Geomechanics and Engineering, *Vol. 40, No. 1 (2025) 69-78*
https://doi.org/10.12989/gae.2025.40.1.069

Optimizing open-pit iron ore mine waste dump stability with an increased height: A geotechnical perspective

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(*Received May 16, 2024, Revised December 16, 2024, Accepted December 30, 2024*)

Abstract. This study pertains to the stability of the waste dump of an iron ore mine near the working pit area in western India, with a focus on exploring the potential to increase the dimensions of dump aligned with sustainable mining practices and ensuring safety, through a process of optimization. The approach combined field investigations, laboratory testing, and numerical modelling of slope, using limit equilibrium method, and evaluating the Factor of Safety (FoS) of the dump. The results indicated that the existing dump exhibited stability, with FoS values ranging from 1.407 to 1.996, adhering to Indian regulations. Slope stability analysis of the dump was performed to evaluate the stability of modified dump with proposed changes in slope parameters. Additionally, moderate increases in height and adjustments in slope angles to 30°-35° was proposed to enhanced the dump capacity. The changes efficiently implemented increased the dump area by 1.01 hectare and dump capacity by 1.16 million tons, without compromising safety of the dump slopes. Additionally, the need for enhanced monitoring especially during adverse weather conditions is stressed.

Keywords: dump slope optimization; dump stability; geotechnical analysis; iron ore mine; slope stability modelling

1. Introduction

The escalating global demand for iron ore, a fundamental component of industrial development, has led to extensive open-cast mining operations. A significant byproduct of these operations is huge quantities of overburden (OB) material, which is typically deposited in mine waste dumps (MWD) adjacent to the mining pits. These OB dumps, often resembling artificial mountains, pose complex geotechnical challenges due to their size, heterogeneous composition, and susceptibility to instability (Tien *et al.* 2019; Yildiz *et al.* 2018). Ensuring the stability of these dumps is critical for operational safety, environmental sustainability, and the longevity of mining projects.

Open-cast mining operations, especially in space-constrained regions, demand rigorous waste management strategies to maximize land use efficiency while maintaining safety standards. In India, the regulations governing dump stability, such as those outlined by the Directorate General of Mines Safety (DGMS), mandate comprehensive stability assessments. However, the dynamic nature of mining activities, coupled with geological complexities and adverse climatic conditions, necessitates continuous monitoring and adaptive management of waste dumps. Historical instances of OB dump failures underscore the consequences of inadequate design and maintenance, highlighting the need for innovative and robust stability solutions (Akdağ 2015, Assis *et al*. 2023).

The geological conditions and lithological variability of the study area—characterized by formations such as laterite, phyllitic clay, lumpy iron ore, and siliceous clays—further compound the complexity of managing slope stability. The Redi Iron Formation, with its diverse lithologies such as laterite and manganiferous clay, presents unique challenges due to variable mechanical properties, including low shear strength in phyllitic clays and high porosity in laterite layers (Carter *et al*. 2023a). These geological features, coupled with structural discontinuities like faults and joints, require comprehensive geotechnical investigations and tailored stability solutions. Advanced numerical modeling tools, such as Slide 6.0 software, have been employed to analyze and optimize the stability of mine benches and waste dumps under varying loading conditions (Ji and Liao 2014).

Previous research has extensively explored various aspects of OB dump stability, including slope optimization, material properties, and numerical modeling approaches. Studies by (Nanehkaran *et al*. 2023, Yang and Pan 2015) have provided insights into optimizing slope angles and assessing stability under seismic and static conditions. Similarly, the application of advanced modeling tools, such

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ISSN: 2005-307X (Print), 2092-6219 (Online)

as the limit equilibrium method and finite element analysis, has enhanced the accuracy of stability predictions (Carter *et al.* 2023a). However, there remains a critical gap in the contextual adaptation of these methodologies to specific geological settings and operational constraints.

This study aimed to address these gaps by focusing on the stability of the MWD in an open-pit iron ore mine (IOM) located in Maharashtra, India. Aligned with sustainable mining practices, the research seeks to evaluate the geotechnical properties of existing dumps, explore the feasibility of increasing dump heights, and propose optimized configurations to enhance dump capacity without compromising safety. The investigation integrates field observations, laboratory testing, and numerical modeling to provide a holistic assessment of dump stability (Koda *et al*. 2020).

The specific objectives of this study are:

1. To evaluate the stability of existing OB dump slopes using established geotechnical methods.
2. To assess the potential for increasing dump heights and modifying slope configurations to optimize capacity.
3. To ensure compliance with safety standards while addressing the challenges posed by regional geological and climatic conditions.

By contributing to the body of knowledge on OB dump management, this study aims to provide a replicable framework for improving waste management practices in the mining industry. The findings are expected to inform policy and operational decisions, fostering a balance between resource extraction and environmental stewardship.

