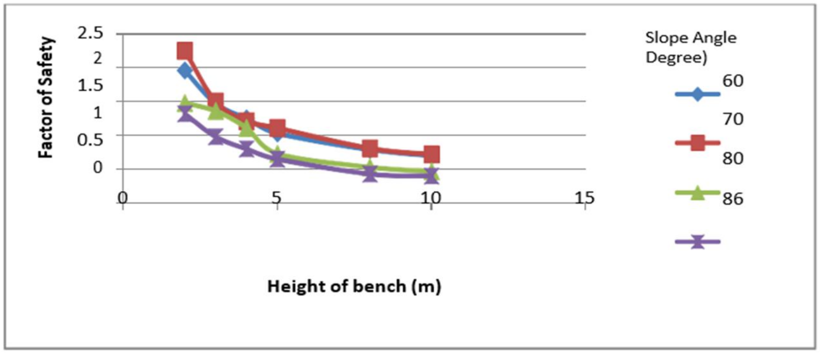



Figure 4.11: Effect of height of slope on factor of safety at different slope angle (Clayey soil)

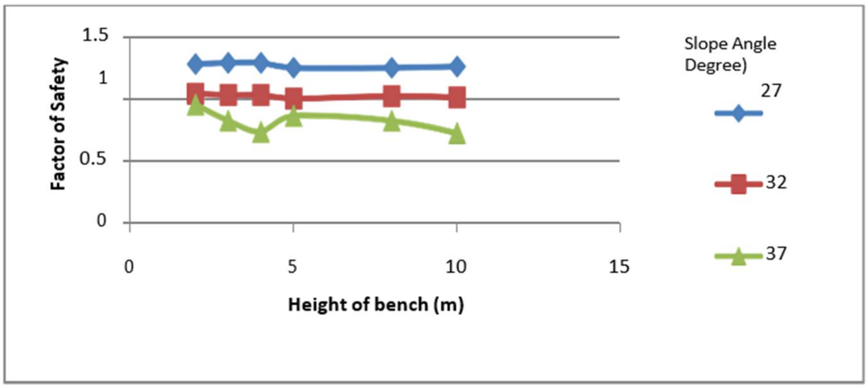



Figure 4.12: Effect of height of slope on factor of safety at different slope angle (running Sand)

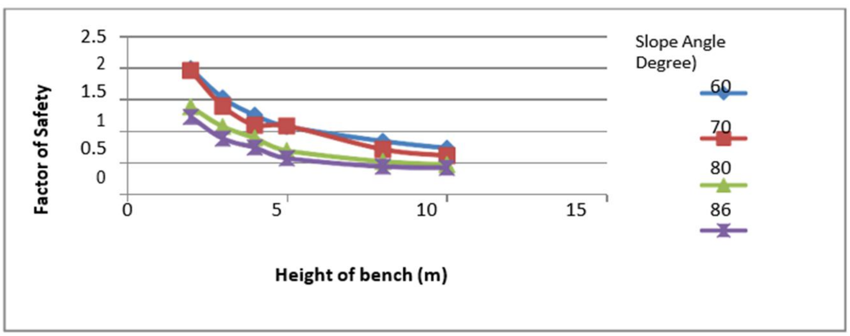



Figure 4.13: Effect of height of slope on factor of safety at different slope angle (Alluvial Soil) Sand)

