Shahrood University of Technology

Journal of Mining and Environment (JME)

Journal homepage: www.jme.shahroodut.ac.ir

Iranian Society of Mining Engineering (IRSME)

Optimization of Resource Extraction with Slope Stability: Sustainable Deepening Practices in Open-Pit Iron Ore Mining

Naresh Kumar Katariya* and Bhanwar Singh Choudhary

Department of Mining Engineering, Indian Institute of Technology, Dhanbad, India

Article Info

Received 17 October 2024

Received in Revised form 10 July 2025

Accepted 24 October 2025

Published online 24 October 2025

DOI: 10.22044/jme.2025.15232.2914

Keywords

Open-pit mine stability

Bench optimisation

Slope stability analysis

Sustainable mining

Limit equilibrium analysis

Abstract

Slope stability and bench safety in iron ore open-pit mines in western India are comprehensively analysed in this research. To evaluate current mining conditions and identify areas at risk, the study integrates comprehensive field observations, laboratory testing, and advanced slope stability modelling using Slide 6.0 software. Factors of safety (FOS) of various mining sections varied from 0.475 to 1.495, as per limit equilibrium analysis with Slide 6.0. This signifies the presence of possibly unstable slopes that require certain stabilisation measures to ensure operational safety. The research considers how significant environmental factors, like temperature, wind speed, rainfall, and soil moisture, influence slope stability in addition to the geotechnical analysis. Rainfall and soil moisture were found to have a high and statistically significant positive correlation (Pearson correlation = 0.706, $p = 0.005$), implying that an increase in rainfall results in increased soil moisture content, which in turn affects the behaviour of slopes. Also, a moderate degree of negative relationship between temperature and wind speed was revealed (partial correlation = -0.593, $p = 0.042$), meaning that smaller wind speeds are characteristically associated with increased temperatures. These findings highlight the importance of continuous monitoring of the environment in open-pit mine operations and the importance of considering environmental factors when assessing slope stability. The information collected in this study provides a solid foundation for developing valuable recommendations intended to enhance safety, better control slopes, and promote the long-term development of mining activities in the region.

1. Introduction

In the context of rising industrial demands, open-pit iron ore mines play a crucial role in fulfilling the global need for raw materials for the steel sector as well as other demanding industries. Yet, the imperative to explore deeper into the earth's crust to access further deposits poses significant challenges to maintaining slope stability, a cornerstone of safe and environmentally sound mining practices [1]. This research delves into the complex dynamics of enhancing bench parameters within an open-pit iron ore mine in Maharashtra, India. The study with the help of limit equilibrium analysis as a foundational tool, optimizes mine design in the pursuit of safer and sustainable excavation practices [2]. The intricacies of optimizing open-pit mine benches are due to their large size, different rock types, and the risks of slope failure [3].

When mines go deeper, slopes often need to be steeper due to limited space, which exacerbates the risk of slope failure [4], a scenario with historical precedence of leading to catastrophic outcomes due to suboptimal design and maintenance regimes [5]. Blasting, excavation, and routine activities can further make slopes less stable [6]. The call for sustainable mining practices is growing, emphasizing the need to balance mining with safety and care for the environment [7]. This study supports this by combining careful mine design with strong stability checks. Thorough geotechnical studies are crucial to mitigating risks and ensuring long-term mine safety [8]. The present research, conducted at

Corresponding author: nareshkumarkatariya5@gmail.com (N.K. Katariya)

the Iron Ore Mine (Maharashtra, India), aimed to design and evaluate the potential for deepening mine benches while ensuring existing slope stability [7]. A step by step method was adopted:

- Field Data Collection: A thorough site investigation collected geological information, rock samples, and details about the current mine layout [9].
- Laboratory Testing: The physical and mechanical properties of the collected rock samples were tested in the controlled laboratory settings to find out their strength and stability under different conditions [10].
- Slope Stability Analysis: Advanced software (Slide 6.0) was used for limit equilibrium analysis to evaluate current slopes and planned modifications of slopes[1].

This analysis aimed to identify potential failure modes and assess if the proposed design changes would help. Upon analysing the results, this research aims to develop precise recommendations for safer slope design based on established best practices [3]. It is expected to identify areas of potential instability within current slopes and suggest changes to make them safer [5].

Furthermore, this study will investigate the robust drainage system's role and how monitoring help keep slopes stable, as underscored by Kramer (1996) and Read & Stacey (2009). Leveraging a data-driven methodology and the integration of proven practices, this research intends to impart useful insights and actionable guidance for safety and maintenance of slopes as they go deeper [7]. By actively addressing potential stability challenges and adopting responsible mine bench management strategies [11], this research contributes to the progress of sustainable mining practices within India [12]. Ultimately, this research shows how mining can be done safely and responsibly, helping move the industry toward a more sustainable future [13]. Nevertheless, the study will also address and discuss the limitations associated with increased slope heights, such as the elevated risk during extreme weather conditions [14], to ensure a thorough understanding.

2. Literature Review

Amongst the slope vulnerabilities caused through rainfall, not all of them happen directly in the course of storm disaster, and the effect of wetting–drying cycles on the process of rainfall–evaporation. This is a significant reason for shallow slope instability. In the existing study [15], the slopes of waste dumps in ospen-pit coal mines in Cam Pha, Quang Ninh, Vietnam were studied. As the objective of research, the existing study carry out investigations on the physical properties of the rock change under different wetting and drying cycles, using both lab tests and computer modelling. The results of the study show that wetting and drying cycles greatly affect the physical properties and permeability of the rock. In the procedure of the wetting–drying cycle, a temporary wet zone forms on the slope surface, and the dry zone inside the slope gets smaller as the number of wetting and drying cycle's increases.

In open pit excavation regions, knowing about ground conditions (like how deep the soil is, the natural slope, and where faults are) helps keep mines safe and plan for land recovery. The Corporation of Greek Public Power started a research program after stability problems happened on the south side of the Mavropigi open-pit mine in northwest Macedonia. Geotechnical boreholes showed steep rock layers and thin fault zones, highlighting the need for detailed underground imaging to plan for future stability. For this perseverance, a geophysical study [16] was done to find out how the schist base meets the newer sediments and limestone above it. Depending upon the high dissimilarity of electrical properties among schists and limestones, and also the differences in sound properties and layer thickness, the seismic methods and ERT (electrical resistivity tomography) techniques were carefully chosen. The usefulness of these seismic methods was tested by creating computer models of how seismic waves move through the ground in this area.

The magnificent super series of mining business from the year 2002-2010 is moved out. Currently, the mining industry has faced many challenges in production in recent years. To recognise the production impacting factors, the existing study [17] identified important factors and organized them using a colour code system for planning. They found 29 factors from past studies and expert opinions, and checked them using principal component analysis. Primary information was gathered through a 5-point Likert scale from large open-cast mines in India. Additionally, depending upon the loading features of qualities, a colour categorization system was used to identify which factors are most important. The existing paper shows how this colour coding can help managers focus on the most important issues, making mine operations more efficient. The attentiveness needed for each trait is associated with colour codes. This insinuation shows that priorities could be stable on productivity inducing attribute in joining them via a colour codification structure. Operational level administration of mining arena could address these production features in a more effectual way. The innovation lies in arranging the production influencing features grounded on a priority of colour coding structure. Application of this method could transform operative strategies in elevating open-cast mining arena.

Mining an open-pit excavation with a steep angle, while keeping both production and safety in mind, is a major challenge. The existing research [18] proposed a plan for designing slopes in a large open pit iron-ore mine with complex geology. The features of the mine were mapped, and lab tests were done to understand the rock properties. The kinematic examination of the early slope design displayed wedges-shaped failures in the benches. To fix this, they studied bench-scale wedge failures and chose the best pit design by changing the slope angle and pit location. It was found that a final slope angle of about 35° with a stripping ratio of about 3.5 gave the best safety and efficiency.

The best way to extract resources while keeping slopes stable has been a main topic in mining engineering. Many studies have helped improve how we understand and apply slope stability.

Notably, research has highlighted the importance of integrating dynamic optimization methods that account for uncertainties in rock mass strength, allowing for differentiated slope designs across various zones of a mine [19]. This makes decision-making more flexible and safer. In another study focused on the Tolay coal mine, the application of **Limit Equilibrium Methods (LEM)** and **Finite Element Methods (FEM)** demonstrated that adjusting slope angles can greatly improve the **Factor of Safety (FOS)**, underscoring the need for tailored slope designs based on local geological conditions [20]. Furthermore, investigations into large-scale slope stability emphasize the geological structure and groundwater are significant in maintaining slopes safe as mines get deeper. The combined use of numerical modelling and traditional stability analysis methods has been found to make slope assessments more reliable, especially in iron ore mines where both safety and high production are important. Overall, these studies support a systematic approach that uses ground studies, advanced modelling, and flexible management to mine resources safely and efficiently [21].

It integrates field data, laboratory tests, and stability analysis using Slide 6.0 software to refine bench parameters for sustainable mining practices [22]. Field data provides insights into geological conditions, while laboratory tests, such as direct shear and triaxial compression tests, determine rock mass properties like cohesion and friction angles [23]. Slide 6.0 checks safety under different slope shapes and rock conditions, showing how slope angle, depth, and features like joints and faults affect safety. However, the study has several weaknesses that need addressing, including not enough field data (which can make geological predictions less accurate), using fixed designs that don't consider changes in rock properties, and not paying enough attention to environmental impacts in slope design. Addressing these gaps is essential for achieving sustainable deepening practices that balance economic viability with environmental responsibility [24].

At the Raniganj coalfield in West Bengal, India, [25] conducted an innovative study that focused on mine dump safety within the mine premises, which is an integral part of operational and economic viability of open-pit mining operations. The research generated high-resolution three-dimensional (3D) models of mine dumps by employing unmanned aerial vehicles (UAVs), enabling accurate mapping and assessment of dump form. The study identified potential areas of instability in the dumps employing numerical modelling and a 3D limit equilibrium method. Apart from facilitating easier and cheaper determination of dump safety, the proposed framework also provided recommendations for the most optimal dump geometry in the prevailing geo-mining situation. This approach demonstrates the effectiveness of integrating advanced modelling and UAV technology for preventive dump control and hazard mitigation in open-pit mines.

The prevailing study [26] applied genetic algorithms to address the problem of slope instability in highly jointed rock masses in the case of Iran's 6th Golbini Jajarm bauxite mine. Following extensive field and laboratory investigation to characterize rock mass behaviour, a genetic algorithm code was developed with the Simplified Bishop method as the target function. The final safety factor was 1.3 following seven iterative steps of identifying and modifying significant slip surfaces. Sensitivity analysis was adopted to tune algorithm parameters. Through systematic removal of weak zones, an improved slope angle of 48.44 degrees was achieved. This research shows how effective evolutionary computation techniques are in enhancing safety and slope design optimization in problematic geology.

By integrating fuzzy set theory with the Romana SMR (Slope Mass Rating) classification system, [27] made great leaps in the field of rock slope stability evaluation. Recognizing the limitations of traditional set theory to cope with the inherent uncertainties of defining rock masses, the study developed a Mamdani fuzzy algorithm with 825 "if-then" rules. The fuzzy SMR system was utilized in open-pit mine slopes, where it showed higher accuracy and reliability in assessing the stability conditions. A more practical and sophisticated assessment of slope stability was facilitated by the application of fuzzy logic, particularly under conditions where geological information may be vague or not very accurate. Abbas's research underscores the significance of advanced computational intelligence methods in geotechnical engineering.

The existing study [28] study at Mine No. 4, Golgohar Sirjan, examined the application of benching to expand waste dump capacity and maintain stability to handle the pressing issue of limited space for waste disposal. The research employed Monte Carlo simulation for probabilistic analysis and the limit equilibrium method utilizing Slide3D software. The capacity of the eastern refuse tip was significantly enhanced by adding benches, and safety factors based on the Spencer, Janbu, and Bishop Methods all approached or exceeded satisfactory levels. The outcome indicates that with cautious stability analysis and systematic geometric adjustment, space constraints in extensive surface mining operations can be effectively resolved and safe disposal of waste ensured.

The evaluation and control of open-pit mining slope and dump stability are distinctly shifting towards the adoption of advanced technologies and computational methods, as is seen from recent literature. Studies based on fuzzy logic, genetic algorithms, probabilistic modelling, and UAV-based mapping have yielded more accurate, efficient, and site-specific solutions to long-standing geotechnical issues. These techniques have facilitated more precise identification of instability zones, slope and dump design optimization, and more advanced risk assessments under a range of geological and operational conditions. Despite such advances, there remain problems, particularly those related to real-time monitoring, handling indeterminate or incomplete data, and implementation of these methods in different mining environments. Based on these developments, the present research aims at improving slope stability assessment by combining sophisticated numerical modelling, laboratory testing, and field data, with special focus placed on the role of environmental conditions. This holistic approach is designed to bridge existing gaps and ensure safer, environmentally friendly mining practices.

2.1. Research Gaps

- ❖ The economic implications of every single attribute that cannot be composed because of an organizational secrecy beneath the existing study [17], and in certain instances not assessed. The conventional study is restricted to some enormously deposited open-cast pits comprising of three major mineral rich Indian states.
- ❖ The existing research [18] has not contemplated about all the geological conditions. It has only considered failure analysis method and not given suggestions for adopting successive and solution measures to overcome the failure in mining process.
- ❖ The dynamic effects of environmental factors (like temperature, wind speed, precipitation, and soil moisture) on dynamic dump or slope stability in real-time are not completely incorporated in the UAV-based stability assessment with a focus on geometric mapping [25].
- ❖ Benchmarking and probabilistic assessments [28] enhance dump capacity and safety, but they often neglect the long-term, cumulative impacts of environmental conditions.

3. Methodology

Investigation scrutinizes an open-pit iron ore mine situated in Maharashtra State, western India. Leveraging full mechanization, the mine achieves efficient ore extraction across a large project area of over 94.7 hectares. It boasts a projected annual production capacity of approximately 3.68 lakh tonnes of iron ore, characterized by an iron content ranging between 55-60%, in addition to the removal of around 13.99 lakh tonnes of waste material. The ore extracted is destined for both domestic consumption and international markets, fulfilling stringent quality standards requisite for export and addressing the demands of the domestic steel industry as necessary. Historically deemed uneconomical due to its lower grade, the prevailing global demand for such iron ore has now made the project commercially viable. The mine is expected to create jobs and help the local economy by improving infrastructure.

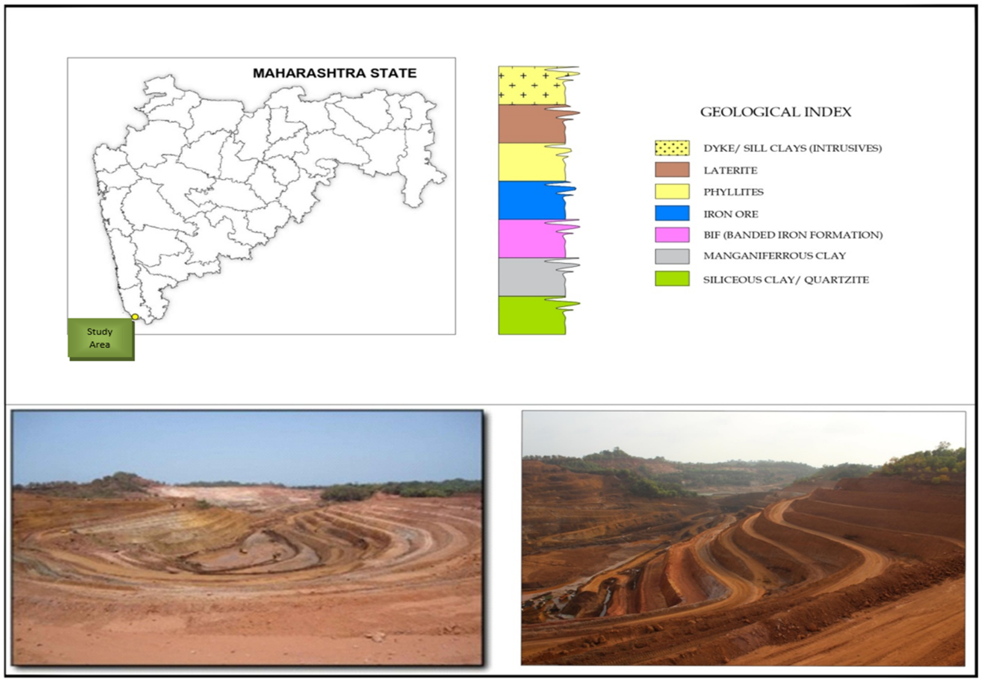


Figure 1. Location of Study Area, Local Geological & Mine Condition

3.1. Local Geology of the Iron Ore Deposit

The iron ore deposit situated within the marked lease area demonstrates a predominant northwest-southeast orientation, with the general strike direction extending from N270° to N290°. Nonetheless, some local changes are seen, with certain sectors exhibiting an east-west strike alignment. The ore body leans toward the northeast at angles ranging from 42° to 55°, displaying dip directions fluctuating between north and northeast. Spanning approximately 2.3 kilometers within the lease area, the deposit features an average thickness varying from 25 to 45 meters. Notable breaks are present in the lease's eastern sector, caused by structural changes and igneous rocks, which have broken up the ore body. Such geological events have likely resulted in the formation of dykes and sills, breaking the ore deposit's continuity. The iron ore deposit is part of a bigger sequence of rock layers, including: Laterite: This topmost stratum is characterized by laterite, with thicknesses typically ranging between 10 to 20 meters. Phyletic Clay: Positioned beneath the laterite layer, this stratum consists of phyletic clay, averaging 20 to 25 meters in thickness. Iron Ore Zone: The primary focus, the iron ore zone, encompasses lumpy iron ore (5-7 meters) and blue dust (20-40 meters). Limonitic/Manganiferous Clay with Schists: Situated below the iron ore zone, this layer comprises limonitic/manganiferous clay mixed with schists, with variable thicknesses from 25 to 55 meters. Basement: The sequence's foundation is formed by siliceous clays/quartzite, making up the bottom of the deposit, and is 30 to 60 meters thick.