2. Materials and methods

1. To achieve the objectives of the study, a multi-pronged approach was employed that involved:
2. Field visit and data collection: A thorough site investigation was conducted to collect geological data, collect MWD samples along with detailed information on the mine layout. This comprehensive data collection aimed to gain a thorough understanding of the specific characteristics and potential challenges as accepted internationally (Navarro Torres *et al*. 2022, Afkhami Hoor and Esmaeili-Falak 2024, Sawant and Thakur 2015) that are unique to the IOM.
3. Laboratory testing: Physico-mechanical properties of the samples collected were determined in laboratory under controlled test settings. This testing methods (Haldar 2018, Revuelta 2017) aimed to assess the shear strength of the samples and their other relevant properties (Rotaru *et al*. 2022).
4. Slope stability analysis: limit equilibrium analysis was performed to evaluate the stability of both the existing slopes and the proposed changes in slope parameters as defined by (Yildiz *et al.* 2018). The analysis aimed to identify potential failure modes and assess the effectiveness of proposed design changes for long-term slope stability.
5. Based on the analysis, specific recommendations were formulated for safe slope design and effective dump management practices (Hawley and Cunning 2017a). The details of the methodology and data collected are explained further.

2.1 Study area, geology and overview of waste dump

A fully mechanized open pit iron ore mine in the Sindhudurg District of Maharashtra State in India (IOM) was selected for the study. The location of the IOM is shown in Fig. 1. The mine has a designated waste dump of 13.3 hectares in the non-mineralized area. The location of the Iron ore mine, geology and mine conditions are shown in Fig. 1.

The general strike of the ore body is NW-SE (around N270° to N290°), but in some places, the direction changes to E-W. The general dip of the ore body is 42° to 55° towards NE. The length of the ore deposit within the lease is about 2.3 km and the average thickness is 25 m - 45 m. Due to structural disturbances and intrusion of a dyke, there is sudden discontinuance of the ore body along the strike direction in the eastern portion of the lease area. The igneous activity in the area has resulted in the formation of dykes and sills and abrupt discontinuation of the ore body. The general succession of the lithology from top to bottom in the study area is provided in Table 1.

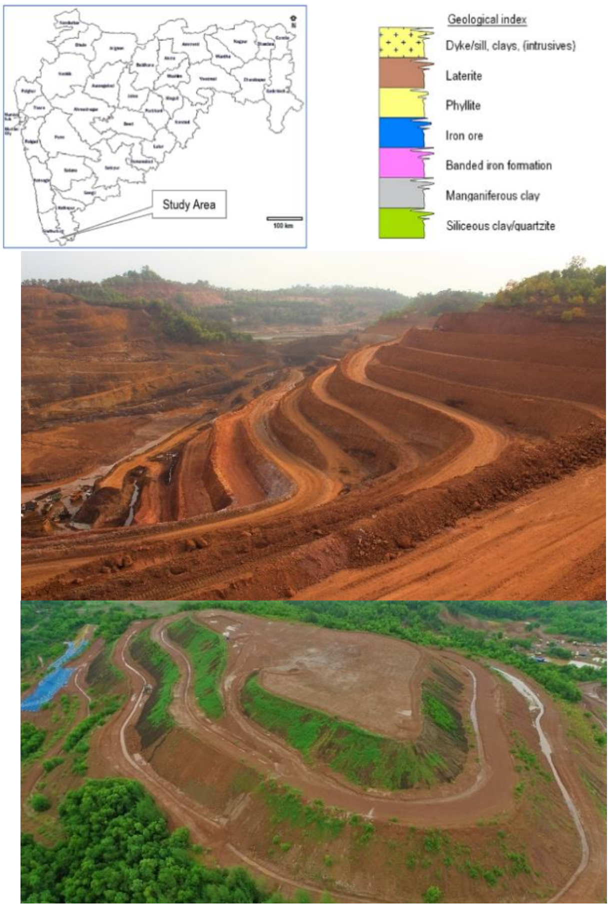


Fig. 1 Location of the mine, regional geology, position of mine and the waste dumps of the study area

Table 1 The general succession of lithology of the mine

Hangwall		Footwall	
Lithology	Thickness	Lithology	Thickness
Laterite	10- 20 m	Phyllitic Clay	20- 25 m
Lumpy Iron Ore	5- 7 m	Blue Dust	20- 40 m
Limonitic/Man-ganiferous Clay Schists	25- 55 m -	Siliceous Clays/Quartzite	30- 60 m

Table 2 Details of the existing dumps in the mine area

Sl. No.	Waste Dump	Quantity	Area (Hect.)	Height of Dump (m)
1	Dump A	8581000	12.65	52
2	Dump B	2780000	5.32	42
3	Dump C	645000	2.66	20

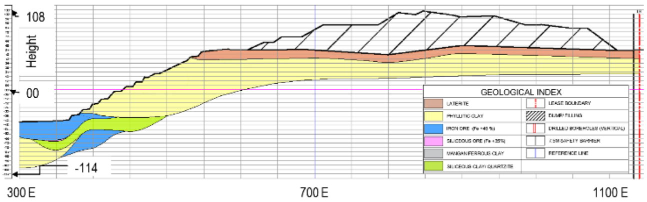


Fig. 2 Profile of the IOM along the section 250 N to 250 N' with the geology of the IOM and MWD

This opencast mining operation (the study area) utilizes three designated waste dumps located within the non-mineralized area (Table 2). The process of transferring excavated overburden from the mine pit to designated dumps is crucial in opencast mining. Hydraulic excavators efficiently load the material onto dumpers for transportation along optimized routes to the waste dumps. Dozers spread and compact the dumped material in layers to ensure stability and minimize erosion (Doderovic *et al*. 2023, Pan *et al*. 2021, Roshanfekr and Hansen 2020).

Due to spatial limitations within the lease boundaries, the dumps are adjacent to the mine pit and waste dumping is essential to continue the mining operation (Geete *et al.* 2023). This study aims to assess the feasibility of increasing the height of Dump A which has a large area for dumping near the pit area as shown in Fig. 2 while maintaining an acceptable Factor of Safety (FOS).

2.2 Methodology

As mentioned earlier, the investigations involved laboratory testing, numerical slope stability analysis (Azam *et al*. 2022; Esmaeili-Falak and Hajialilue-Bonab 2012, Epiga and Rupprecht 2017, Hosseini *et al*. 2023, Mhaske *et al.* 2020) to assess the geotechnical properties, determine potential instabilities and pave the way for optimized management and long-term sustainability of the dumps. The methodology adopted is presented in Fig. 2.

2.2.1 Field Investigations

Preliminary field visits were conducted to collect basic data of the mine like topography, collection of soil samples, and structural information yielding insights into the existing conditions of the mine, as detailed below:

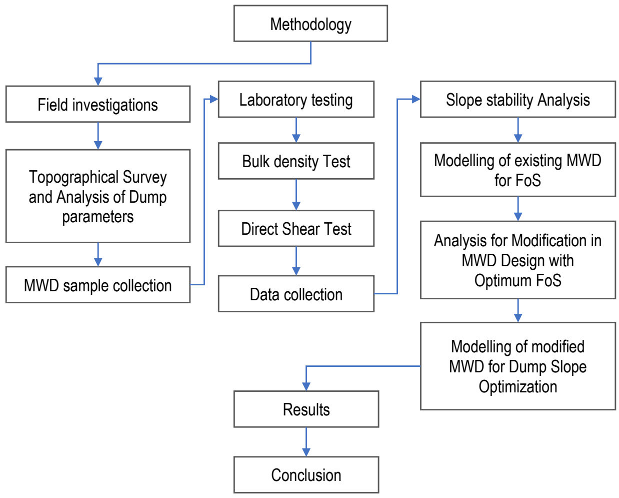


Fig. 3 Methodology adopted for the slope analysis

- Topographical Surveys: Standard survey instruments like total stations and differential GPS were used and a precise topographical map of the dump sites was created. These detailed maps enabled analysis of slope angles, identification of critical failure zones, and assessment of potential instability conditions.
- Sampling: Representative samples of soil and rock materials were collected from various depths with diverse data representing the geotechnical makeup of the dumps, for subsequent laboratory testing.

2.2.2 Laboratory testing

The samples obtained from the mine dumps were tested in the laboratory to determine physico-mechanical properties(Azzam 2016, Hosseini *et al.* 2023). The bulk density and direct shear tests were performed using standard soil testing procedures, adopting ASTM standards D2937-17e2 for bulk density and D3080/D3080M-11 for direct shear tests, with considerations for the characteristics of Indian soil.

2.2.3 Bulk density test

Bulk density tests (Duncan *et al.* 2014a) were conducted on the soil samples for assessment of soil properties influencing water infiltration and potential for mass movement (Duncan *et al.* 2014a). Utilizing the core cutter method as per ASTM D2937-17e2, a cylindrical steel core cutter of a defined volume was positioned to extract soil samples with minimal disturbance. The core cutter was carefully driven into the soil until filled (Fig. 4), and subsequently, the soil-laden cutter was weighed. The bulk density was calculated by dividing the mass of the soil by the volume of the cutter. This measure of bulk density is pivotal in evaluating the porosity and compaction levels of the soil, which significantly impact its hydraulic properties of the material. Elevated bulk densities generally indicate lower porosity, leading to diminished infiltration rates and increased surface runoff, thus heightening the risk of erosion and mass movement.

Fig. 4 In-situ bulk density determination and sample collection

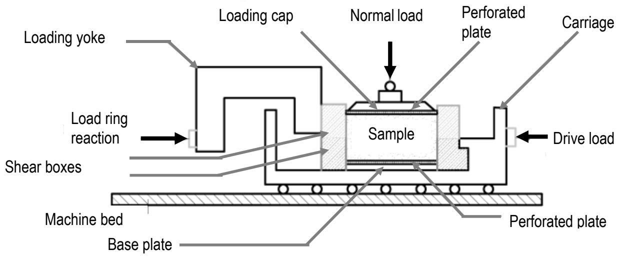


Fig. 5 Schematic of Direct Shear Testing in the Laboratory (Wang *et al*. 2023)

2.2.4 Direct shear test

The soil shear strength properties like friction (φ) and cohesion (c) assume paramount significance in slope design (Duncan *et al*. 2014a). Frictional resistance is contingent upon the soil stress state and the internal friction angle (φ) between particles (Duncan *et al*. 2014a) as expressed in the Eq. (1).

$$\tau = \sigma \times n \times \tan\varphi \quad (1)$$

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

The direct shear test of Coulomb, 1776, stands as the earliest method for evaluating soil shear characteristics (Khatri *et al.* 2022, Lacasse 2023). This technique involves confining soil within a bisected box, with the lower segment fixed to prevent lateral movement. A normal confining force (*n*) is applied, followed by a tangential shear force (τ) to induce relative displacement between the two halves of the box as illustrated in Fig. 5. The resultant shear force is recorded in relation to the shear displacement, often accompanied by the monitoring of changes in thickness of the soil sample. The shear strength and internal friction angle of the soil are determined using a direct shear apparatus (Fig. 5).

The shear strength and internal friction angle, as emphasized (Duncan *et al*. 2014a), are central to estimating slope stability under various loading conditions and guide the analysis of potential failure scenarios.

In the study, direct shear tests were conducted in the laboratory to evaluate the shear strength properties of soil samples. The samples underwent shearing under

Fig. 6 The Collection & Preparation of Sample and Direct Shear Testing in the Laboratory

Table 3 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
8	Dump	19.6	35.81

vertical/normal stresses of 0.2 kg/cm^2, 0.5 kg/cm^2, 0.75 kg/cm^2, and 1 kg/cm^2, and the maximum loads at shear were systematically recorded. These test results were then utilized to calculate the cohesion (C) and angle of friction (φ). Detailed procedures (Cofie and Koolen 2001) for sample preparation and testing in the laboratory are illustrated in Fig. 6. Table 3, provides the shear properties of various samples collected from the IOM dumps.

2.2.5 Slide 6.0 Software for Limit Equilibrium Analysis

Slide 6.0 (Rocscience Inc., 2020), is a software application utilized for slope stability analysis in mining and geotechnical engineering. Based on the limit equilibrium method, it evaluates potential failure surfaces, calculating the Factor of Safety (FoS) with precision. The software incorporates analysis techniques including Bishop's Simplified, Janbu's Simplified, and Morgenstern-Price methods, offering flexibility in addressing varying assumptions about interslice forces.

Input parameters such as cohesion, friction angle, unit weight, slope geometry, and pore water pressures are integrated into the analysis, enabling detailed assessments under a range of conditions. Slide 6.0 accommodates both circular and non-circular slip surfaces. Furthermore, the software supports anisotropic material properties, groundwater effects, and structural discontinuities, essential for accurate modeling in open-pit mining environments.

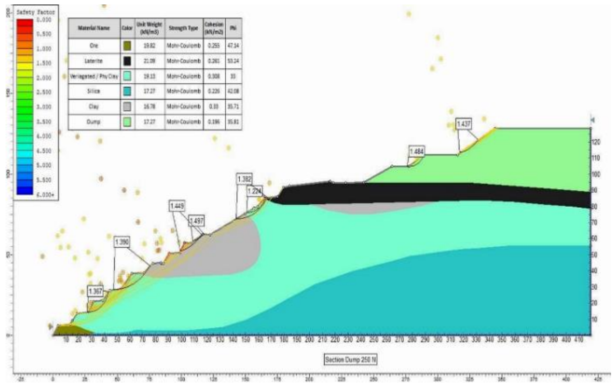
Its interface and robust visualization tools allow generation of 2D depictions of slopes, failure planes, and stress distributions. This visual clarity aids in interpreting results and informing design adjustments. The use of Slide 6.0 ensured evaluation of stability for both existing and proposed slope configurations.

2.2.5 Slope stability analysis

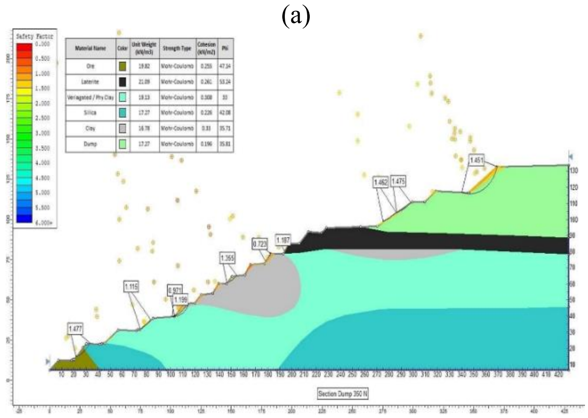
The stability analysis utilized the limit equilibrium method using two-dimensional (2-D) sections, assuming plane strain conditions and circular slip surfaces (Singh *et al.* 2024) . The Factor of Safety (FoS) was used as a key indicator of stability, with adjustments for Indian geological complexities (Singh *et al.* 2018, 2024). With the field data and material properties slope stability analysis could be performed as detailed below.

- Limit Equilibrium Method: Employing the widely accepted limit equilibrium method implemented in Slide 6.0 Software (Rodriguez *et al*. 2023) the stability of the dumps under various loading conditions was analyzed. This established technique, similar to the approach allows for robust assessments of potential failure mechanisms
- Circular Slip Surfaces: Recognizing the prevalence of circular slip surfaces in dump failure scenarios, the study considers these potential failure planes alongside relevant material properties obtained from laboratory testing(Singh *et al*. 2019a, b, 2024). This focused analysis provides targeted insights into the most likely instability scenarios.
- Factor of Safety (FoS): As the key indicator of stability, the Factor of Safety (FoS) is meticulously analyzed for each dump section. Adjustments are made to account for the complexities of the Indian geological setting, drawing upon the expertise (Hawley and Cunning 2017b, Pan *et al*. 2021) to ensure accurate and context-specific stability assessments.

The data thus acquired was used to determine the FoS for MWD slopes and their optimization in terms of their angle and height.



(a)



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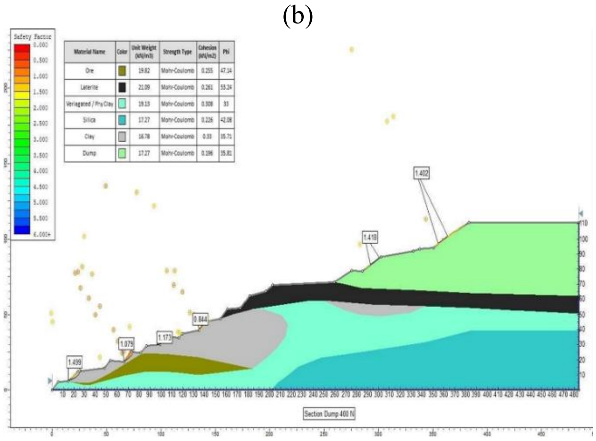


(c)

Fig. 7 The factor of safety in existing the dump at Section (a) 250° N (b) 350° N and (c) 400° N

3. Results

Dump slope stability assessment

Utilizing the fundamental equation of FoS (Eq. (2)), the values of the Factor of Safety (FoS) were calculated for various cross-sections within each dump.

$$FoS = \text{Resisting Shear Force}/\text{Driving Shear Force} \quad (2)$$

This FoS metric, defined as the ratio of resisting shear force to driving shear force, serves as the cornerstone of the stability assessment (Duncan *et al*. 2014b), to understand the current state of the dumps (Duncan *et al.* 2014b). By using the advanced slope stability modelling the results of the existing dump sections have been analyzed. Figs. 7(a) to 7(d), visually present the FoS values for the dumps at 250° N, 350° N, and 400° N, respectively, prior to optimization. In this manner, the areas of potential failure condition and the overall stability of the existing dump configurations were evaluated.

The data of the slopes of the MWD before the optimization of slope configuration (Table 4) were analyzed for FoS to ascertain their stability and further treatment.

Table 4 presents the Factor of Safety (FoS) values for different sections of the existing MWD where the section "250 North" "350 North" and "400 North" report minimum

Table 4 Factor of safety values of different sections of the MWD

Sl No	Existing Sections	Minimum Factor of Safety	Maximum Factor of Safety
1	250 North	1.437	1.484
2	350 North	1.451	1.475
3	400 North	1.402	1.418

Table 5 The Optimized FoS for the Modified Dump cross-sections

Sl. No.	Modified Section	Minimum Factor of Safety	Maximum Factor of Safety
1	Four Dump Benches	1.314	1.496
2	250° North	1.447	1.871
3	350° North	1.572	1.886

FoS values of 1.402 and maximum up to 1.484 confirming the satisfactory stability for a working dump as per DGMS (Tech.) Circular No .03 of 2020 Dated 16.02.2020, issued guidelines for Scientific study under regulation 106 of the MMR-2017. Overall, the sections demonstrate adequate safety margins.

Dump slope optimization

Considering the space constraints for dumps and recognizing the potential for resource optimization within the limited area through increased dump heights, modifications were proposed to crucial parameters like height, width, and slope angles, modifications to dump parameters, including height (Eq. (3)), width, and slope angles, were proposed to assess the feasibility of increased dump heights.

$$\text{Height} \frac{Volume\ m^3}{Base\ aream^2} \tag{3}$$

By using the advanced slope stability modelling the parameters of the MWD were modified for the heightening of the dump and the results of the modified dump sections have been evaluated for their feasibility considering the challenges posed by specific soil properties in the Indian context (Hawley and Cunning 2017b). Fig. 8(a) shows the stability analysis of a modified dump with four benches, providing a visual of its behavior under the adjusted parameters. Similarly, Figs. 8(b), and 8(c) depict the FoS values for the modified dump at the sections 250° N and 350° N offering a clear understanding of its stability characteristics. Fig. 8(d) is the modified bench configuration with specifications of the height of the dump benches being 15 m, width 10 m, angle of the individual bench is 33 degree and overall angle is 25 degree in all the sections of the dump. The FoS values of the optimized bench configurations are compiled in Table 5.

The detailed results in Table 5 present the minimum and maximum FoS values for each modified dump cross-section wherein a quick comparison and identification of optimal configurations can be made. The proposed modifications,

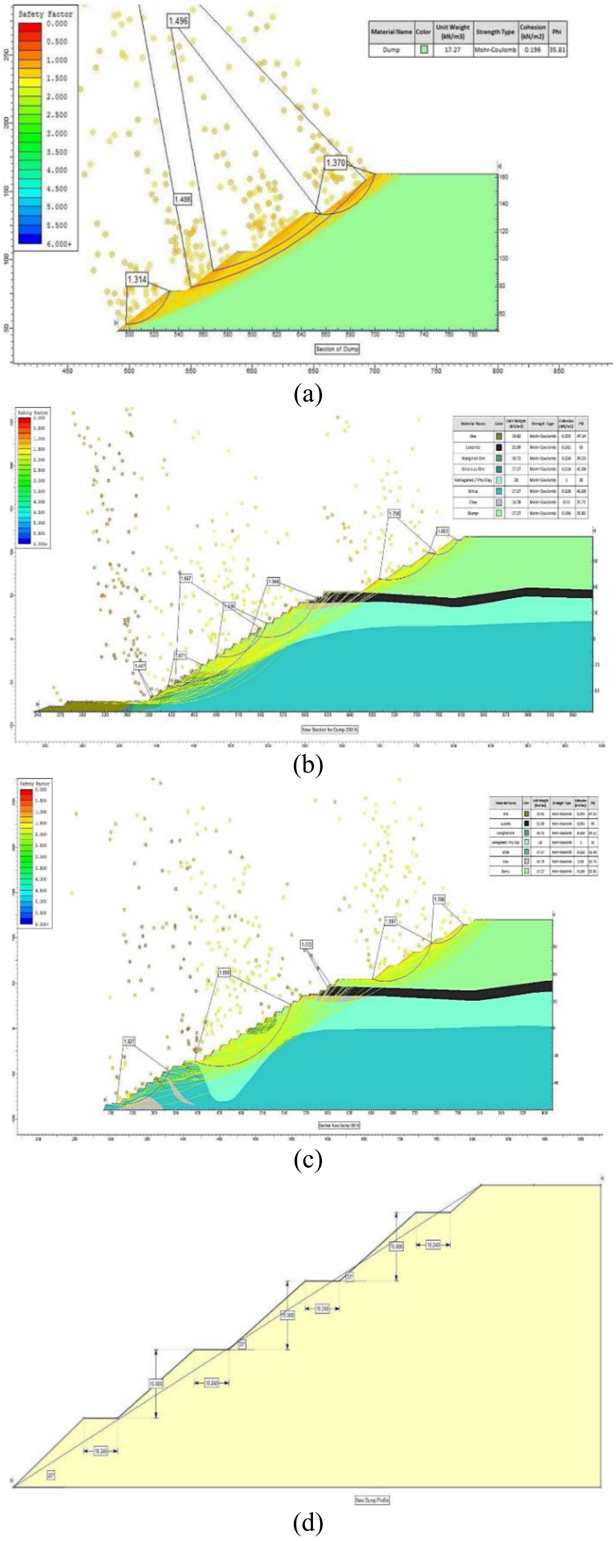
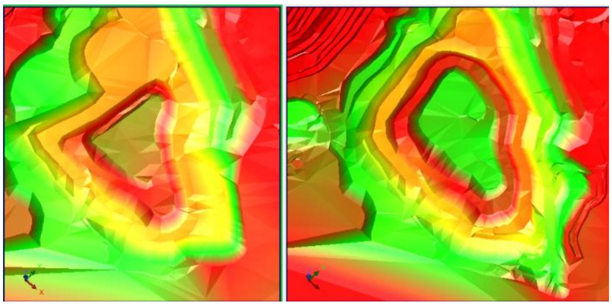
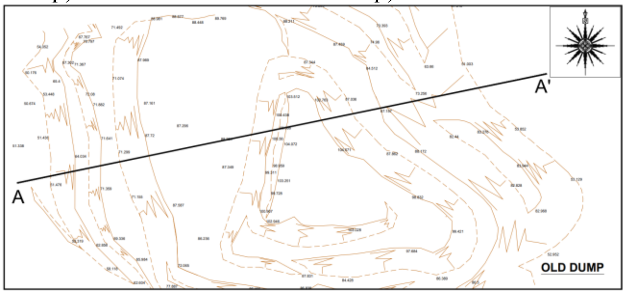


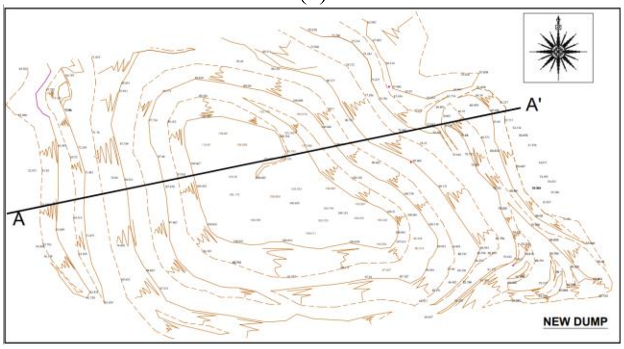
Fig. 8 (a) Stability analysis of modified dump with four benches, (b) The FoS of the modified dump at 250 °N, (c) The factor of safety of the modified dump at 350 °N and (d) Modified dump design with specifications of the MWD



(a) Existing Dump (old dump) (b)Modified Dump (new dump)



(c)



(d)

Fig. 9 (a) & (b) 3D representation of the terrain executed using the SURPAC software. (c) plan of the old dump with section line A-A'. (d) plan of the new dump with the section line A-A'

including increased dump heights near the pits, demonstrated promising results. Configurations with four bench heights and individual slope angles between 30 degree and 35 degree exhibited FoS values ranging from 1.314 to 1.996, with the sections showing satisfactory stability. Based on the comprehensive analysis, it was recommended to maintain widths of 10 to 12 m and a bench height of 15 m. Additionally, an overall slope angle of 25 degree emerges as the optimal choice for ensuring long-term stability and operational efficiency of the MWD. These adjustments considered the challenges of monsoon and seismic activity while adhering to Indian standards of FoS. The modified configurations of the benches were implemented at the site and the benches were monitored over three years. The results indicated that the optimized configuration did not show any signs of failure. In this manner the optimized bench configuration provided extra dump space and helped in sustainable operations as demonstrated in Fig. 9 and Table 6.

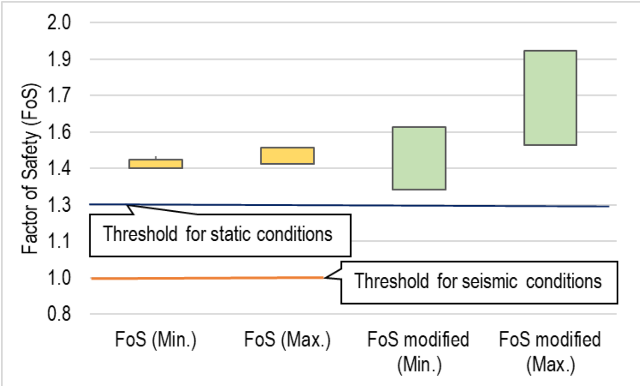


Fig. 10 Comparison of FoS for various sections before and after (modified) optimization

It was be observed that after the optimization of the bench configuration, a total of 1.01 Ha area increased for the dumping and 1.16 million Tons of extra OB could be dumped on the MWD, which was a significant quantity as the mine has no surplus area for the dumping.

4. Discussion

Iron ore mine dumps are essential components of mining operations, serving as repositories for overburden and waste material. The stability of these dumps is critical for ensuring operational safety, environmental sustainability, and the prevention of catastrophic failures. Stability issues arise due to various factors such as dump height, slope angle, material properties, drainage conditions, and external forces like seismic activity or heavy rainfall.

The stability of mine dumps is primarily governed by the geotechnical characteristics of the dumped material, including cohesion, angle of internal friction, and moisture content. Materials with low shear strength are prone to sliding, particularly when subjected to increased pore water pressure during heavy rainfall (Duncan *et al*. 2014b).

Several studies pertain to the optimization of the dump slopes that can be crucial to the sustainability of a mining operations in a space constrained area, (Bazaluk *et al*. 2023, Doderovic *et al*. 2023, Kumar 2013). Proper slope design, including the use of benching and optimized slope angles, is crucial to enhancing dump stability. Research indicates that the factor of safety (FoS) should typically remain above 1.3 for static conditions and above 1.0 for seismic conditions to ensure stability (Hoek and Bray 2010).

The proposed modifications with the help of proper testing and analysis, including increased dump heights near the pits with change of bench heights at four places and modified slope angles between 30° and 35° exhibited FoS values ranging from 1.314 to 1.996 (Fig. 9), thus are stable.

Fig. 10 demonstrates that the lower limit of FoS in optimized bench configuration is smaller than that observed in previous conditions. However, the optimized values are higher than the threshold limits of both static and dynamic conditions.

Table 6 Results of the application of optimized bench configurations

Sl. No.		Location	Earlier bench configuration			Area and Quantity for dumping	Optimized bench configuration			Area and Quantity for dumping	Extra area and Qty achieved for dumping
		1	2			4	3			4	5
			H	W	A		H	W	A		
1	SECTION 250N	B1	10			12.65 Ha and 8.581 (Million Tonnes)	15			13.66 Ha and 9.741 (Million Tonnes)	1.01 Ha and 1.16 (Million Tonnes)
		B2	7	13	33		15	13	33		
		B3	15	27	29		15	27	33		
		B4	15	75	31		10	75	33		
2	SECTION 350N	B1	15	-	-		15	-	-		
		B2	6	10	36		15	10	33		
		B3	15	27	35		15	27	33		
3	SECTION 400N	B1	11	-	-		15	-	-		
		B2	9	10	29		15	10	33		
		B3	15	13	33		15	13	33		

Comparative analysis with studies (Singh *et al*. 2019b, Singh and Chakravarty 2023), are also in agreement that the FoS values fall within acceptable ranges. However, the areas with lower values of FoS need continuous monitoring as advocated by several authors (Carter *et al*. 2023b, Mitma 2020). Such vigil is crucial, particularly during adverse weather conditions, to prevent slope failures. (Carter *et al*. 2023b, Mitma 2020)

In the process, the techno-economics of the mine could be improved while saving on space that in turn lead to sustainable operations using advanced modelling tools. The study highlights the importance of integrating empirical data with model predictions, (ARAVINDA, 2022, Sawant and Thakur 2015) to manage environmental and operational risks effectively paving the way for safer mining practices. This study thus is an example of balancing the demand for iron ore with the crucial responsibility of ensuring environmental and operational safety, paving the way for a more sustainable future for the mining industry. However, it is crucial to acknowledge the potential limitations of increased heights, such as heightened vulnerability during extreme weather events (Hawley and Cunning 2017b) and is a limitation which can be addressed through robust drainage systems and continuous risk assessment (Das *et al*. 2022, Khatri *et al*. 2022). However, during a monitoring of over 3 years, the slopes have stabilized and no failure could be recorded.

This study demonstrated that dump slopes can be re-evaluated to optimize these to create space for dumping of the waste material. This can be achieved, as demonstrated, with the help of evaluation of FoS and its careful evaluation using standard methods of analysis and simulation such as limit equilibrium method.

5. Conclusions

A comprehensive analysis of the dump slopes of an iron ore mine in India was performed through standard methods in which data of an iron ore mines, geological information, soil sample collection of the dumps, laboratory investigations of the geotechnical properties of the samples and was used to model FoS through using limit equilibrium method. The FoS of the slopes revealed varying values for different sections of the dump. The higher values of the FoS presented an opportunity to increase the bench height and slope angle. The following observations were made

- The pre-modification analyzed sections 250° N, 350° N and 400° N demonstrated stable configurations, complying with Indian regulations.
- Moderate increases in dump heights were found feasible in IOM, offering potential efficiency gains.

The sections where FoS was found to be high were further numerically simulated with modified bench configurations of bench height, width, and angle. The results were implemented in the field and the dump benches were monitored over a period of three years. It was observed that there was no failure of the dump slopes during the monitoring period. This provided a solution for the optimization of the slopes studied. In addition, a significant area of 1.01 hectare with additional dumping capacity of 1.16 MT of waste material could be created. The findings lay a foundation for further improvements in similar types of slopes, particularly in iron ore mines, where space constraints hamper sustained mining. The limitations of excessive rain that is characteristic of the area can be addressed by effective drainage systems. The properties of soil are within a small range and hence restrict evaluation of certain statistical parameters.

Acknowledgements

This work is a part of the Ph.D. thesis of the first author. The authors express gratitude to the Director, IIT-ISM Dhanbad and the Director, CSIR-CIMFR for their approvals to publish. Thanks are due to Mr. Vivek Iyer for his help. We are also thankful to the mine management for their help which was instrumental in facilitating the research activities necessary for the successful completion of this research work.

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