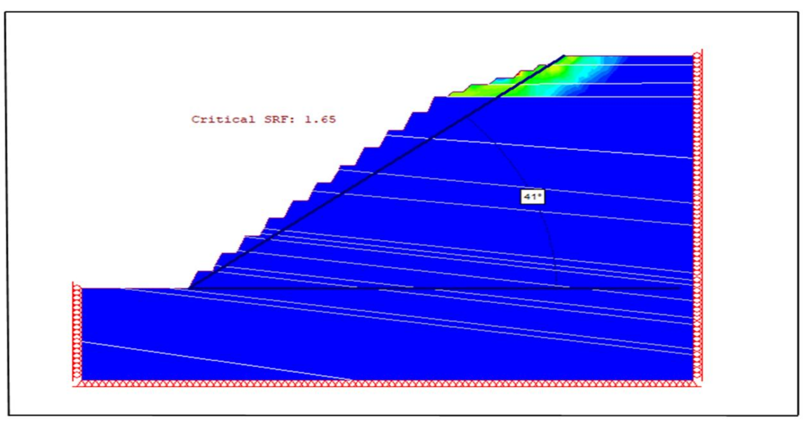



Figure 4.14: Overall slope angle of Mine

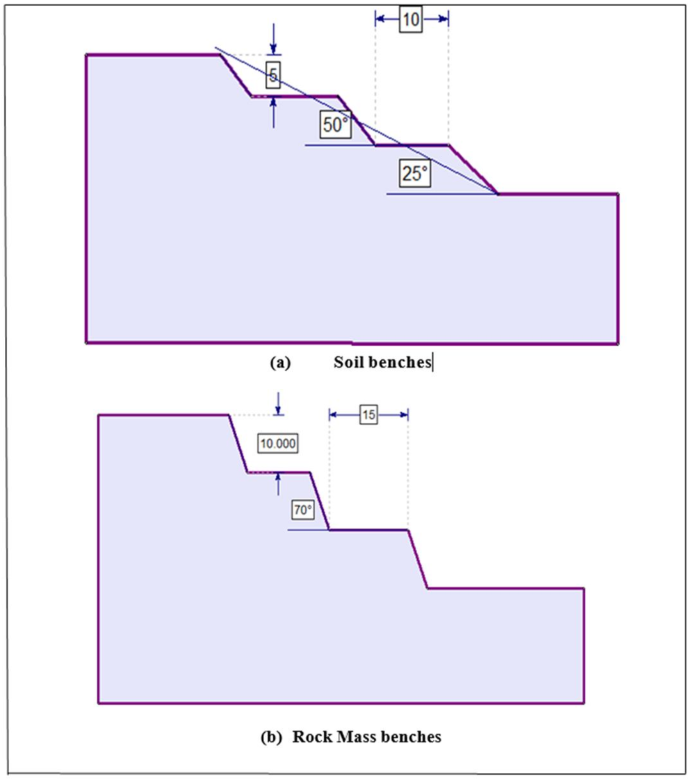



Figure 4.15: Recommended bench parameters during working mine

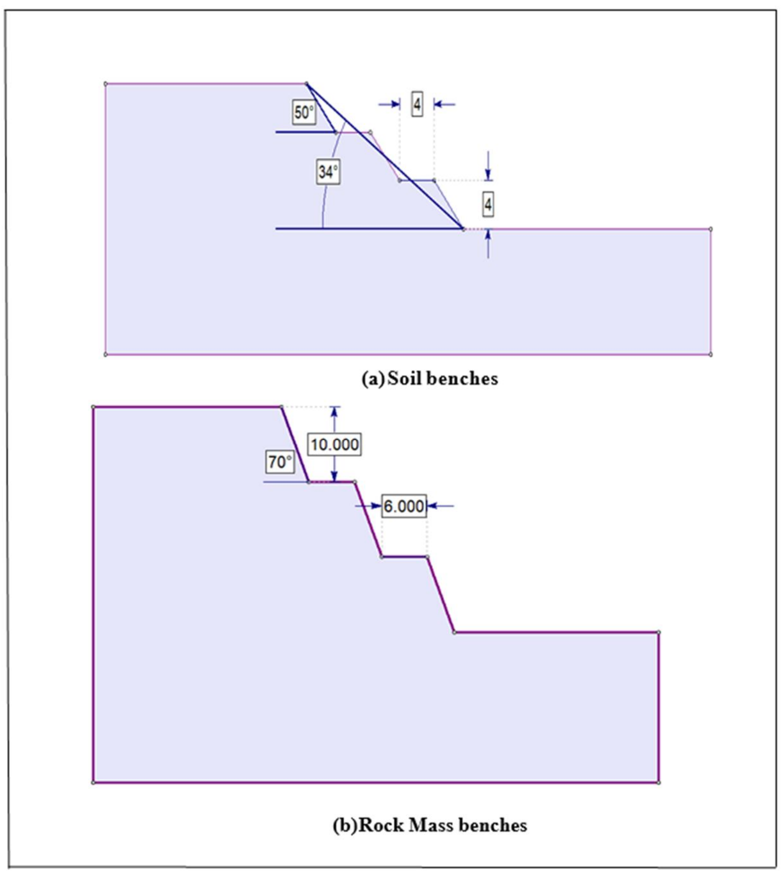



Figure 4.16: Recommended bench parameters during final operation in mining

## IV. CONCLUSION

Based on the detailed geotechnical assessment and slope stability analysis of the Singhori Opencast Coal Mine, using both the Limit Equilibrium Method (LEM) and Finite Element Method (FEM), the following conclusions and recommendations have been drawn. These findings incorporate results from current and final mining conditions, under varying geological formations and slope configurations, while also considering critical factors such as water saturation and weather influences:

1) Long-Term Stability of Hard Rock Slopes: The factor of safety (FOS) for hard rock sections under current conditions ranges from 1.67 to 2.04, and for the final benches of the Singhori Opencast Mine, the FOS ranges from 1.80 to as high as 3.17. These values exceed the threshold of 1.5, indicating that the hard rock slopes are stable in both short and long-term scenarios. Hence, the existing slope designs for hard rock strata are considered geotechnically sound for sustainable mining operations.
2) Instability Due to Water Pressure: The analysis highlights that the FOS of the slope can fall below 1.0 when water pressure from groundwater tables or surface runoff (especially during the monsoon season) is accounted for. This indicates a high risk of slope failure due to water infiltration. Therefore, it is strongly recommended that proper drainage systems (surface and sub-surface) be implemented and that slopes be closely monitored and reinforced during and after heavy rainfall events to avoid catastrophic failure.
3) Black Cotton Soil Slope Recommendation: In black cotton soil, a maximum safe bench height of 5 meters with a slope angle of 60 degrees yields an FOS of 1.51, which is within the acceptable limit for short-term to moderate stability. However, due to the expansive nature of black cotton soil and its drastic reduction in strength upon saturation, conservative design and careful seasonal inspection are necessary.
4) Alluvial Soil Slope Recommendation: For alluvial soil, the maximum safe bench height is 4 meters at a slope angle of 60 degrees, producing an FOS of 1.26. While this is marginally acceptable for short-term use, it is advised to reduce the slope angle further or introduce reinforcement techniques for longer operational periods.
5) Sandy Soil Slope Recommendation: The optimal configuration for sandy soil is 5 meters bench height at a 30-degree slope angle, resulting in an FOS of 1.28. Sandy soils, being cohesionless and more prone to sliding, necessitate lower slope angles for maintaining stability, especially in wet conditions.
6) Clayey Soil Slope Recommendation: In clayey soils, which are plastic and retain water, the safe configuration is 4 meters in bench height with a 60-degree slope angle, corresponding to an FOS of 1.24. While suitable for short-term stability, it is crucial to prevent water logging and monitor for surface cracking or bulging during wet seasons.
7) Safe Configuration for Overburden Dump Slopes: For long-term stability, the maximum bench height in overburden (OB) dumps should not exceed 20 meters. The overall dump slope height may safely reach 75 meters, provided that the slope angle remains around 23 degrees and benches are configured with a height of 15 meters and width of 20 meters. This stepped configuration ensures dissipation of shear stresses and reduces the likelihood of large-scale dump failures.
8) Impact of Blasting on Embankment Stability: The slope stability analysis of the embankment revealed a factor of safety (FOS) of 2.38 when blasting effects were not considered, and an FOS of 1.50 after incorporating the effects of blasting. Both values exceed the minimum threshold of 1.5, suggesting that the embankment remains structurally stable under long-term conditions, even with blasting activities in the vicinity. This indicates that blasting has no significant adverse impact on the stability of the embankment, provided that proper precautions are taken. However, to maintain this stability and avoid any localized disturbances, it is recommended that the blasting charge per delay be limited to a maximum of 30 kg, especially when the distance between the blasting point and the embankment is less than 100 meters. This measure ensures the ground vibrations remain within safe limits, preserving the integrity of the embankment structure and minimizing the risk of stress propagation or slope deformation due to dynamic loading.

## REFERENCES

[1] Alemayehu, E., Chala, E.T., Jilo, N.Z. et al. Optimizing design and stability of open pit slopes in Tolay coal mine, Ethiopia. Sci Rep **15**, 1570 (2025). https://doi.org/10.1038/s41598-025-86034-7.
[2] Ashish, R. (2022). Advancement in bench slop stability in open cast mines. NeuroQuantology, 20(21), 215–222. https://doi.org/10.48047/NQ.2022.20.21.NQ99028
[3] Behera, P. K., Sarkar, K., Singh, A. K., Verma, A. K., & Singh, T. N. (2016). Dump slope stability analysis – A case study. Journal of the Geological Society of India, 88(6), 725–735. https://doi.org/10.1007/s12594-016-0540-4
[4] Chachadi, P. S., & Patil, P. (2021). A review on fly ash slope stability. International Research Journal of Engineering and Technology (IRJET), 8(5), 901–904. http://www.irjet.net.
[5] D.P. Sainsbury, M.E. Pierce, L.J. Lorig, 2003, Two- and three-dimensional numerical analysis of the interaction between open-pit slope stability and remnant underground voids, 5th Large Open Pit Conference, Kalgoorlie, Western Australia, pp.251-257.

