

Scientific Study on Embankment Design, Barrier Adequacy, and Slope Stability for Motaghat Nallah in Chandrapur Mining Region

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Abstract— A detailed geotechnical assessment was performed at the Padmapur Opencast Mine in Chandrapur to examine embankment design, barrier sufficiency, and slope stability concerning Motaghat Nallah and Sector III. The fieldwork involved drilling three boreholes to a depth of 50 meters, conducting standard penetration tests, in-situ permeability tests, and collecting soil samples systematically. Laboratory analyses, including grain size distribution, Atterberg limits, free swell index, natural moisture content, bulk density, and direct shear tests, were carried out following Bureau of Indian Standards specifications. The underground geological formation was mainly characterized by medium-grained sandstone interlayered with coal seams, with no observable groundwater table. Slope stability assessments, employing the Limit Equilibrium Method with Bishop's algorithm, revealed a Factor of Safety of 1.81 under existing conditions, decreasing to 1.6 under a critical scenario involving the extraction of a 50-meter coal seam and a submerged embankment up to Reduced Level 180 m. These findings validate that a minimum barrier width of 120 meters at RL 169.20 m is sufficient for stability, provided water levels are maintained below RL 170 m. The study offers crucial design recommendations for benching, slope monitoring, and barrier adequacy, thereby promoting safer and more sustainable opencast mining practices.

Keywords— Soil Investigations, embankment, design, mining, Slope stability.

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thickness in relation to the Motaghat Nallah and Sector III concerning the Padmapur Opencast Mine within the Chandrapur Area, WCL.

As part of this endeavor, Rajiv Gandhi College of Engineering, Research and Technology, Chandrapur, was entrusted with conducting the requisite geotechnical investigations to ascertain the essential geotechnical parameters mandated by the client, WCL.

I. INTRODUCTION

Western Coalfields Limited, situated in Chandrapur, initiated a scientific investigation focused on the engineering design and construction of an embankment along the Motaghat Nallah and Sector III. This study also sought to evaluate the adequacy of the barrier

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RG CER&T successfully completed comprehensive geotechnical investigations across three borehole locations. The precise test locations and investigation depths were determined by the research team. In-situ testing included Standard Penetration Tests and field permeability tests. Additionally, both disturbed and undisturbed soil samples were meticulously collected from these boreholes for subsequent laboratory analysis. All laboratory testing procedures strictly adhered to the guidelines stipulated by the Bureau of Indian Standards codes. These comprehensive analyses aimed to characterize the subsurface. The geotechnical study is crucial for preventing potential hazards like slope failure, which are common in mining areas [1].

For the slope stability analysis, the Limit Equilibrium Method was employed, and the critical cross-section chosen for modeling was established based on the actual mine profiles. This methodology is not only widely recognized but also considered the most common and robust design tool for comprehensively assessing slope stability in opencast mining environments [2]. The analysis incorporated seven finite slope stability methods, including Morgenstern-Price, Spencer, Sarma, Bishop, Janbu, and ordinary methods, utilizing GeoSlope software to evaluate the dump slope in the Makardhokara site [3].

II. LITERATURE REVIEW

The efficacy of such approaches is further enhanced when considering the impact of mine floor inclination on the stability of backfilled dumps, as highlighted by prior research [2]. Moreover, the integration of advanced computational modeling, such as probabilistic analysis based on Limit Equilibrium and Finite Element Method-based shear strength reduction, provides a more comprehensive determination of the safe overall slope angle against circular failure, especially when considering complex geological conditions [4]. These methods are crucial for predicting and mitigating risks associated with dump failures, which are frequently reported due to improper dump