3.2. Mining Method and Equipment

The mine adopts an open-cast mechanized methodology for the effective extraction of minerals, employing an array of heavy machinery such as excavators, dumpers, loaders, rippers, and dozers. This equipment replaces conventional drilling and blasting techniques, ensuring a safer and more controlled operational environment. Presently, the lease area encompasses two operational pits, with the foremost, Pit 1, extending over dimensions of 203m by 660m and reaching depths from 51.8m to -49.3m. Benches are made 6 meters high and 8-10 meters wide in both ore and waste areas to help with organized digging. Furthermore, mine roads are carefully developed to be 10-12 meters wide, featuring a 1:16 incline, so machines can move easily. The overarching principles guiding operations are safety and mineral conservation, which are meticulously integrated in the slope design to fit the local geology. Hydraulic excavators are employed for the loading of run-of-mine (ROM) material and overburden/waste, which are then conveyed to predetermine disposal areas or to mobile crushing and screening units. These units, with a processing capacity of 400 tons per hour, process the ROM by separating crushed and screened materials, getting them ready for storage or shipping. In meeting the varied requirements of users, fines and lumps are carefully separated and sold differently.

3.3. Geotechnical Framework and Methodology

This research examines the stability of open-pit mine benches through a comprehensive, multi-stage methodology that encompasses field work, laboratory testing, and advanced slope stability analysis [9]. Each phase of the study yields critical insights about the geotechnical characteristics and potential instability risks for the mine benches. Leveraging a data-centric strategy, the investigation facilitates the formulation of optimized management practices aimed at enhancing the long-term sustainability of the mining operations [29]. For visual reference, Figure 1 shows the layout of the current mine benches.

3.3.1. Field Investigation

The foundation of effective and sustainable mine deepening strategies is rooted in thorough field investigations. This research collected important ground data using standard methods and new technology to understand the geology and current conditions of the mine benches in the Indian milieu.

A. Topographical Surveys: Precision Mapping of the Terrain

Utilization of advanced surveying technologies, including total stations and Differential GPS systems, facilitated the generation of highly accurate topographical maps of the dump sites. These maps helped with:

- Precise Slope Angle Analysis: Identification of areas with potential instability risks associated with steep or irregular slopes.
- Topographical Feature Assessment for Instability Risks: Examination of drainage patterns, erosion channels, and other geomorphological elements contributing to instability.
- Optimized Bench Design and Mitigation Strategy Formulation: Customization of bench geometries and implementation of specific mitigation measures targeting identified topographical vulnerabilities.

B. Lithological Sampling: Revealing Material Composition

- Systematic collection of soil and rock samples from varied bench depths ensured a comprehensive representation of the geotechnical characteristics of the dumps. This vital information underpinned further laboratory analyses, facilitating:
- Determination of Material Physical and Mechanical Properties: Insights into strength, cohesion, and density vital for stability assessments and design enhancements.
- Weathering Susceptibility and Material Behavior Evaluation: Identification of materials vulnerable to degradation and their anticipated response under diverse environmental conditions.
- Stability Enhancement Recommendations: Formulation of advice tailored to the specific material attributes and identified vulnerabilities.

C. Structural Mapping: Unravelling Geological Vulnerabilities

Acknowledging the profound impact of geological structures on bench stability, this study meticulously charted faults, fractures, or bedding planes potentially affecting stability. This comprehensive mapping yielded critical insights into:

- Identification of Zones with Elevated Failure Risks: Pinpointing regions at heightened risk of collapse or movement due to structural frailties.
- Targeted Mitigation Strategy and Preventive Measures Development: Application of specific reinforcement or drainage interventions to mitigate structural challenges.
- Further Investigation and Monitoring Area Identification: Highlighting regions with intricate or ambiguous structural characteristics for additional scrutiny and continuous observation.

Through addressing these pivotal components of field investigations, this research established a solid groundwork for devising effective and sustainable strategies for mine deepening, with an unwavering commitment to safety and ecological stewardship.

3.3.2. Laboratory Testing

Comprehensive laboratory analyses were performed on geological samples retrieved from the mine benches to determine their significant geotechnical attributes, essential for the assessment of slope stability dynamics and the guidance of design frameworks. These investigative procedures rigorously conformed to internationally recognized protocols while integrating specific considerations pertinent to the geotechnical characteristics of Indian terrains.

Bulk Density Assessment

Utilizing standard compaction methodologies, the density of soil specimens was quantified. Soil density emerges as a critical factor impacting hydrological penetration and the propensity of mass displacement phenomena. An in-depth understanding of soil density facilitates the forecasting of hydro-logically induced instabilities, thereby guiding the development of the appropriate countermeasures.

To ascertain the shear strength properties of the soil specimens collected from the mine benches, direct shear examinations were conducted [30]. This technique, despite its invention by Coulomb in 1776, remains a valuable tool for understanding soil behavior [31]. The assay encases a soil specimen within a bisected shear box apparatus, where the lower segment remains static while the upper segment is subjected to a regulated lateral shear force under an applied normal load to mimic in-situ stress conditions.

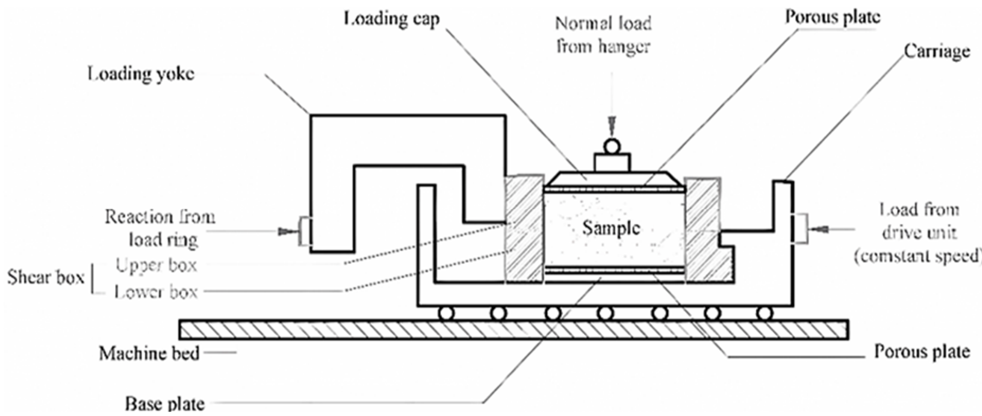


Figure 2. Schematic diagram of Direct Shear Testing in the Laboratory [32]

The experiment records shear displacement and stress, enabling the quantification of vital geotechnical metrics such as cohesion (C) and internal friction angle (φ), paramount for deducing the soil's shear capacity and, by extension, the stability of mine benches under diverse load conditions (Mitra & Singh, 2022), as expressed by:

$$\tau = \sigma . n . \text{Tan}\,(\varphi) \tag{1}$$

Where, τ is the shear stress,
τ n is the normal stress,
And φ is the friction angle.

This foundational knowledge underpins effective assessments and designs for slope stability. Collection, Preparation and testing of samples in the Laboratory is illustrated in the Figure 2.

In this study, the direct shear tests were conducted in the laboratory following established testing procedures. The samples were subjected to varying vertical stresses (e.g., 0.2 kg/cm², 0.5 kg/cm², 0.75 kg/cm², and 1 kg/cm²) to simulate different loading scenarios within the mine. The maximum shear forces recorded during the tests were then used to calculate the cohesion and angle of friction for each sample [33].

3.3.3. Slope stability Analysis: Quantifying stability

The limit equilibrium method, implemented through Slide 6.0 software, was employed to analyse the stability of the mine benches under various loading conditions [34]. This well-established approach is widely used in slope stability assessments and facilitates the evaluation of potential failure mechanisms and their impact on stability [35]. Shear properties of various samples have been illustrated in the Table 1.

The table 1 presents the geotechnical properties of various strata types, specifically their cohesion values (in kilopascals) and angles of friction (in degrees). Dyke Clay exhibits the highest cohesion at 33.3 kPa and a moderate angle of friction of 35.71°, indicating good stability, while Phyllitic Clay shows slightly lower cohesion at 30.8 kPa with a reduced angle of friction of 32.96°. High Grade Ore has a lower cohesion of 25.5 kPa but a notably high angle of friction at 47.14°, suggesting that while it may not be as cohesive, it can resist sliding effectively due to its frictional properties. Manganiferous Clay and Silica (BIF) have similar cohesions (25.6 kPa and 22.6 kPa, respectively) but differ in friction angles, with Silica showing a higher resistance to sliding at 42.08°. Laterite Clay possesses a cohesion of 31.7 kPa and an angle of friction of 38.75°, while Laterite stands out with the lowest cohesion at 26.1 kPa but the highest angle of friction at 53.24°, indicating its potential for stability despite lower cohesiveness. Overall, the data highlights the varying mechanical properties of these strata, which are crucial for understanding their behavior in engineering applications and slope stability assessments.

Table 1. Shear Properties of Various Samples

SL. No.	Strata type	Cohesion, KPa	Angle of Friction (deg)
1	Dyke Clay (Altered dyke)	33.3	35.71
2	Phyllitic Clay	30.8	32.96
3	High Grade Ore	25.5	47.14
4	Manganiferous Clay	25.6	39.23
5	Silica (BIF)	22.6	42.08
6	Laterite Clay	31.7	38.75
7	Laterite	26.1	53.24

The investigation employed a two-dimensional (2D) analytical framework under plane strain conditions, aligning with standard methodologies in slope stability assessment [36]. This approach incorporated the examination of circular slip surfaces, commonly identified in the failure mechanisms of mine dumps [37], in conjunction with material characteristics ascertained through exhaustive laboratory evaluations.

The Factor of Safety (FoS) served as the principal metric for evaluating stability, incorporating adjustments to address the unique geological intricacies present within the Indian mining landscape [38]. Through the meticulous analysis of these elements, the study aspires to achieve an intricate understanding of the geotechnical attributes and stability considerations pertaining to the benches of the Iron Ore Mine [7]. The insights garnered from this analysis are anticipated to facilitate the refinement of bench design parameters, bolster long-term operational sustainability, and foster adherence to ethical mining practices within the Indian context [2].

3.3.4. Comprehensive Evaluation of Slope Stability

This study employed a multifaceted approach to comprehensively assess the stability of the mine benches, moving beyond traditional stability analysis. This approach considered various factors that can influence slope behavior:

Geological and Soil Characteristics: The analysis integrated the influence of geological features and soil composition on slope stability. Understanding the interplay between geological structures and soil properties is crucial for accurate stability assessments [39].

External Forces: The impact of external forces such as seismic events and heavy rainfall on slope stability was evaluated [40]. Considering these potential triggers for slope failure is essential for designing and implementing effective mitigation strategies.

Diverse Loading Conditions: Slope behavior was assessed under various loading scenarios to predict potential risks and identify critical conditions. Analyzing stability under different loading conditions allows for a more robust understanding of potential failure mechanisms [41].

Optimization for Increased Heights: The study explored potential modifications to bench configurations to enhance stability and enable the possibility of increased bench heights, if feasible. Optimizing bench design is crucial for balancing operational efficiency with slope stability [33].

Advanced Modelling Techniques: While specific software references were removed, the text acknowledges the use of advanced modelling techniques to gain a comprehensive understanding of slope behaviour and inform responsible management strategies [34].

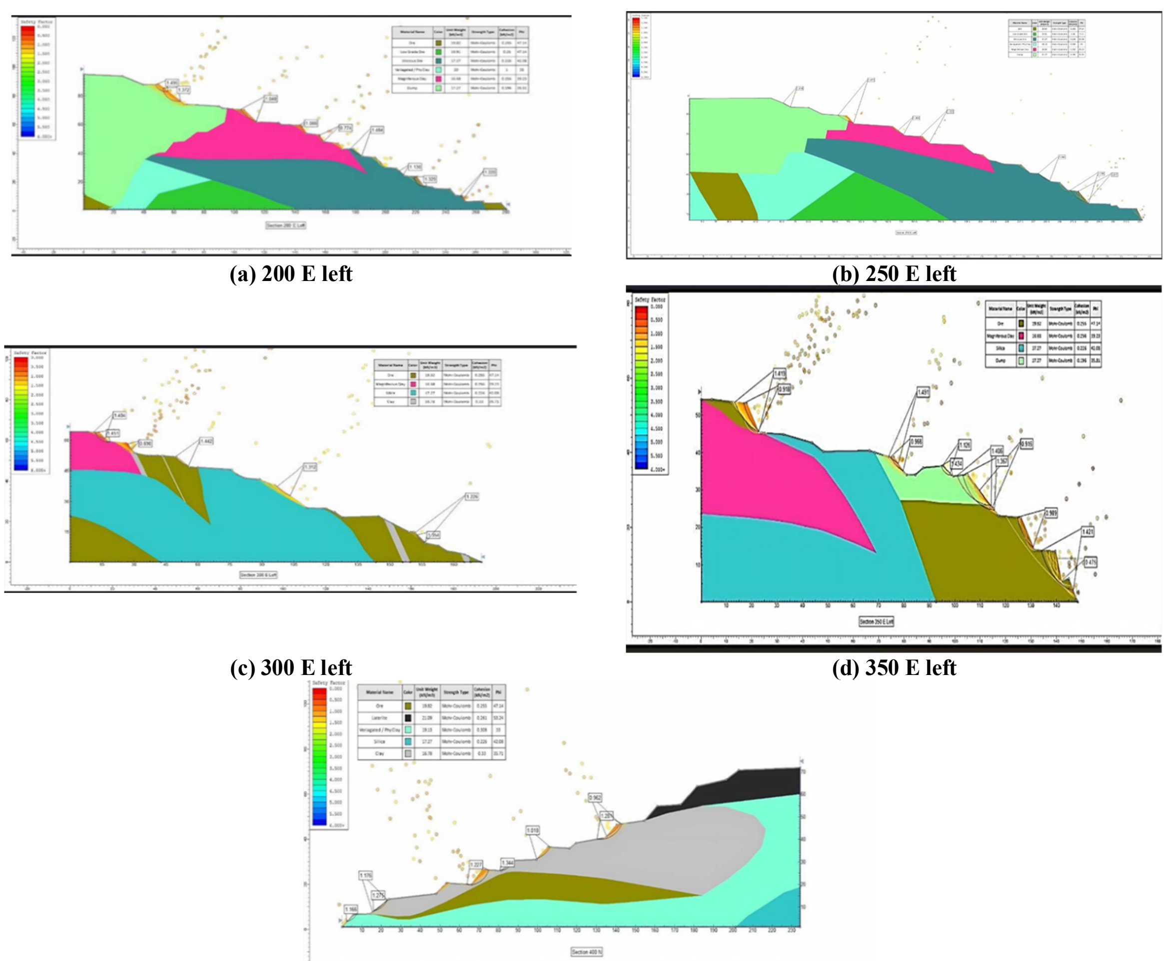
This comprehensive approach, combining slope stability analysis with multifaceted assessments, provided valuable insights into the stability of the mine benches. This knowledge will be used to develop data-driven recommendations for optimized bench design, effective mitigation of potential hazards, and ultimately contribute to sustainable and responsible mining practices.

4. Results

4.1. Analysis of Existing Bench Stability

This section examines the stability of the existing mine benches using a limit equilibrium approach implemented through specialized slope stability software. Twelve key sections, strategically chosen and labelled "200 East Left" to "400 North," were rigorously analyzed to assess the balance between soil masses and gravitational forces [42]. The Factor of Safety (FOS), an essential metric for evaluating slope stability, was determined for each cross-section. This metric quantifies the balance between the slope's resisting forces, which counteract movement, and the driving forces that precipitate instability. An elevated FOS denotes a higher safety margin. Adjustments were made within the analysis to accommodate the unique geological conditions prevalent in India.

Employing the limit equilibrium approach, recognized for its applicability in slope stability evaluation, the analysis presumed two-dimensional (2D) sections and circular slip surfaces as standard models for simulating potential failure mechanisms in slopes [6]. An advanced computational technique within the software facilitated a nuanced assessment of each section's stability [10], adhering to industry norms and setting a minimum acceptable FoS at 1.2 for ensuring long-term structural integrity [43]. Visual outcomes, delineated in Figures and concisely aggregated in Table 3, revealed divergent FOS values across the sections, indicating varying stability levels. Notably, sections labeled 250 north and 350 East Left necessitate additional scrutiny due to their diminished FOS values, highlighting them in Figs 2 to 6. The spectrum of FOS values observed, ranging from 0.475 to 1.495, intimates the potential for both superficial and profound instabilities, the former involving minor soil displacement and the latter encompassing comprehensive bench movement. Presently, the pit maintains an angle between 18 to 20 degrees, with bench heights fluctuating between 5 and 6 meters [44].



(a) 200 E left

(b) 250 E left

(c) 300 E left

(d) 350 E left

(e) 400 North

Figure 3. FOS of existing benches at Different Sections

Table 2. Summary of Factor of Safety (FOS) Values for Existing Sections

Sl No.	Existing Section	Minimum FoS	Maximum FoS
1	200 East Left	0.774	1.495
2	250 East Left	0.817	1.471
3	300 East Left	0.69	1.404
4	350 East Left	0.475	1.491
5	400 North	0.962	1.281

The table 2 summarizes the factor of safety (FoS) values for various existing sections, indicating the stability of each section under consideration. The "Minimum FoS" represents the lowest stability threshold, with the 350 East Left section exhibiting the most critical condition at 0.475, suggesting a significant risk of failure. In contrast, the 200 East Left section shows a minimum FoS of 0.774, which, while still below the safe threshold of 1.0, indicates relatively better stability than the 350 East Left. The maximum FoS values across all sections range from 1.281 for the 400 North section to 1.495 for the 200 East Left section, demonstrating that while some sections have acceptable stability under certain conditions, others may require immediate attention and remedial measures to enhance their safety and prevent potential slope failures. Overall, this analysis highlights the varying levels of stability across different sections and underscores the importance of monitoring and addressing areas with low FoS values.

A systematic analysis of existing bench parameters has been conducted. This analysis identified potential areas of instability in sections 250 and 350 east Left, as evidenced by their lower FOS values (Table 2). These sections warrant further investigation and potential mitigation strategies. Considering relevant external factors and potential weaknesses will guide informed decision-making to ensure the long-term stability and safety of the mine operations. Ultimately, this approach contributes to responsible and sustainable mining practices that minimize environmental and safety risks.

4.2. Analysis of modified bench stability

Following the initial stability assessment that identified potential concerns, this study optimized bench parameters to enhance stability and resource utilization within the limited operational area. The analysis considered the unique challenges of the Indian subcontinent, such as variable rainfall patterns, seismic activity, and specific soil properties.

It focused on optimizing key parameters like bench height, width, and slope angles. The redesigned configurations, as shown in Figure 8 adopted a standardized format with a consistent height pof 6 meters, width of 8 meters, and individual bench angles of 63° within an overall slope angle of 36°. These modifications aimed to achieve a balance between maximizing resources extraction and maintaining slope stability.

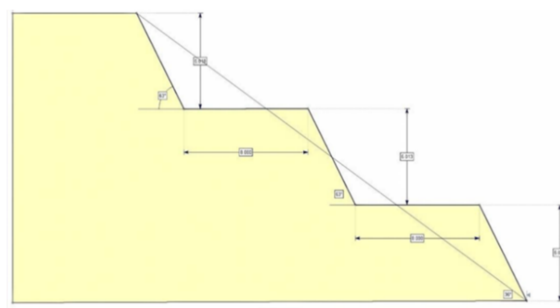
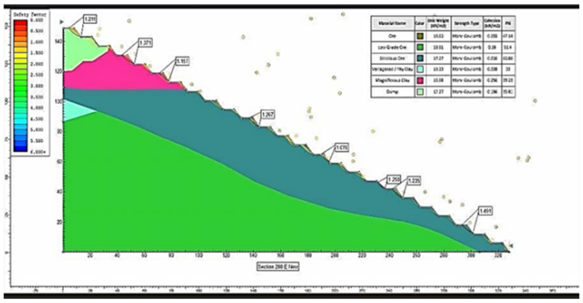
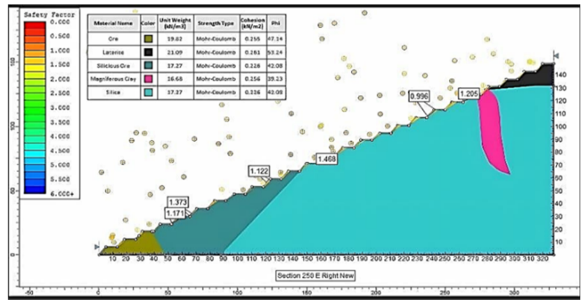


Figure 4. New modified bench parameters for stability

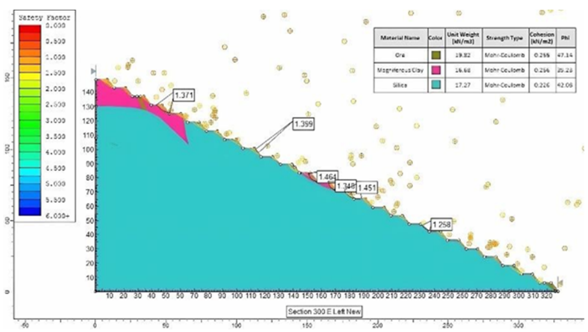
To rigorously assess the effectiveness of these redesigned benches, limit equilibrium analysis was employed using specialized slope stability software. Figures 9 visually represent the Factor of Safety (FOS) values for each modified section (200 East Left to 400 North), providing a spatial illustration of their stability behaviour under the proposed design.



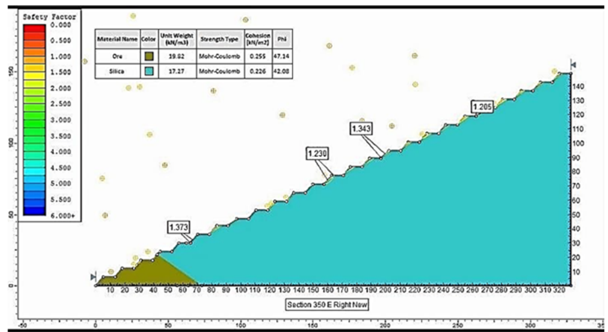
(a) 200 with FoS East Left



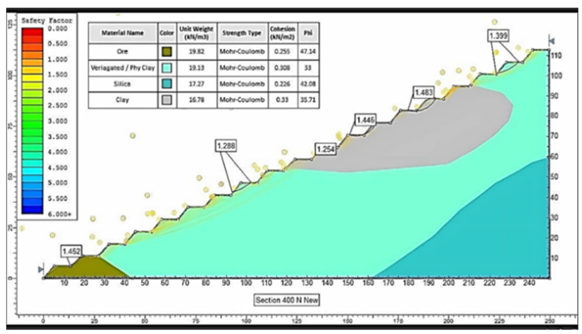
(b) 250 with FoS East Left



(c) 300 with FoS East Left



(d) 350 East Left



(e) 400 North with FOS

Figure 5. Modified Sections

The limit equilibrium analysis of the redesigned benches yielded minimum FOS values ranging from 0.905 to 0.996 across sections. While these values suggest the potential for isolated, shallow instability issues in certain areas like sections 200 east Left and 250 East Left, the maximum FoS values reached a reassuring 1.390 to 1.491 for critical zones prone to failure. This signifies an overall improvement in stability for most sections due to the proposed modifications. Table 3 summarizes the minimum and maximum FOS values for each modified section, providing a clear comparison for informed decision-making regarding bench design.

Table 3. Summary of FOS Values for Modified Bench Sections

Sl No	Modified Section	Minimum FoS	Maximum FoS
1	200 East Left	1.075	1.491
2	250 East Left	0.914	1.439
3	300 East Left	1.258	1.464
4	350 East Left	1.313	1.468
5	400 North	1.288	1.483

The table 3 presents the factors of safety (FoS) for various modified sections in a slope stability analysis. Each section is evaluated with a minimum and maximum FoS, indicating the range of stability under different conditions. For instance, the 200 East Left section has a minimum FoS of 1.075 and a maximum FoS of 1.491, suggesting that it is relatively stable but close to the threshold of safety. In contrast, the 250 East Left section shows a concerning minimum FoS of 0.914, which falls below the commonly accepted safety threshold of 1.0, indicating potential instability. The other sections, such as 300 East Left (minimum FoS of 1.258) and 350 East Left (minimum FoS of 1.313), demonstrate adequate safety margins, while the 400 North section maintains a minimum FoS of 1.288. Overall, these findings highlight varying levels of stability across the modified sections, with particular attention needed for the 250 East Left section due to its insufficient safety factor.

Based on the stability analysis, maintaining the ultimate pit angle of 36° with the redesigned bench parameters (height= 6 meters, width = 8 meters, individual bench angle = 63°) is recommended. This configuration appears to achieve a well-balanced approach between stability and maximizing resource extraction [45]. For long-term stability, implementing effective water drainage systems for the benches is crucial. This will mitigate potential risks associated with water accumulation and saturation within the slopes[10].

4.3. Analysis of the Correlation between the environmental factors that affect mining process Correlation – Bivariate

Bivariate correlation is generally used to define the consequence that two or more phenomena happen at the same time and hence they are associated. This test is adopted to prove the correlation between soil moisture and rainfall.

Table 4. Bivariate Correlations

		Rainfall	Soil Moisture (%) (Season wise data)
Rainfall	Pearson Correlation	1	.706**
	Sig. (2-tailed)		.005
	N	13	13
Soil Moisture (%) (Season wise data)	Pearson Correlation	.706**	1
	Sig. (2-tailed)	.007	
	N	13	13

**. Correlation is significant at the 0.01 level (2-tailed).

The table 4 presents the Pearson correlation analysis between rainfall and soil moisture based on seasonal data. A correlation coefficient of 0.706 indicates a strong positive relationship between rainfall and soil moisture, suggesting that higher rainfall is associated with increased soil moisture levels. The significance value of 0.005 ($p < 0.01$) confirms that this correlation is statistically significant, indicating that the observed relationship is highly unlikely to be due to chance. With a sample size (N) of 13 for both variables, these results underscore the importance of rainfall in influencing soil moisture content in the analysed seasons, highlighting a robust connection that can have implications for agricultural practices and water resource management.

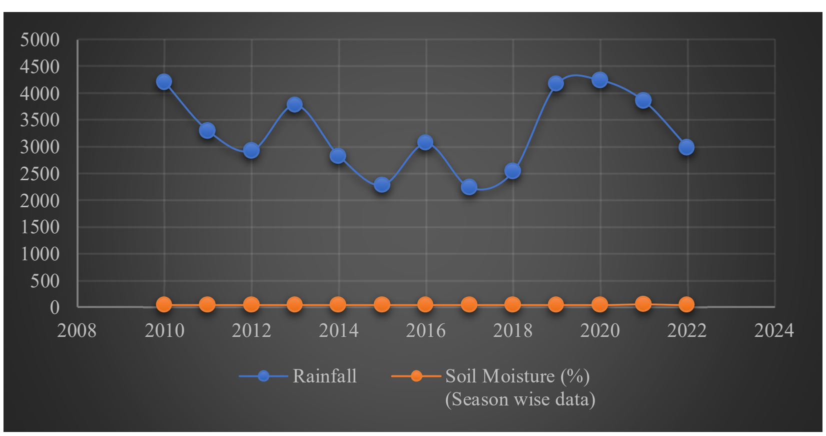


Figure 6. Model for Correlation between Rainfall and Soil Moisture

The table and figure mentioned above demonstrate the correlation test outcome and visual model to determine the association among test variables such as rainfall and soil moisture for season-wise data. With a p-value of 0.005 and a Pearson correlation of 0.706, rainfall and soil moisture show a strong and statistically significant positive relationship. A 1.0 on the diagonal of the correlation matrix only reflects the degree to which each variable is related to itself and has nothing to say about the degree to which multiple variables relate to each other. These results corroborate the idea that during the seasons being investigated, greater rainfall is associated with greater soil moisture.

Correlation – Partial

This analysis test is implemented to determine the relationship among two variables considered for the study. The correlation value demonstrates the relationship among the variables. This test is adopted to prove the correlation between the temperature and wind speed.

Table 5. Partial Correlations

Control Variables		Temperature (°C) (Season wise data)	Wind Speed (Season wise data)
Temperature (°C) (Season wise data)	Correlation	1.000	-.593
	Significance (2-tailed)	.	.042
	df	0	10
Wind Speed (Season wise data)	Correlation	-.593	1.000
	Significance (2-tailed)	.042	.
	df	10	0

The table 5 presents the correlation analysis between temperature and wind speed based on seasonal data. A correlation coefficient of -0.593 indicates a moderate negative relationship between temperature and wind speed, suggesting that as temperature increases, wind speed tends to decrease, or vice versa. The significance value of 0.042 ($p < 0.05$) indicates that this correlation is statistically significant, implying that the observed relationship is unlikely to have occurred by chance. The degrees of freedom (df) for the analysis is 10, which supports the robustness of the findings within the context of the sample size used. Overall, these results highlight a noteworthy inverse relationship between temperature and wind speed in the analyzed seasons.

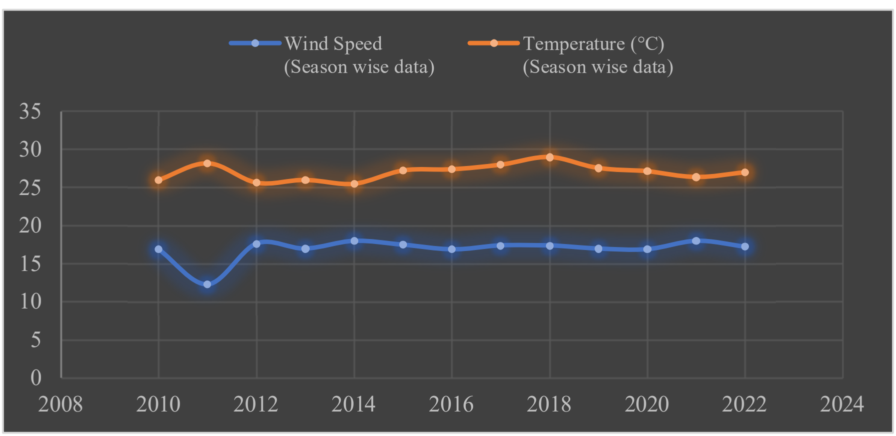


Figure 7. Model for Correlation between temperature and wind speed

The table and figure mentioned above validate the correlation test result and visual model to determine the association between temperature and wind speed. For a p-value of 0.042, the partial correlation coefficient between wind speed and temperature is -0.593. This indicates a moderately significant negative correlation, i.e., wind speed decreases as temperature increases or vice versa. A value of 1.000 on the diagonal of the correlation matrix indicates the correlation of each variable with itself; this value does not matter when analysing correlations between other variables. These findings suggest that temperature and wind speed are inversely related during the study seasons, an observation that may have implications for the mining process.

5. Discussion

This investigation elucidates the stability framework of the mine through an integration of detailed field investigations, thorough laboratory testing, and advanced slope stability analyses. It reveals different stability scenarios across different sections, showing the differences. The research underscores the utility of limit equilibrium analysis for assessing and refining bench parameters to enhance the safety of mine-deepening operations. The adoption of the recommendations proposed herein is anticipated to bolster slope stability, thereby facilitating continued mine development in compliance with prevailing study standards. Further exploration of specific geotechnical attributes and environmental conditions may be requisite for tailored site-specific applications.

The attained consequences of the existing study [46] showed that changes in the Songun copper mine had the biggest effect on financial growth (67.72%). The effects on environmental and social factors were 41.74% and 39.84%. The biggest impacts were on things like productivity, mine life, costs, mineral value, revenue, closure cost, investment return, and land use after mining. Likewise, the results of the present study also included a careful check of current bench designs. This found possible unstable areas in sections 250 and 350 East Left, which had low FOS values. These areas need more study and possible fixes. A detailed case study on modified bench parameters in open-pit iron ore mining can provide valuable insights into sustainable deepening practices and slope stability. For instance, specific sections such as "250 North" and "350 East Left" can illustrate the practical implications of optimizing bench designs. By adjusting parameters like slope angles, bench widths, and heights, significant improvements in FoS values can be achieved, ensuring enhanced stability and operational efficiency. Visuals such as cross-sectional diagrams or comparative data tables showing changes in FoS values before and after modifications would strengthen the practical aspect of these findings. Additionally, incorporating design adjustments tailored to geological and geotechnical conditions in these sections can demonstrate how localized interventions contribute to overall mine safety and sustainability. Such case studies highlight the importance of integrating slope stability analysis with sustainable resource extraction practices to mitigate risks while maximizing productivity. Considering relevant external factors and potential weaknesses will guide informed decision-making to ensure the long-term stability and safety of the mine operations [47].

Comparing Slide 6.0's limit equilibrium method (LEM) results with finite element analysis (FEA) provides a robust validation framework for slope stability assessments in open-pit mining. Slide 6.0, as an LEM-based tool, is simple, fast, and easy to use, so it is good for quick checks of safety factors. However, its reliance on set failure surfaces means it may not work well in complex cases. In contrast, FEA offers greater versatility by modelling stress-strain behavior without prior assumptions about failure surface geometry, enabling more accurate analysis in heterogeneous or anisotropic conditions. Despite its precision, FEA is computationally intensive, requires advanced expertise, and may face convergence issues in certain cases. By benchmarking Slide 6.0 against FEA, researchers can leverage the strengths of both methods: Slide 6.0 for rapid preliminary assessments and FEA for detailed investigations ensuring a balanced approach to sustainable slope stability practices [48].

The Outcomes of the prevailing study [49] specified that the operations of mining in whole are somewhat maintainable, with a complete score of 4.20%, and have marginally improved the financial and social circumstances when having pretended unsustainability in the ecological index. Lastly, as the future holistic model reflects both adverse and optimistic impacting aspects and also provided an accurate value for the distinct and entire sustainability in mining activities score. Similarly, the results of the current study followed the initial stability assessment that identified potential concerns, this study optimized bench parameters to enhance stability and resource utilization within the limited operational area. The analysis considered the unique challenges of the Indian subcontinent, such as variable rainfall patterns, seismic activity, and specific soil properties. It focused on optimizing key parameters like bench height, width, and slope angles. The redesigned configurations, as shown in Figure 11, adopted a standardized format with a consistent height of 6 meters, width of 8 meters, and individual bench angles of 63° within an overall slope angle of 36°. These modifications aimed to achieve a balance between maximizing resources extraction and maintaining slope stability.

The results of the prevailing study [50] indicated that the most serious social influence groups in profound open-pit mines are workshop safety with 13.8%, occupation with 10.9%, and income generation with 10.7%. Subsequently, the factor's score of social impact was denoted through the scenarios defined in the conventional study. Lastly, the approach was used to the Sungun Copper Mine (SCM) in the northwest of Iran for confirmation. The Score of

Social Sustainability (S_s) for the SCM was demonstrated to be 6.364% that shows a mid-level of sustainability. Likewise, the consequences of the present research applied the correlation test outcome to determine the association among test variables such as rainfall and soil moisture for season-wise data. If the p-value of correlation test is less than 0.05 and Pearson correlation value is 1, then the test variables for which we see the correlation is positive. The obtained p value for the present variables of current research is 0.07 and Pearson correlation value is also 1. Hence, it demonstrates that safety factors involved in mining and environmental parameters such as rainfall and soil moisture are correlated.

Existing Bench Stability:

- A precise evaluation of the current bench configurations uncovered stability issues in certain segments.
- Utilizing Slide 6.0 for limit equilibrium analysis, the study discerned Factor of Safety (FOS) values spanning from0.475 to 1.495. Notably, segments such as 250 North and 350 East Left registered critically low FOS values (0.477and 0.475, respectively), signaling a heightened risk of failure.
- Although some sections presented acceptable FOS values, the observed range indicated the potential for both superficial and comprehensive bench failure mechanisms.

Modified Bench Parameters and Improvement:

- In pursuit of enhanced stability and efficient exploitation of resources, a uniform design for modified benches was proposed, featuring consistent dimensions: Height of 6 meters, Width of 8 meters, an Individual bench angle of 63°, and an Overall slope angle of 36°.
- Subsequent analysis with Slide 6.0 software illustrated marked stability improvements across the majority of sections. FOS values were recalibrated, now ranging from 0.905 to 0.996 (minimum) and 1.390 to 1.491 (maximum), evidencing the substantial efficacy of the redesigned bench parameters.

5. Conclusions

In conclusion, this geotechnical study successfully evaluated the stability of existing open-pit mine benches at the Iron Ore Mine and proposed optimized parameters for safe and sustainable mine deepening. Serious stability problems were found in sections with low FOS, leading to clear suggestions that balance working well and staying safe. The decision-making framework employed prioritized criteria directly influencing slope stability, including FoS as the primary metric, geological characteristics such as soil composition and structural discontinuities, and environmental conditions reflected in the correlations between rainfall and soil moisture (Pearson correlation = 0.706) and temperature and wind speed (correlation = -0.593). While explicit weighting of these criteria was not included, their selection aligns with the study's objectives to enhance slope stability and optimize resource utilization. To mitigate risks associated with localized failures, the study recommends maintaining optimal bench geometry, implementing robust water management systems, and regularly monitoring critical zones for potential slope movement. Future research should explore the economic feasibility of these modifications and consider incorporating advanced numerical methods like Finite Element Analysis (FEM) or Discrete Element Method (DEM) for more accurate assessments. By integrating decision-making criteria into slope stability assessments, this study contributes significantly to responsible mining practices that prioritize safety while optimizing resource extraction, ultimately benefiting both industry stakeholders and the environment.

References

[1] M. Hawley and J. Cunning, *Guidelines for mine waste dump and stockpile design.* CSIRO Publishing, 2017.

[2] V. Navarro Torres, R. Dockendorff, J. Girao Sotomayor, C. Castro, A. J. J. o. t. S. A. I. o. M. Silva, and Metallurgy, "Probability of failure and factor of safety in the design of interramp angles in a large open iron ore mine," *Journal of the Southern African Institute of Mining and Metallurgy,* vol. *122*, no. 7, pp. 363-376, 2022.

[3] S. Sengupta, A. Krishna, and I. J. J. o. E. S. S. Roy, "Slope failure susceptibility zonation using integrated remote sensing and GIS techniques: A case study over Jhingurdah open pit coal mine, Singrauli coalfield, India," *Journal of Earth System Science,* vol. *127*, pp. 1-17, 2018.

[4] S. Akdağ, "Determination of optimum overall slope angle for an open pit iron mine," *Middle East Technical University*, 2015.

[5] T. G. Carter, L. J. Lorig, E. Eberhardt, and P. J. Graaf, "Approaches for Estimating Slope Breakback and Stability Longevity for Closure of Large Open Pits," in *Rocscience International Conference (RIC 2023)*, 2023: Atlantis Press, pp. 505-521.

[6] C. A. O. Mitma, "Slope Stability Analysis of Open Pit Mines under Geomechanical Uncertainty," *McGill University (Canada)*, 2020.

[7] G. Das, A. Burman, A. Bardhan, S. Kumar, S. S. Choudhary, and P. J. A. J. o. G. Samui, "Risk estimation of soil slope stability problems," *Arabian Journal of Geosciences,* vol. *15*, no. 2, p. 204, 2022.

[8] T. Assis, F. Cordeiro, L. J. I. R. o. L. Schiavon, and Economics, "How stock market reacts to environmental disasters and judicial decisions: A case study of Mariana's dam collapse in Brazil," *International Review of Law and Economics,* vol. *73*, p. 106105, 2023.

[9] A. Yildiz, F. Graf, C. Rickli, and S. M. J. C. Springman, "Determination of the shearing behaviour of root-permeated soils with a large-scale direct shear apparatus," *Catena,* vol. *166*, pp. 98-113, 2018.

[10] J. M. Duncan, S. G. Wright, and T. L. Brandon, *Soil strength and slope stability*. John Wiley & Sons, 2014.

[11] D. Balya, "Stability assessment of mine waste dump, case study: optima mines and minerals limited," 2023.

[12] S. K. Singh and D. J. A. o. M. S. Chakravarty, "Efficient and Reliable Prediction of Dump Slope Stability in Mines using Machine Learning: An in-depth Feature Importance Analysis," *Archives of Mining Sciences,* vol. *68*, pp. 685-706-685-706, 2023.

[13] M. Koopialipoor, P. G. Asteris, A. S. Mohammed, D. E. Alexakis, A. Mamou, and D. J. J. T. G. Armaghani, "Introducing stacking machine learning approaches for the prediction of rock deformation," *Transportation Geotechnics,* vol. *34*, p. 100756, 2022.

[14] O. Bazaluk, O. Anisimov, P. Saik, V. Lozynskyi, O. Akimov, and L. J. S. Hrytsenko, "Determining the safe distance for mining equipment operation when forming an internal dump in a deep open pit," *Sustainability,* vol. *15*, no. 7, p. 5912, 2023.

[15] V. S. Bang *et al.*, "The Influence of Rainfall and Evaporation Wetting–Drying Cycles on the Open-Pit Coal Mine Dumps in Cam Pha, Quang Ninh Region of Vietnam," *Applied Sciences,* vol. *14*, no. 5, p. 1711, 2024.

[16] N. Andronikidis *et al.*, "Geophysical Research on an Open Pit Mine for Geotechnical Planning and Future Land Reclamation: A Case Study from NW Macedonia, Greece," *Sustainability,* vol. *15*, no. 19, p. 14476, 2023.

[17] P. C. Mishra, M. K. Mohanty, and M. J. I. J. o. B. E. Mall, "Exploration of attributes influencing productivity in opencast mines," *International Journal of Business Excellence,* vol. *17*, no. 1, pp. 1-20, 2019.

[18] S. Nanda, S. Choudhury, and S. Patel, "Assessment of Structurally-Controlled Slope Failure in a Steeply Dipping Iron Ore Mine," in *ISRM Congress*, 2023: ISRM, pp. ISRM-15CONGRESS-2023-488.

[19] S. Wang, B. Cao, R. Bai, and G. Liu, "Dynamic optimization design of open-pit mine full-boundary slope considering uncertainty of rock mass strength," *Scientific Reports,* vol. *14*, no. 1, p. 19710, 2024/08/24 2024, doi: 10.1038/s41598-024-70902-9.

[20] E. Alemayehu, E. T. Chala, N. Z. Jilo, T. Tiyasha, and B. Moges, "Optimizing design and stability of open pit slopes in Tolay coal mine, Ethiopia," (in eng), *Sci Rep,* vol. *15*, no. 1, p. 1570, Jan 10 2025, doi: 10.1038/s41598-025-86034-7.

[21] W. R. Abdellah, C. Hirohama, A. Sainoki, A. R. Towfeek, and M. A. M. Ali, "Estimating the Optimal Overall Slope Angle of Open-Pit Mines with Probabilistic Analysis," *Applied Sciences,* vol. *12*, no. 9, p. 4746, 2022. [Online]. Available: https://www.mdpi.com/2076-3417/12/9/4746.

[22] S. Wang, Z. Zhang, and C. Wang, "Prediction of stability coefficient of open-pit mine slope based on artificial intelligence deep learning algorithm," *Scientific Reports,* vol. *13*, no. 1, p. 12017, 2023/07/25 2023, doi: 10.1038/s41598-023-38896-y.

[23] Y. Zhang, J. Zhang, and J. Ma, "Stability Analysis of a Steep Rock Slope in a Large Open-Pit Mine in a High-Intensity Area: A Case Study of the Yejiagou Boron Iron Mine," *Geofluids,* vol. *2022*, pp. 1-14, 08/18 2022, doi: 10.1155/2022/9113173.

[24] S. Li, Z. Zhao, B. Hu, T. Yin, G. Chen, and G. Chen, "Three-Dimensional Simulation Stability Analysis of Slopes from Underground to Open-Pit Mining," *Minerals,* vol. *13*, no. 3, p. 402, 2023. [Online]. Available: https://www.mdpi.com/2075-163X/13/3/402.

[25] K. Chand and R. Koner, "Internal mine dump slope stability and failure zone identification using 3D modelling," *Journal of Mining and Environment,* vol. *14*, no. 4, pp. 1105-1119, 2023.

[26] K. Goshtasbi, M. Ataei, and R. Kalatehjary, "Slope modification of open pit wall using a genetic algorithm-case study: southern wall of the 6th Golbini jajarm bauxite mine," *Journal of the Southern African Institute of Mining and Metallurgy,* vol. *108*, no. 10, pp. 651-656, 2008.

[27] A. Daftaribesheli, M. Ataei, and F. Sereshki, "Assessment of rock slope stability using the Fuzzy Slope Mass Rating (FSMR) system," *Applied Soft Computing,* vol. *11*, no. 8, pp. 4465-4473, 2011.

[28] S. Rezaei, R. Rafiee, M. Ataei, and M. Javadi, "*Sustainability Analysis of Waste Dump in Mine No. 4 of Golgohar, Sirjan, for Purpose of Increasing Waste Dump Volume*," *Journal of Mining and Environment,* vol. *14*, no. 4, pp. 1373-1391, 2023.

[29] A. Azam *et al.*, "Modeling resilient modulus of subgrade soils using LSSVM optimized with swarm

intelligence algorithms," *Scientific Reports,* vol. *12*, no. 1, p. 14454, 2022.

[30] R. J. E. Azzam, "Shear Failure Criterion and Constant Volume Ring Shear Testing Method for Clayey Soil," *Engineering,* vol. *8*, no. 8, pp. 545-560, 2016.

[31] S. Epiga and S. Rupprecht, "Slope design considerations for shallow open pit mines: a case study at Mamatwan mine, Northern Cape Province, South Africa," in *ISRM AfriRock-Rock Mechanics for Africa*, 2017: ISRM, pp. ISRM-AFRIROCK-2017-022.

[32] Y. Wang, T. Dong, H. Dong, and Y. J. S. Fang, "The Effect of a Moving Boundary on the Shear Strength of Granular Materials in a Direct Shear Test," *Symmetry,* vol. *15*, no. 9, p. 1734, 2023.

[33] S. Mhaske, I. Kapoor, K. Pathak, and N. Kayet, "Slope stability analysis of the overburden dump of meghahatuburu iron ore mines in Singhbhum Region of India," in *Proceedings of the International Field Exploration and Development Conference 2019*, 2020: Springer, pp. 3591-3605.

[34] A. Roshanfekr and D. J. J. o. H. E. Hansen, "Hydraulic behavior of progressively lengthened mine-waste dumps," *Journal of Hydraulic Engineering,* vol. *146*, no. 10, p. 04020068, 2020.

[35] S. K. Haldar, *Mineral exploration: principles and applications*. Elsevier, 2018.

[36] J. Singh, A. K. Verma, and H. Banka, "Application of biogeography based optimization to locate critical slip surface in slope stability evaluation," in *2018 4th International Conference on Recent Advances in Information Technology (RAIT)*, 2018: IEEE, pp. 1-5.

[37] J. Singh, H. Banka, and A. K. J. A. J. o. G. Verma, "Locating critical failure surface using meta-heuristic approaches: a comparative assessment," *Arabian Journal of Geosciences,* vol. *12*, pp. 1-20, 2019.

[38] S. J. R. F. d. G. Lacasse, "Charles Augustin de Coulomb, the artisan of modern geotechnical engineering," *Revue Française de Géotechnique,* no. 175, p. 9, 2023.

[39] H. ARAVINDA, *THE EFFECT OF IRON ORE MINING ON ENVIRONMENT & IT'S REGULATION IN INDIA*. Nitya Publications, 2022.

[40] A. Doderovic, S.-M. Doderovic, S. Stepanovic, M. Bankovic, and D. J. M. Stevanovic, "Hybrid Model for Optimisation of Waste Dump Design and Site Selection in Open Pit Mining," *Minerals,* vol. *13*, no. 11, p. 1401, 2023.

[41] W. Pan *et al.*, "Slope stability of increasing height and expanding capacity of south dumping site of Hesgoula coal mine: a case study," *International Journal of Coal Science & Technology,* vol. *8*, pp. 427-440, 2021.

[42] S. D. Shome, S. Chakraborty, and S. J. J. o. T. I. o. E. S. D. Sinha, "Development of a Sustainable Development Framework for Mining Regions: A Case Study Approach," *Journal of The Institution of Engineers (India): Series D,* pp. 1-14, 2023.

[43] V. N. Khatri, L. Nainegali, R. Sarkar, and S. K. J. C. S. Das, "Assessment of overburden dump and highwall slope stability for Jambad open cast coal mine, West Bengal, India, using in situ and laboratory testing," *Journal of Cleaner Production,* pp. 184-193, 2022.

[44] R. Krishna, J. Mishra, S. Meher, S. K. Das, S. Mustakim, and S. K. J. M. t. p. Singh, "Industrial solid waste management through sustainable green technology: Case study insights from steel and mining industry in Keonjhar, India," *Materials today: proceedings,* vol. *33*, pp. 5243-5249, 2020.

[45] W. R. Abdellah, C. Hirohama, A. Sainoki, A. R. Towfeek, and M. A. J. A. S. Ali, "Estimating the Optimal Overall Slope Angle of Open-Pit Mines with Probabilistic Analysis," *Applied Sciences,* vol. *12*, no. 9, p. 4746, 2022.

[46] N. Badakhshan, K. Shahriar, S. Afraei, and E. J. J. o. S. M. Bakhtavar, "Evaluating the impacts of the transition from open-pit to underground mining on sustainable development indexes," *Journal of Sustainable Mining,* vol. *22*, no. 2, p. 154, 2023.

[47] C. Bayón *et al.*, "Development and Evaluation of BenchBalance: A System for Benchmarking Balance Capabilities of Wearable Robots and Their Users," (in eng), *Sensors (Basel),* vol. *22*, no. 1, Dec 24 2021, doi: 10.3390/s22010119.

[48] W. C. Chong, "Comparative slope analysis by methods of slices and finite element analysis," 2020.

[49] M. Hosseinpour, M. Osanloo, and Y. J. J. o. C. P. Azimi, "Evaluation of positive and negative impacts of mining on sustainable development by a semi-quantitative method," *Journal of Cleaner Production,* vol. *366*, p. 132955, 2022.

[50] M. Heydari, M. Osanloo, and A. J. R. P. Başçetin, "Developing a new social impact assessment model for deep open-pit mines," *Resources Policy,* vol. *82*, p. 103485, 2023.

انجمن مهندسی معدن ایران
نشریه مهندسی معدن و محیط زیست
نشانی نشریه: www.jme.shahroodut.ac.ir
دانشگاه صنعتی شاهرود

بهینه‌سازی استخراج منابع با پایداری شیب: شیوه‌های پایدار تعمیق در معدنکاری روباز سنگ آهن

نارش کومار کاتاریا* و بهانوار سینگ چوداری

گروه مهندسی معدن، موسسه فناوری هند، دنباد، هند

اطلاعات مقاله

تاریخ ارسال: ۲۰۲۴/۱۰/۱۷

تاریخ داوری: ۲۰۲۵/۰۷/۱۰

تاریخ پذیرش: ۲۰۲۵/۱۰/۲۴

DOI: 10.22044/jme.2025.15232.2914

کلمات کلیدی

پایداری معادن روباز

بهینه‌سازی پله‌ای

تحلیل پایداری شیب

استخراج پایدار

تحلیل تعادل حدی

چکیده

پایداری شیب و ایمنی سکو در معادن روباز سنگ آهن در غرب هند در این تحقیق به طور جامع مورد تجزیه و تحلیل قرار گرفته است. برای ارزیابی شرایط فعلی معدن و شناسایی مناطق در معرض خطر، این مطالعه مشاهدات میدانی جامع، آزمایش‌های آزمایشگاهی و مدل‌سازی پیشرفته پایداری شیب را با استفاده از نرم‌افزار Slide 6.0 ادغام می‌کند. ضرایب ایمنی (FOS) بخش‌های مختلف معدن از ۰.۴۷۵ تا ۱.۴۹۵، طبق تحلیل تعادل حدی با Slide 6.0، متغیر بود. این نشان دهنده وجود شیب‌های احتمالاً ناپایدار است که نیاز به اقدامات تثبیت خاصی برای تضمین ایمنی عملیاتی دارند. این تحقیق علاوه بر تجزیه و تحلیل ژئوتکنیکی، بررسی می‌کند که چگونه عوامل محیطی مهم، مانند دما، سرعت باد، بارندگی و رطوبت خاک، بر پایداری شیب تأثیر می‌گذارند. مشخص شد که بارندگی و رطوبت خاک همبستگی مثبت بالا و از نظر آماری معنی‌داری دارند (همبستگی پیرسون = ۰.۷۰۶، $p = 0.005$)، به این معنی که افزایش بارندگی منجر به افزایش رطوبت خاک می‌شود که به نوبه خود بر رفتار شیب‌ها تأثیر می‌گذارد. همچنین، درجه متوسطی از رابطه منفی بین دما و سرعت باد آشکار شد (همبستگی جزئی = -۰.۵۹۳، $p = 0.042$)، به این معنی که سرعت باد کمتر به طور مشخص با افزایش دما مرتبط است. این یافته‌ها اهمیت نظارت مستمر بر محیط زیست در عملیات معادن روباز و اهمیت در نظر گرفتن عوامل محیطی هنگام ارزیابی پایداری شیب را برجسته می‌کند. اطلاعات جمع‌آوری‌شده در این مطالعه، پایه محکمی برای تدوین توصیه‌های ارزشمند با هدف افزایش ایمنی، کنترل بهتر شیب‌ها و ترویج توسعه بلندمدت فعالیت‌های معدنی در منطقه فراهم می‌کند.

نویسنده مسئول مکاتبات: *nareshkumarkatariya5@gmail.com* (ن.ک. کاتاریا)