[6] Francisco, C. S., Li, M., Li, B., & Deon, M. G. (2024). Study of slope stability of the mining wall in an open-pit coal mine by the paste cut-and-backfill method. Applied Sciences, 14(14), 6141. https://doi.org/10.3390/app14146141.

[7] G S Utami and B A M Bali 2019 IOP Conf. Ser.: Mater. Sci. Eng. 462 012014.

[8] J.M. Girard, R.T. Mayerle, E.L. McHugh, 1998, Advances in Remote Sensing Techniques for Monitoring Rock Falls and Slope Failures, Proceedings of the 17 International Conference on Ground Control in Mining, NIOSHTIC-2, No 20000186, pp. 326-331.

[9] Kumar, M. S., & M., R. K. (2022). Factors affecting slope stability of an opencast mine: A brief study. International Journal of Innovative Science and Research Technology, 7(4), 878–882. https://www.ijisrt.com

[10] Kumar, R. E. S. C., Gadepaka, P. R., & Jaiswal, A. (2024). Numerical analysis of dump slope stability using material properties obtained by parallel gradation method. Mining, Metallurgy & Exploration, 133(1). https://doi.org/10.1177/25726668231222996.

[11] Liu, W.; Sheng, G.; Kang, X.; Yang, M.; Li, D.; Wu, S. Slope Stability Analysis of Open-Pit Mine Considering Weathering Effects. Appl. Sci. 2024, 14, 8449. https://doi.org/10.3390/app14188449.

[12] Malekian, M., Momayez, M., Bellett, P., Mancino, S., & Carrea, F. (2022). Stability investigation of open-pit slopes during blasting activities. International Journal of Engineering Research & Technology (IJERT), 11(8). http://www.ijert.org

[13] Rezaei, M., & Mousavi, S. Z. S. (2024). Slope stability analysis of an open pit mine with considering the weathering agent: Field, laboratory and numerical studies. Engineering Geology, 107503. https://doi.org/10.1016/j.enggeo.2024.107503.

[14] Rudra ESCK, Gadepaka PR, Rai R, Jaiswal A. Numerical analysis of dump slope stability using material properties obtained by parallel gradation method. Mining Technology. 2024;133(1):31-41. doi:10.1177/25726668231222996.

[15] Roy, I. (2008). Slope stability study of external dump of Sonepur-Bazari opencast coal mine, India – A case study. 6th International Conference on Case Histories in Geotechnical Engineering, Missouri University of Science and Technology. https://scholarsmine.mst.edu/icchge/6icchge/session02/48

[16] Satyanarayana, I., Budi, G., Sen, P., & Sinha, A. K. (2018). Stability evaluation of highwall slope in an opencast coal mine – A case study. Modelling, Measurement and Control C, 78(3), 253–273. https://doi.org/10.18280/mmc_c.780301

[17] Simao Francisco, C., Li, M., Li, B., & Deon, M. G. (2024). Study of slope stability using paste cut-and-backfill method. Applied Sciences, 14(14), 6141. https://doi.org/10.3390/app14146141

[18] Soren, K., Budi, G., & Sen, P. (2014). Stability analysis of open pit slope by finite difference method. International Journal of Research in Engineering and Technology (IJRET), 3(5), 326–331. http://www.ijret.org