geometries in mining regions [3]. Furthermore, understanding the bearing capacity of subsurface strata is essential to ensure the stability of disposal embankments, as inadequate foundational support can significantly contribute to structural failures [1]. The subsurface strata at the Padmapur Opencast Mine primarily consist of medium-grained sandstones interbedded with coal seams, with no groundwater table identified, which influences the foundational support for such structures [5]. Given these geological conditions, detailed analysis of the sandstone's mechanical properties, including uniaxial compressive strength and elastic moduli, becomes imperative for accurate embankment design. Such detailed analyses are critical for validating the proposed embankment designs and ensuring long-term stability against potential failures [6]. The consideration of local basement replacement has also been shown to be effective in stabilizing dump slopes, particularly for those susceptible to landslides associated with cutting layers, bedding layers, and swelling [7]. This strategy can be particularly relevant in regions with soft soil basements, where specialized control methodologies are needed to enhance overall stability [7]. The probabilistic slope stability analysis, accounting for spatially variable geotechnical properties of municipal solid waste or waste rock, further refines these stability assessments by incorporating uncertainty into material parameters, leading to more robust and reliable designs for landfill slopes and mine waste dumps [8]. This comprehensive approach ensures that design considerations extend beyond conventional stability analyses to encompass the intricate interplay of geological, hydrological, and geotechnical factors [9] [7].

III. METHODOLOGY

The careful selection of methods for assessing slope stability is paramount, especially considering the intrinsic variability and diverse mechanical characteristics of post-mining waste materials [8], [10]. This necessitates the deployment of a broad spectrum of techniques,

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spanning from empirical estimations to sophisticated numerical simulations, to accurately evaluate the stability of waste dumps [11]. For example, a more thorough assessment can be achieved through integrated probabilistic analyses that combine the Limit Equilibrium and Finite Element Method-based shear strength reduction, particularly when dealing with intricate geological conditions and spatially variable geotechnical properties [4], [8], [9]. These rigorous analyses are vital not only for protecting operational staff and machinery but also for reducing risks such as landslides to nearby communities [7], [11], thereby averting common problems like dump failures stemming from inadequate geometries [3] and ensuring enduring stability [6]. Consequently, the amalgamation of extensive geotechnical investigations with these advanced stability analyses is essential for effective risk mitigation and fostering sustainable mining operations [5].

A. Scope of Services

The scope of services, as delineated by the work order, encompasses the following key activities:

- i) The meticulous collection of both disturbed and undisturbed soil samples from three distinct borehole locations and along the embankment slopes.
- ii) The execution of standard penetration tests and field permeability assessments within the boreholes.
- iii) The conduction of pertinent laboratory analyses on the retrieved soil samples.
- iv) The comprehensive preparation and submission of a geotechnical investigation report.

B. Slope Stability Acceptability Criterion

The phrase "Factor of Safety" is often used to refer to the acceptance requirement for stable slopes. The FoS is the ratio of capacity to demand. The value of the FoS is a deterministic expression that is utilised to communicate between the designer, practitioner, and law enforcement agency. A slope profile with a higher FoS is more likely to survive longer. However, the FoS does not always correspond

with the longevity of a slope profile. The design load shall be constant, and the slope profile should react similarly for applicability of the FOS criterion. A FoS number provides a rapid indication of the degree of confidence in design safety margins. However, acceptance of a FoS must be based on the possibility of repercussions, exposure, and preparation to monitor changes in slope conditions.

The most recent DGMS technical circular No. 2 of 2020 emphasizes the need of scientific research in developing a thorough design, implementation, and monitoring strategy for each open pit mine operator with the following major design aim.

The Minimum Factor of Safety that must be considered when designing a pit, bench, or dump slope should in no instance be less than 1.50 for permanent or long-standing slopes and 1.30 for all other slopes.

While the DGMS technical circular specifies a minimum Factor of Safety of 1.30 for short-term slopes, such as those associated with the planned 50m coal seam extraction, the inherent risks warrant a more conservative approach. Specifically, the potential for the embankment to involve water filling up to a 185m RL presents significant stability challenges. Consequently, to account for these elevated risks and ensure enhanced safety margins, an acceptable FoS criterion of 1.65 has been adopted for this study.

C. Geology of Chandrapur

General Geology

The Chandrapur district is occupied by varied rock formations. Geologically, the Chandrapur region is characterized by a diverse range of stratigraphic units, extending from the Archaean Eon to recent alluvium and laterites. The district possesses significant deposits of various minerals, including coal and iron. Historically, this mineral wealth has contributed approximately 29% of the state's total mineral production value.

To comprehensively understand the geotechnical characteristics and potential stability challenges

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within the region, the detailed geological sequence of formations is presented below:

TABLE I
GEOLOGICAL SEQUENCE OF FORMATIONS

Age	Formation	Lithology
Recent to Sub-recent	Alluvium, Soils, Laterites	Sand, Clay, Silt
Lower Eocene to Upper Cretaceous	Deccan Traps	Basalts, medium-grained, vesicular and massive basalts
Triassic	Upper Gondwanas group: Maleri Formation	Clay, Shales, Sandstones
Lower Triassic to Upper Carboniferous	Lower Gondwanas group: Kamthi, Barakar, Talchir	Kamthi Formation: Reddish-brown sandstone, shale, clay; Barakar Formation: Light grey to white feldspathic sandstones, coal seams, clay; Talchir Formation: Greenish to dark olive green shales, coarse-grained sandstones.
Pre-Cambrian	Vindhyan	Shales, Sandstones, flaggy and massive limestones and sandstones of variegated colours
Archaean	Crystalline and older metamorphic rocks	Gneisses, quartzites, schists with acidic and basic intrusives.

D. Seismicity

India's seismic hazard map, updated by the Bureau of Indian Standards in 2000, indicates that the study area and its surroundings are seismically active and fall within Seismic Zone III. The tectonic characteristics of this region are deemed capable of generating earthquakes of moderate intensity.



Fig.. 1: India's seismic hazard map, updated by the Bureau of Indian Standards in 2000, indicates that the study area and its surroundings are seismically active and fall within

IV. SUB-SOIL PROFILE

A comprehensive characterization of the sub-surface profile is essential for comprehending the prevailing subsurface conditions and guiding subsequent geotechnical analyses. The generalized soil profile, derived from samples obtained at designated borehole locations and subjected to laboratory testing, is presented below.

A. Borehole No. 1

At Borehole No. 1, medium-grained yellow sandstone was identified from the surface to a depth of 6.00 m from the existing ground level. This was underlain by a 3.00 m thick stratum of medium-grained reddish sandstone, extending to 9.00 m EGL. Subsequently, another 3.00 m thick layer of medium-grained yellow sandstone was observed, reaching 12.00 m EGL. A 9.00 m thick layer of medium-grained reddish sandstone followed, found up to 21.00 m EGL. Below this, a 3.00 m thick layer of medium-grained sandstone with breccias was encountered, extending to 24.00 m EGL. A 1.50 m thick layer of medium-grained reddish sandstone was then present, reaching 25.50 m EGL. The deepest stratum, up to 50.00 m EGL, consisted of a 24.50 m thick sequence of coal seams. No groundwater table was detected during the investigation.

B. Borehole No. 2

Borehole No. 2 revealed medium-grained yellow sandstone from the surface to 9.00 m EGL. Beneath this, a substantial 41.00 m thick layer of grayish medium-grained sandstone was identified, extending to a total depth of 50.00 m EGL. No groundwater table was observed during the investigation.

C. Borehole No. 3

In Borehole No. 3, medium-grained yellow sandstone was initially found from the surface to 6.00 m EGL. This was succeeded by a 1.50 m thick layer of medium-grained grayish sandstone, extending to 7.50 m EGL. A 7.50 m thick layer

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of medium-grained yellow sandstone was then encountered, reaching 15.00 m EGL, followed by another 7.50 m thick layer of medium-grained grayish sandstone up to 22.50 m EGL. A 1.50 m thick coal layer was identified next, extending to 24.00 m EGL. Subsequently, a 1.50 m thick layer of highly fractured jointed gneiss was found, reaching 25.50 m EGL. The deepest stratum, up to 50.00 m EGL, comprised a 24.50 m thick layer of fine-grained to medium-grained grayish sandstone. No groundwater table was encountered at the time of investigation.[1]–[8]

V. INVESTIGATIONS

The investigative activities encompassed both field and laboratory testing phases, as detailed below.

A. Field Tests

1) Drilling Operations

Boring was conducted utilizing the rotary wash method with a double-tube core barrel. These operations were performed in general accordance with IS: 1892-1979. Comprehensive borelogs are provided in Annexure-1, Sheet Nos. 1 to 6, of this report.

2) Standard Penetration Test

The Standard Penetration Test quantifies penetration resistance, denoted as the N-value, representing the number of blows required for a 30 cm penetration of a split spoon sampler.

3) Collection and Preservation of Disturbed Soil Samples from Boreholes and Embankment Slopes

Disturbed soil samples were collected and sealed for subsequent laboratory analyses. These samples were transported to the laboratory with meticulous care and stored appropriately. Further testing was then conducted on the preserved samples. Please note that representative soil samples will be retained for a period of three months from the date of this report; any inquiries regarding these samples should be raised within this timeframe.

4) Groundwater Table

No groundwater table was observed at the investigated test locations during the field assessment.

5) Field Permeability Test

Field permeability tests were performed using the constant head method with a double packer system in clayey-sandy soil strata. The permeability values were calculated based on the methodology prescribed by the Maharashtra Engineering Research Institute – Nashik, with results presented in Annexure: III, Sheet Nos. 1-6.

$$Y = \frac{10 \times \text{water loss (in liters)}}{\text{Test depth} \times \text{time (min.)} \times \text{Pressure}} = 1.3 \times 10^{-5} \frac{\text{cm}}{\text{sec}}$$

B. Laboratory Tests

1) Grain Size Analysis

In the laboratory, the collected soil samples underwent grain size analysis for classification purposes. A summary of these analyses is presented in Annexure II, Sheet No. 1, of this report.

2) Atterberg Limits, Free Swell Index, Natural Moisture Content, and Classification

Tests for liquid limit, plastic limit, plasticity index, natural moisture content, and free swell index were conducted on the soil samples. The classification of these soils was performed in accordance with IS: 1498, and a summary of the results is provided in Annexure II, Sheet No. 1, of this report.

3) Direct Shear Test

Unconsolidated Undrained Direct Shear Tests were performed on undisturbed soil samples to determine the cohesion (C) and angle of internal friction parameters.

This section presents the key findings derived from the systematic review and empirical data analysis, highlighting advancements in energy-efficient and green infrastructure. These findings will be categorized and discussed to elucidate current trends, identify successful implementations, and pinpoint areas requiring further research and development. For instance, digital transformation in Russia's transport sector, a domain ripe for smart and sustainable innovations, integrates cutting-edge information

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technologies to boost efficiency and environmental stewardship [66]. Further, the application of sophisticated decision-making methodologies, such as quantitative SWOT analysis integrated with multi-criteria decision models, provides a robust framework for selecting optimal eco-materials in civil engineering projects

Slope stability analysis was performed using the STABL FOR WINDOWS software, a widely recognized program based on established and validated limit equilibrium methodologies. All input parameters were specified in SI units (length in meters, cohesion in kPa, and density in kN/m). The Bishop Method, which accounts for multiple circular slip surfaces, constituted the analytical framework for these calculations.[9] To enhance the robustness and reliability of the results, the number of initiation and surface points for each circular failure profile was progressively increased from an initial 10, 10 to 50, 50, while simultaneously reducing the profile segment length from 40 to 1. This procedural refinement substantially increased the iterative search for critical failure profiles, thereby improving the confidence in the derived factors of safety. The foundational simulation model was meticulously developed using actual surface profile data, precisely surveyed by mine management, and incorporated an estimated water level at RL 150m. Additionally, a "worst-case scenario" model was established to assess stability under the most adverse plausible conditions, simulating an embankment filled to RL 187.4m with 50m of coal mining. Notably, the phreatic surface was deliberately omitted from the analysis. This decision was strongly supported by comprehensive field investigations that detected no groundwater and further substantiated by the absence of reported seepage under fully submerged conditions during previous rainy seasons. The complete range of input parameters employed in these analyses is

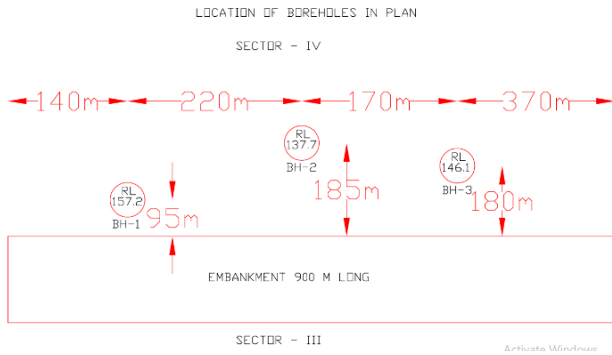


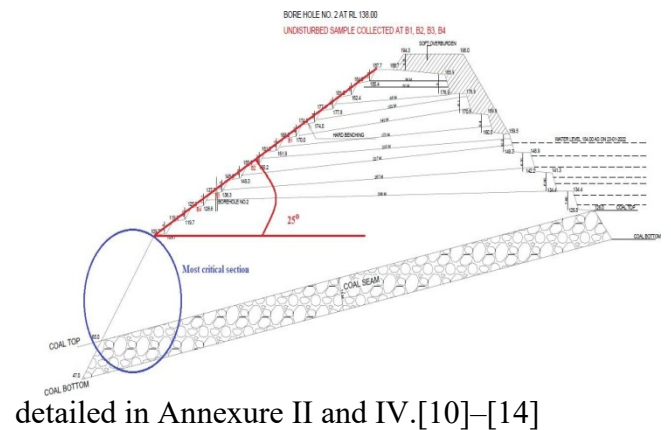
Fig.. 2: Locations of Boreholes

VI. RESULT & ANALYSIS

The slope stability analysis yielded critical strength reduction factors, shear strains, and total displacements, providing crucial insights into potential failure mechanisms [12]. These findings are pivotal for informing robust embankment design and barrier adequacy assessments to ensure long-term stability within the mining region [13] [6] [14]. Specifically, the application of the Bishop Circular Failure algorithm within the Limit Equilibrium Method demonstrated a Factor of Safety of 1.81 for the overall slope section in the basic simulation model. Furthermore, considering the "worst-case scenario" with an embankment filled to RL 187.4m and 50m of coal mining, the calculated Factor of Safety provided a lower bound for stability under extreme loading conditions.

A. Slope Stability Analysis

1) Model Preparation



detailed in Annexure II and IV.[10]–[14]

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Fig.3 - Typical section for slope stability analysis

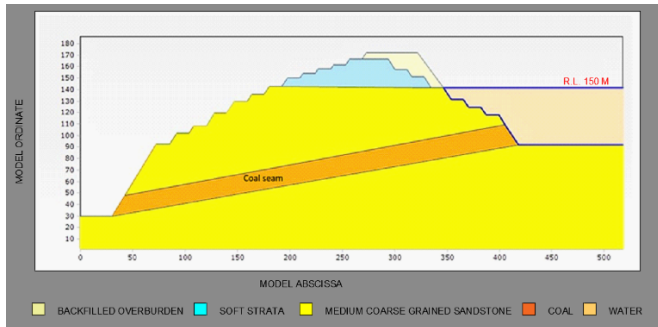


Fig.4 – Basic Simulation Model 1

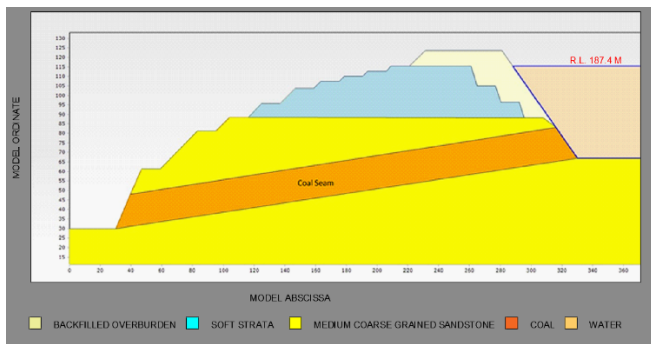


Fig.5 – Model 2 for Analysis of after 50m extraction of the coal seam with submerged embankment

2) Analysis

The analysis by Limit Equilibrium Method using Bishop Circular Failure algorithm showed that the model 1 has the Factor of Safety, $FoS = 1.81$ for the overall slope section wherein the individual lift of pit carries $FoS = 1.78$ (Fig.6 and Fig.7). These higher FoS values are consistent with the field behaviour of the pit slopes those are standing firm with a long-term perspective even under full embankment load condition. These FoS values are much higher than the suggested long-term $FoS = 1.6$.

The Model-2 also showed $FoS = 1.6$ for the critical failure profile after 50m wide coal seam extraction for the overall slope section under submerged embankment to the water level at RL 180m. The individual pit lifts have the FoS as $FoS = 1.61$ with the height of water (Fig.8 and 9) but the reduction of water level to 170m results into $FoS = 1.66$ (Fig.10). The results indicate that the mine shall be cautious when the water level in the embankment crosses 170m RL and they shall not continue with the coal extraction.

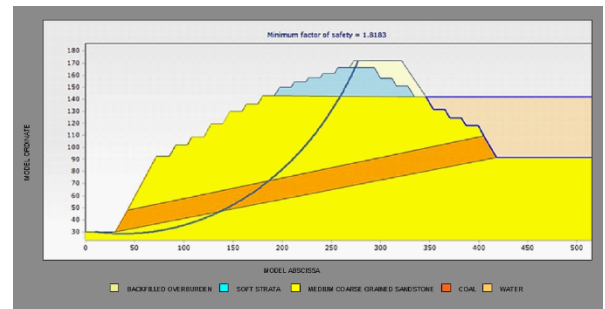


Fig.6 – FoS for Overall pit Angle of Coal and Sandstone (Overall Slope with $FoS 1.81$ without water pressure)

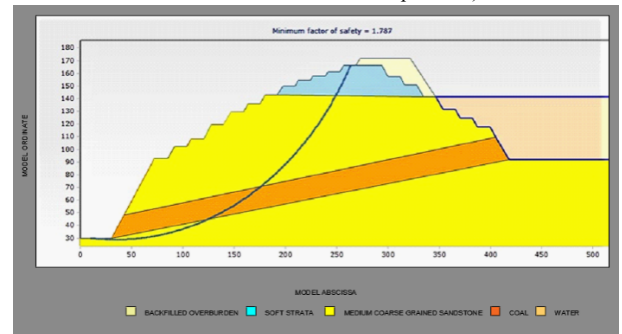
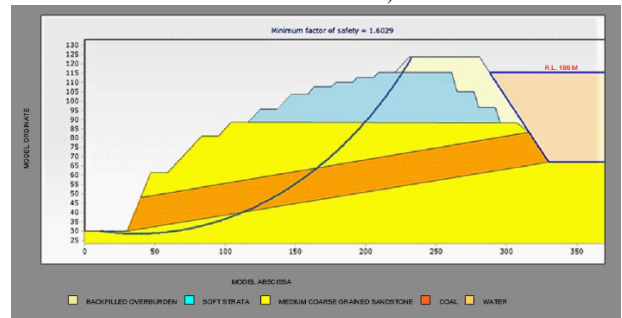


Fig.7 – FoS for Individual 3 Lift of Coal and Sandstone (Individual Lift of Pit with $FoS 1.78$)



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Fig. 8 – FoS for Overall Pit after 50 m wide coal extraction with submerged embankment up to 180m RL

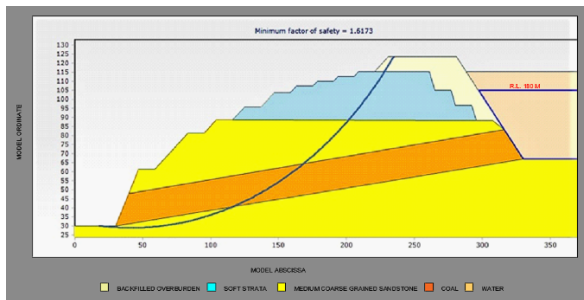


Fig.9– FoS for Individual Pit after 50 m wide coal extraction with submerged embankment up to 180m RL

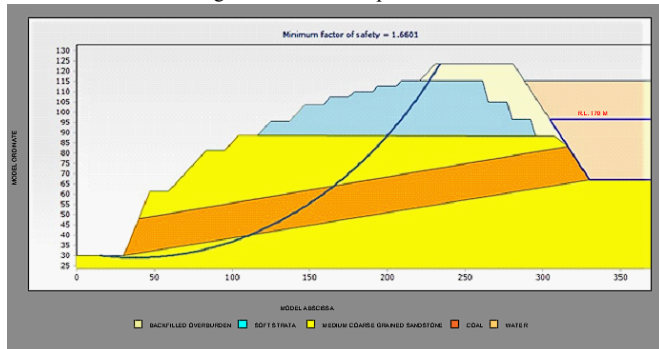


Fig.10 – FoS for Overall Pit after 50 m wide coal extraction with submerged embankment up to 170m RL

TABLE II
RELATED WORKS TABLE DESIGN PARAMETERS FOR MINING SLOPE

Sr. No.	Types of materials	Maximum height (m)	Maximum Slope angle (°)	Minimum Bench Width (m)	Overall slope angle (in benches) °
1	Soft Soil	3	45	9	14
2	Coal	10	70	10	30
3	Hard Rock	10	70	10	28

VII. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

The following is concluded based on field tests conducted at the Padmapur Opencast Mine Chandrapur and laboratory tests conducted at RCERT, Chandrapur.

1. The boreholes made for the investigations had found sandstone as the main rock massive above the coal seam. The boreholes were

drilled up to the coal seam and had the depth more than 25m in all cases.

2. No water was found in the boreholes during drilling. It is also reported that there was no seepage when the embankment was submerged in the last rainy season up to the height of 185m RL.

3. The sandstone has an average cohesion as 10 kPa and Angle of Friction as 30°.

4. The limit equilibrium method of slope stability analysis using Bishop Method of Algorithm showed that the mine at the present condition has Factor of Safety, FOS > 1.8 for the overall pit slope profile with water level up to 145m RL.

5. The limit equilibrium method analysis showed that the mine will have a Factor of Safety, 1.6173 after 50m coal seam extraction with submerged embankment upto 170m RL. Mining works execute at the minimum FOS = 1.5. (Fig.9)

B. Recommendations

The following is concluded based on field tests conducted at the Padmapur Opencast Mine Chandrapur and laboratory tests conducted at RCERT, Chandrapur.

1. The Total barrier width at 169.20 m RL (Top of Hard Strata) as per section provided shall not be less than 120m between Sector III and Sector IV as shown in Fig. no. 11

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2. The mine can extract coal by having benching of 3m height & 9m width with maximum Slope angle of 45° from surface RL to 169.20 m RL (soft strata) and benching of 10m height & 10m width with maximum slope angle of 51.34° from 169.20 m RL to coal top RL (hard strata) as shown in Fig.. 12 in Sector IV provided the water level in Sector III never rises beyondto 170.00 m RL.
3. The mine shall carry out regular slope monitoring by using Total Station and Visual Monitoring Regularly.
4. The blasting operation shall be carried out in such a manner that anyBench pit shall not Slide down.
5. The present average 25.00m top width of embankment between sector III & IV shall be maintained.

6. The mine shall abide with all statutory directives issued time to time.

C. Disclaimer

1. This study and the conclusions there from are solely based on the conditions of the embankment on the dates of inspection. All the observations and predictions are therefore, dependent upon the then embankment structure. The authors shall not be responsible for any consequences arising out of any tinkering with the existing embankment structure and the

resultant changes in the structural stability of the latter for which the this report will not be supportive.

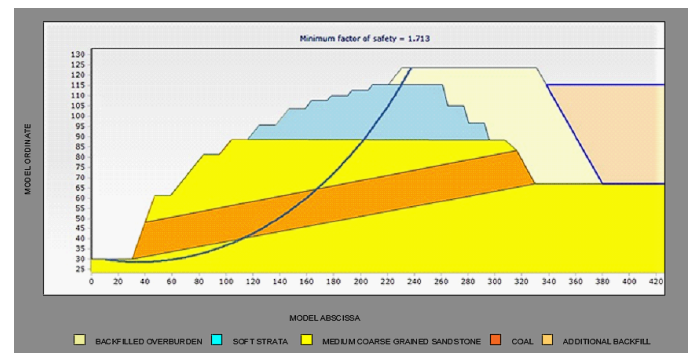


Fig.11 – FoS for Overall Pitafter 50 m wide coal extraction with submerged embankment up to 180m RL and 50m additional backfill

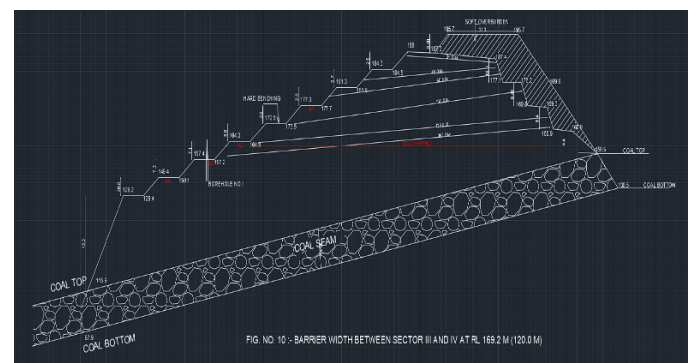


Fig. 12 – Barrier Width at RL 169.20 m between sector III and IV (120.0 m)

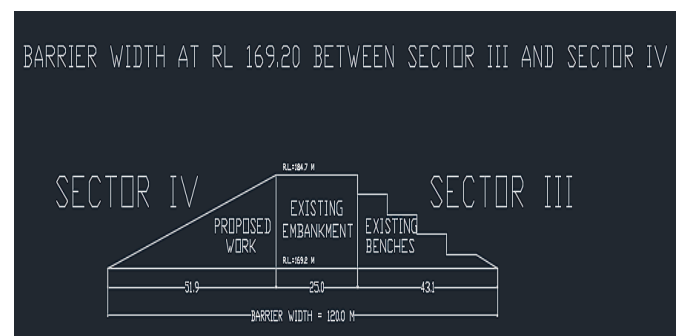


Fig. 13 – Proposed Barrier Width at RL 169.20 M

D. Design of Benches

As per the Tests on field and at laboratory, the design of Benches is as shown in Fig. no. 12 and Table No.03 (As per Work order No. 432/4674 Dated 25-10-2021).

TABLE III
PROPOSED DESIGN PARAMETERS FOR MINING SLOPES

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Sr. No.	Types of materials	Maximum height (m)	Maximum Slope angle (°)	Minimum Bench Width (m)	Overall slope angle (in benches) °
1	Soft Soil	3	45	9	14.44
2	Medium Coarse Sandstone	10	51.34	10	27.49

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