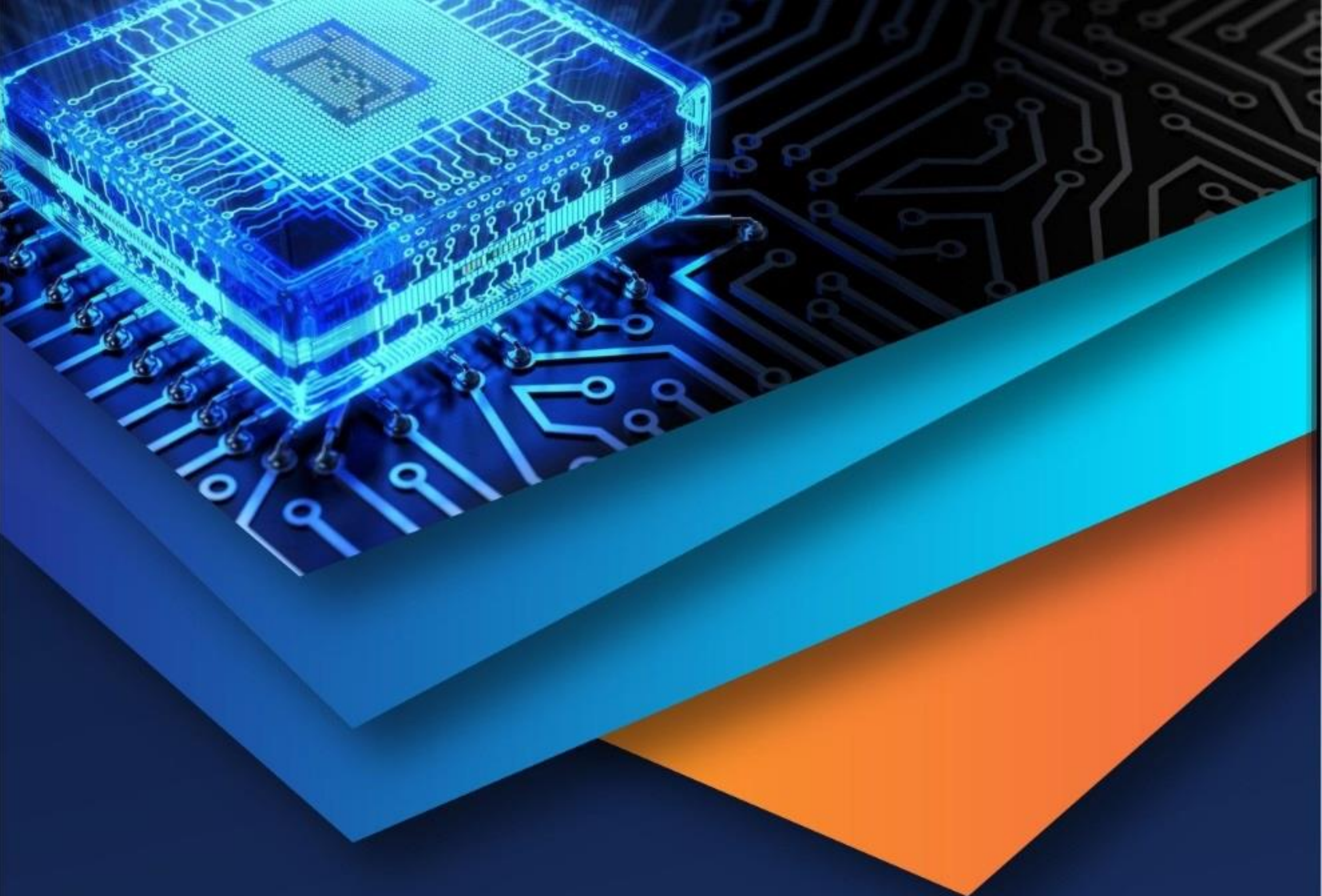
[19] Tavitinaidu, P., & Bhatnagar, A. (2019). Assessment of slope stability in opencast coal mines using software. International Research Journal of Engineering and Technology (IRJET), 6(9), 1792–1796. http://www.irjet.net

[20] Umrani, A. N., Memon, M. B., & Hakro, M. R. (2023). Slope stability analysis of open pit mine by using finite element method. International Research Journal of Modernization in Engineering, Technology and Science (IRJMETS), 5(6), 2213–2220. https://www.irjmets.com

[21] Utami, G. S., & Bali, B. A. M. (2019). Slope stability analysis under a complex geotechnical condition – A case study. IOP Conference Series: Materials Science and Engineering, 462, 012014. https://doi.org/10.1088/1757-899X/462/1/012014.

[22] W.G. Min, C.G. Wen, H.G. Jing, L.D, Shib, B.S. Yub, 2016, Effects of Water-Level on Water Quality of Reservoir in Numerical Simulated Experiments, Journal of Chemical Engineering Transactions, Vol.51, pp.1.

[23] Yusuf, I., Ramdhani, S., & Tawil, S. (2024). Study on the stability of open pit slopes based on geotechnical and safety aspects at the PT. Integra Mining Nusantara Indonesia Nickel Mine. International Journal of Research in Engineering and Science (IJRES), 12(5), 1–11. https://www.ijres.org




10.22214/IJRASET

INDEX COPERNICUS
45.98

IMPACT FACTOR:
7.129

IMPACT FACTOR:
7.429


# INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY