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Contents
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A Saga of Success towards Sustainable Mining: Concurrent Fly-Ash Filling in the Mine Void- A Case Study of JPL Mines

Om Prakash*

ABSTRACT

The rapid increase in coal consumption in India's thermal power plants—from 489 million tonnes (MT) in 2014 to 859.25 MT in 2023–24—has led to a substantial rise in fly ash generation, currently at approximately 304.78 million tonnes per year, despite an average utilization rate of 85–90%. Over time, more than 1,670 million tonnes of fly ash have accumulated, posing serious environmental challenges. The unutilized fraction of fly ash is expected to grow by 30–35 million tonnes annually, requiring 48–56 hectares of fresh land every year considering 1.6 hectares land per million tonne of fly ash disposal. Currently, 413 coal mines, covering a total lease area of 210,000 hectares, are operational in India, of which 228 are opencast. Considering that approximately 30% of an opencast coal mine area is decoaled, about 35,000 hectares of mine voids could potentially be concurrently backfilled with unutilized fly ash annually. This strategy of using fly ash to fill mine voids not only addresses the environmental issues associated with massive fly ash accumulation but also promotes sustainable development by reducing the risk of harmful impacts such as heavy metal leaching and fine particle emissions. M/s Jindal Power Limited (JPL) has pioneered a method that not only helps mitigate the environmental footprint of coal combustion but also promotes the circular economy by recycling industrial waste in a productive manner as land fill for reclamation of mine voids.

Keywords: Fly ash accumulation, Concurrent Backfilling, Mine Voids, Reclamation, Environmental footprint

INTRODUCTION

India's rapid economic growth has positioned it as the fifth-largest economy in the world by GDP. This unprecedented development has resulted in an escalating demand for energy, a key driver of progress. The National Electricity Policy aims to provide universal access to electricity, with a target of increasing per capita consumption to 1,395 kWh by FY24, up from 883.6 kWh in FY12 (and just 18.2 kWh in 1950). Alongside this growing demand, India's installed generation capacity has surged from a modest 1.4 GW at the time of Independence to an impressive 446 GW in 2024. Thermal power generation remains a cornerstone of India's energy mix, contributing 243 GW to the total capacity, with 211 GW coming from coal-based power generation.

India holds the world's fifth-largest coal reserves, ranking second in global coal production and consumption. As coal plays a central role in India's energy infrastructure, its consumption in power plants has escalated, rising from 489.4 million tonnes (MT) in 2014 to 859.24 MT in 2023-24. However, the burning of coal results in the generation of fly ash—a by-product that presents a significant environmental challenge.

Annually, approximately 305 MT of fly ash is produced in India. This massive volume of fly ash, if not managed properly, can have severe environmental consequences. The gross under-utilization of fly ash has led to the accumulation of over 1,670 million tonnes, according to the "Summary of Ash Generation and Utilisation" report compiled by the Joint Committee appointed by the National Green Tribunal (NGT) for the period 2020-2021. The increasing stockpile of fly ash necessitates immediate action to find sustainable, innovative solutions for its management and disposal.

Jindal Power Ltd (JPL) operates a 3,400 MW power plant at Tamnar, located in the heart of the coal-rich Mand-Raigarh coalfield. The plant is strategically positioned near the Gare Palma Coal Mine (IV/1 and IV/2 & 3 Coal Mines), which has provided JPL with a unique opportunity to address the two concerns- raw material security & fly ash disposal.

Recognizing the limitations of conventional fly ash disposal methods—such as brick production and low-lying

**CEO-Mining Business JPL*

landfills—JPL took a step toward more sustainable waste management by returning fly ash to its source: the mine voids from which the coal was extracted. In January 2009, JPL submitted a proposal to the Directorate General of Mines Safety (DGMS) for the experimental disposal of fly ash into mine voids, in combination with overburden (OB) material. This initiative was driven by the realization that using mined-out pits for backfilling could significantly mitigate the environmental impact of fly ash accumulation while contributing to the rehabilitation of mined land.

In collaboration with the CSIR-Central Institute of Mining and Fuel Research (CSIR-CIMFR) in Dhanbad, JPL conducted scientific studies to assess the stability of mine slopes when fly ash was mixed with OB material. Initial tests mixed 8% fly ash with OB, resulting in successful slope stability. This led to JPL becoming the first company to receive DGMS approval on October 7, 2009, for the backfilling of fly ash into mine voids as part of a comprehensive mine rehabilitation strategy.

Fig. 1: Fly Ash Backfilling and Plantation on Ash Filled Dumps at JPL Mines

Building on the success of this initiative, subsequent studies expanded the fly ash content to 25% in the OB mixture, further optimizing the backfilling process and leading to revised permissions. By October 2009, JPL began the operational backfilling of fly ash generated from its power plant into its captive coal mines (GP IV/2 & IV/3), marking a major milestone in fly ash disposal practices. Additionally, JSPL's Dongamahua Captive Power Plant, which was designed without an ash pond, adopted a similar approach by backfilling fly ash into its own captive mines (GP IV/1). This solution not only adheres to the statutory Fly Ash Notification of 2009 but also exemplifies JPL's commitment to environmental stewardship and compliance with national standards.

FLY ASH COMPOSITION AND ITS IMPACT

Fly ash refers to the fine particulate matter generated during the combustion of coal in power plants, encompassing various forms such as Electrostatic Precipitator (ESP) ash, dry fly ash, bottom ash, pond ash, and mound ash. The composition of fly ash is primarily made up of significant quantities of silicon dioxide (SiO_2), aluminium oxide (Al_2O_3), and calcium oxide (CaO). These compounds, along with the presence of toxic heavy metals, pose serious environmental and health risks.

Fly ash particles are known to be harmful air pollutants, containing trace amounts of heavy metals like arsenic, lead, and mercury. These metals can lead to severe health issues, including heart disease, cancer, respiratory illnesses, and stroke. Additionally, when fly ash interacts with water, it can cause the leaching of heavy metals into groundwater, contaminating drinking water sources. This contamination can also adversely affect soil quality, disrupting the root development systems of plants and trees, thereby impacting agricultural productivity and ecosystem health.

FLY ASH DISPOSAL & GUIDELINES

Fly ash, a by-product of coal combustion in thermal power plants, is collected through electrostatic precipitators (ESPs) to reduce fugitive dust emissions. The collected ash is often converted into a wet slurry and transported via pipelines to designated ash ponds. These ponds, however, require large land areas for accommodation and pose significant environmental risks. In cases of failure, these ponds can collapse, leading to flooding of fly ash into agricultural fields, causing substantial loss of life, property, and land productivity.

Fly ash finds utilization in several industries, such as cement manufacturing, ready-mix concrete production, road construction, and the filling of low-lying areas. As per the Central Electricity Authority (CEA), the breakdown of fly ash utilization is as follows: **Cement Manufacturing:** 47.81%, **Low Land Filling:** 15.59%, **Bricks & Tiles:** 12.89%, **Road Construction:** 15.04%, **Ash Dyke Raising:** 7.94%, **Mine Backfilling:** 6.20%

While these applications demonstrate some level of fly ash utilization, its use in mine backfilling remains relatively underutilized.

To mitigate the environmental impact of fly ash disposal and reduce the need for large land areas for ash ponds, the Ministry of Environment, Forest and Climate Change (MoEFCC) has issued a series of notifications to regulate and encourage the use of fly ash. The first such notification was issued on September 14, 1999, and was amended in 2003, 2009, and 2016. The 2009 amendment established a phased approach for achieving 100% fly ash utilization across all coal- and lignite-based thermal power stations in India.

MoEFCC notification dated December 31, 2021 further refined the targets and strategies for fly ash utilization. The amendment issued on December 30, 2022 and January, 1 2024 introduced additional measures to enhance the implementation of these guidelines, encouraging industries to increase fly ash use in diverse sectors, including mining.

Method of Fly Ash Dumping:

Broad Guidelines of dumping fly ash in mine as implemented by JPL are as below:

The fly ash shall be dumped in alternate layers or stages, with each layer not exceeding a height of 5 meters.

Initially, a series of overburden (OB) dumps, each not less than 15 meters in width, shall be placed around the designated ash dump area. These OB dumps shall be constructed to a height of up to 5 meters. Multiple such areas shall be created in layers or stages, with each fly ash dump separated by a 15-meter-wide OB dump.

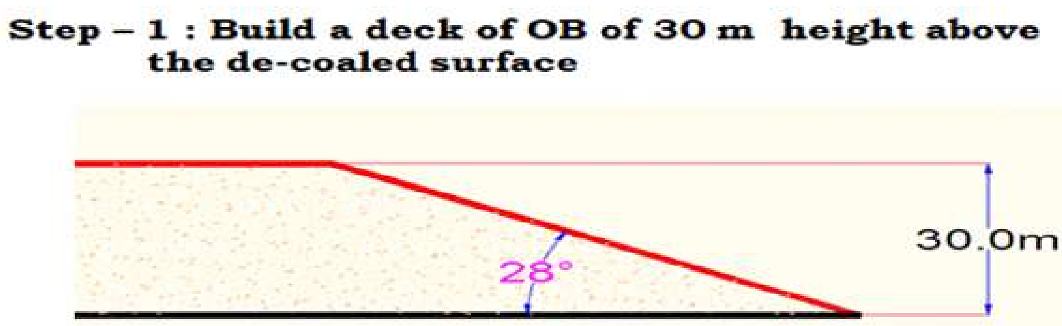

Figure 2: Deck Preparation

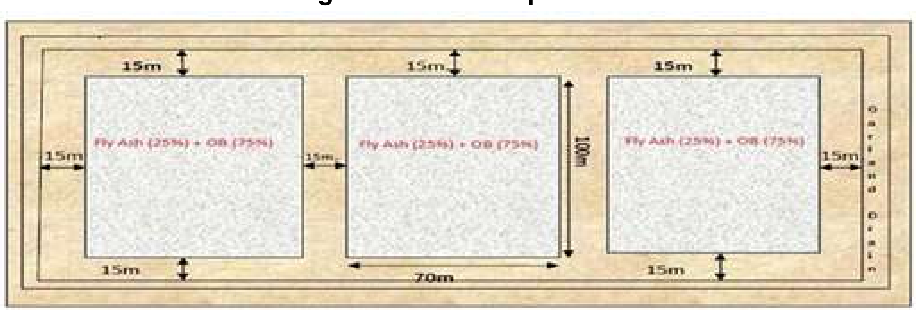

Figure 4: Methodology of Fly Ash Dumping at GP-IV/1 (Section Showing Methodology of Fly Ash Dumping)

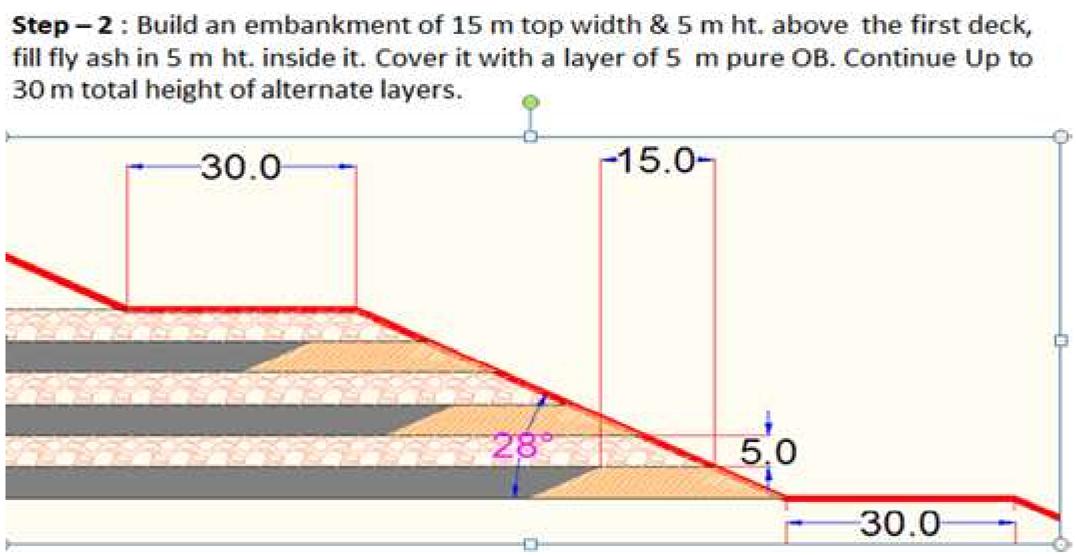

Figure 3: Embankment Preparation

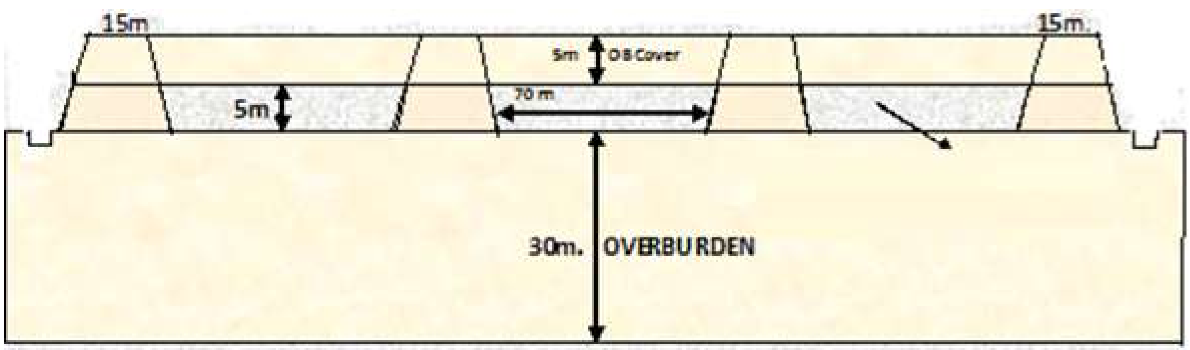

Figure 5: Section View of Fly Ash Dumping

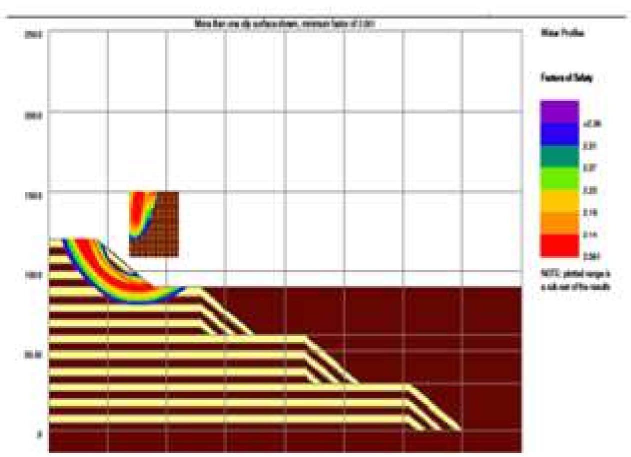

Figure 6: Slope Stability Analysis (Alternate Layers of OB & OB+Fly Ash) with Bench Angle 32 Degrees

Following the initial phase, a mixture of coal combustion waste (CCW)—comprising 25% fly ash and overburden—shall be deposited within the area surrounded by the OB dumps. The deposition shall occur in 5-meter high layers, ensuring that each section contains both OB and fly ash. The maximum height of the fly ash and OB deck shall not exceed 30 meters, with a minimum distance of 30 meters between two consecutive decks.

Above the bottom layer, only overburden shall be dumped to ensure that the fly ash is fully covered and protected by the surrounding OB dumps.

In the same sequence as described above, alternate layers of OB and OB mixed with fly ash shall be dumped. Each layer shall be adequately compacted using dozers.

At the final stage, the top of the dump shall be covered with a 2-meter thick soil layer, which shall be compacted using dozers. To protect the area from rainfall, additional measures such as plantation, geosynthetics, or jute/coir reinforcement shall be implemented. Additionally, gully drains, toe walls, and peripheral drains shall be constructed as recommended by the scientific agency conducting the geotechnical study. These protective measures shall be periodically inspected to ensure their effectiveness.

A detailed plan and section, drawn to an appropriate scale (e.g., 1:2000), shall be maintained to show the layout of both external and internal dumps. The plan shall include the height of each deck, the distance between fly ash dumps, the distance from active working faces, plantation areas, gully drains, peripheral drains, and toe walls. The plan shall be signed by the surveyor and countersigned by the Mine Manager, as required by regulations.

A code of safe practices shall be developed for the transportation, dumping, and compaction of fly ash. This code shall include studies, methodologies, and the organization of the ash filling operation, which shall be documented and followed.

The entire fly ash dumping operation shall be overseen by an Assistant Manager holding a First Class Manager's Certificate of Competency. Each shift shall be supervised by an Assistant Manager/Under Manager with at least a Second Class Manager's Certificate of Competency, in addition to an Overman and Mining Sirdar who shall be exclusively responsible for the operation.

DUMP SLOPE MANAGEMENT

The sides of the overburden (OB) dumps shall be benched, with the height not exceeding 30 meters. The slope angle shall not exceed the angle of repose of the dumped material, or 28°, whichever is less.

The width of the OB dumps shall not be less than 40 meters and shall be adequately compacted. The benches shall be designed in such a way that the overall slope of the dump does not exceed 21° horizontally.

The toe of the OB dumps shall be protected or armored to prevent the runoff of sludge into the active mining faces.

A geotechnical study shall be conducted and continuously monitored to assess the stability of the dump. This monitoring shall be carried out throughout the dumping process and after completion, continuing until the mine is permanently closed.

Dust Control Measures

To prevent fly ash from becoming airborne, the fly ash dumps, including the OB dumps, shall be kept moist at all times. Additionally, the quality of the ash shall undergo chemical and physical testing at least once every four months to ensure it is free from silica and toxic dust. If harmful levels of these substances are detected, they shall be treated to bring them within safe limits.

SURFACE AND GROUNDWATER QUALITY CONTROL MEASURES

Surface and groundwater quality measurements shall be conducted quarterly in collaboration with the State Pollution Control Board (SPCB) and the Central Pollution Control Board (CPCB). These tests will ensure that no harmful heavy metals or other chemicals contaminate surface or groundwater resources in the area.

A scientific study and continuous monitoring shall be carried out by the CSIR-Central Institute of Mining and Fuel Research (CIMFR), Dhanbad, to assess the effectiveness of the above measures.

PROVISION OF CHECK DRAINS

Adequate check drains or garland drains, of sufficient width and cross-sectional design, shall be constructed around the OB dumps. These drains will ensure that sludge, waste materials, and ash do not flow into rivers, streams, or other surface water bodies.

PRECAUTIONS AGAINST POLLUTION OF AQUIFERS

It shall be ensured that fly ash is not directly dumped into the aquifers. Proper precautions shall be implemented to prevent any contamination of groundwater and aquifer systems.

A comprehensive hydrological study has been conducted to identify the presence of surface and groundwater streams, aquifers, and their interconnectivity. The study also recommends remedial measures, including a monitoring system and schedule to prevent potential contamination.

IMPACT ASSESSMENT ON FLORA, FAUNA, AQUATIC LIFE, HABITAT, WATER & AIR QUALITY

A scientific study conducted by CSIR-Central Institute of Mining and Fuel Research (CSIR-CIMFR), Dhanbad, evaluates the impact of fly ash backfilling on local flora, fauna, aquatic life, habitat quality, as well as water and air quality. This study is carried out both prior to and during the ash dumping process.

Jindal Power Ltd (JPL) has entrusted CSIR-CIMFR to perform ongoing analyses of air, soil, and water quality in and around the Gare Palma IV/1 Coal Mine on a quarterly basis. This ensures continuous monitoring of environmental parameters and helps in early detection of any adverse effects.

Study and Reports

Detailed study and reports, covering slope stability, surface and groundwater quality control, pollution prevention in aquifers, and impact assessments on flora, fauna, aquatic life, and habitat, as well as water and air quality, are conducted and documented on a quarterly basis.

A dedicated team has been formed at the mine level, responsible for overseeing the entire fly ash backfilling operation. This team is also tasked with conducting the required studies and maintaining all necessary records as per the prescribed guidelines.

A comprehensive risk analysis of the potential hazards arising from the fly ash filling operation has been conducted. This analysis is regularly reviewed to ensure that risks are managed effectively. Additionally, a Safety Management Plan, including control mechanisms, has been developed and implemented in compliance with DGMS (Tech) (S&T) Circular No. 13 of 2002.

In collaboration with CIMFR, JPL is also conducting advanced scientific studies on the backfilling of **coal washery rejects and steel plant slag, in combination with fly ash, in mine voids.** The studies aim to determine optimal mixing ratios with overburden material under different dump scenarios. This approach is expected to yield significant environmental and sustainability benefits, supporting the circular economy and further minimizing the ecological footprint of mining operations.

ADDITIONAL CONDITIONS APPLICABLE FOR FLY ASH DUMPING

The distance between the dump area and the working faces shall not be less than 100 meters to ensure safe operational practices and prevent potential interference with active mining activities.

The designated area for fly ash backfilling shall be clearly earmarked and marked on the project plan. Fly ash dumping shall be carried out strictly within this designated area to ensure organized and controlled disposal.

The height of each deck in the fly ash dump shall not exceed 30 meters. The total height of the fly ash dump shall be limited to a maximum of 90 meters, in accordance with safety and stability guidelines for dump construction.

The access road leading to the fly ash dump site shall be distinct and separate from the main haul road used for transporting overburden (OB) to the dump. This segregation ensures smooth operations and minimizes traffic congestion, reducing the risk of operational delays and safety hazards

Fig. 8: Plantation on Fly Ash Dumps

INDIA'S EVOLVING APPROACH TO FLY ASH MANAGEMENT

In a significant step towards environmental protection and optimal resource utilization, the Ministry of Coal (MoC) is actively driving initiatives to ensure the responsible disposal and repurposing of fly ash generated by thermal power plants (TPPs). By repurposing this by-product from coal-based power generation, the Ministry is paving the way for a more sustainable future, emphasizing environmental stewardship and fostering a circular economy.

As part of this forward-looking strategy, a total of 19 mines have been allocated to 13 TPPs. Standard Operating Procedures (SoPs) have been established to guide the safe and efficient utilization of fly ash through backfilling in mine voids, addressing both safety and administrative considerations. To encourage broader participation and ease the operational burden on mine owners, the following measures are recommended:

- **Mine Declaration and Volume Calculation:** Mine owners shall declare the available void space and the annual volume of fly ash that can be accommodated within the mine, along with an estimate of total ash accommodation over the life of the mine.

- **Modification of Mining and Closure Plans:** The Mining Plan and Mine Closure Plan must be updated in accordance with the MoC guidelines issued on May 29, 2020. The associated costs for these modifications shall be borne by the TPPs.
- **Stability and Safety Assessments:** A reputable institution must conduct studies on the stability of dump slopes before fly ash is dumped into mine voids. The costs for these studies shall be covered by the TPPs.
- **Cost of Reclamation and Fly Ash Filling:** The costs related to the filling of fly ash, as well as the reclamation of fly ash dumps, shall be borne by the TPPs.
- **Transporter Management and Compliance:** Transporters engaged for the transportation of fly ash shall be under the administrative control of the Mine Management. They must comply with CMR-109. Any transporter or truck operator failing to follow the instructions of the Mine Manager or established guidelines shall be suspended, following a warning issued by the Mine Management and communicated to the TPP management.
- **Training of Tipper Operators:** All tipper operators shall undergo training at the Mine's Vocational Training Centre (VTC) before entering the mine. This training, which will be provided at the TPP's expense, ensures compliance with CMR-63 (Duties of Truck, Tipper, and Dumper Operators).
- **Monitoring Manpower and Training:** The TPP shall bear the cost of additional manpower required to monitor fly ash dumping operations as per regulatory requirements. This personnel shall be trained under VTC rules and certified by the Mine Management.
- **Environmental and Hydrogeological Studies:** The TPPs shall cover the costs of scientific studies, including environmental monitoring and hydrogeological studies, to ensure comprehensive assessment and management of the fly ash disposal process.
- **Haul Road Construction and Maintenance:** The TPPs shall bear the cost of constructing and maintaining the designated haul road for transporting fly ash to the mine.
- **Roadworthiness and Compliance of Transport Vehicles:** All trucks used for fly ash disposal in the mine shall be inspected for roadworthiness, and must present a valid certificate of fitness for operation. Any vehicle found unfit for use on mine haul roads shall be immediately suspended. All operators and transporters must adhere to the established Traffic Rules, and vehicles must be equipped with GPS monitoring systems, the cost of which will be borne by the TPPs.

TECHNOLOGICAL IMPLEMENTATION AND INNOVATION

JPL is going to implement a slurry pipeline system to transport fly ash in slurry form to the mine site. The slurry, with a concentration of 73% fly ash and 27% water, has a density of 1.52 gm/cc. The slurry will be pumped through a 9-kilometer pipeline to the mine voids, where it will be discharged and compacted to create a stable backfill.

This high-density slurry pipeline system ensures the efficient transport of fly ash over long distances while minimizing the environmental risks associated with traditional transportation methods. Booster pumps are installed along the pipeline to handle any head loss incurred during the transportation process, ensuring a smooth and uninterrupted flow.

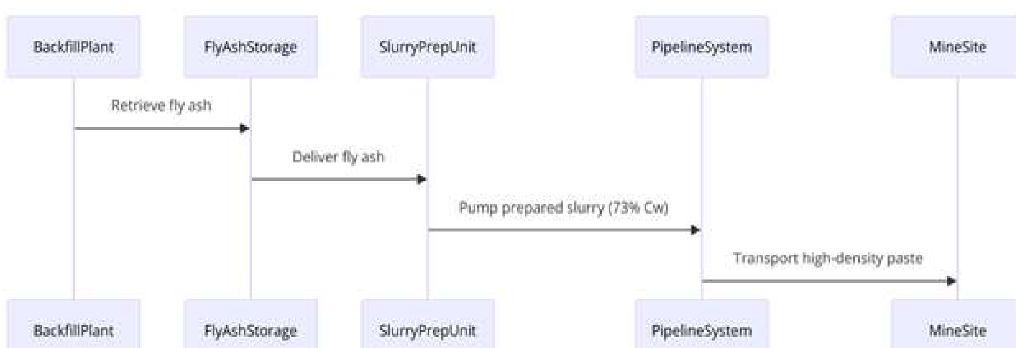

Fig 9.: Fly Ash Disposal Flow Diagram

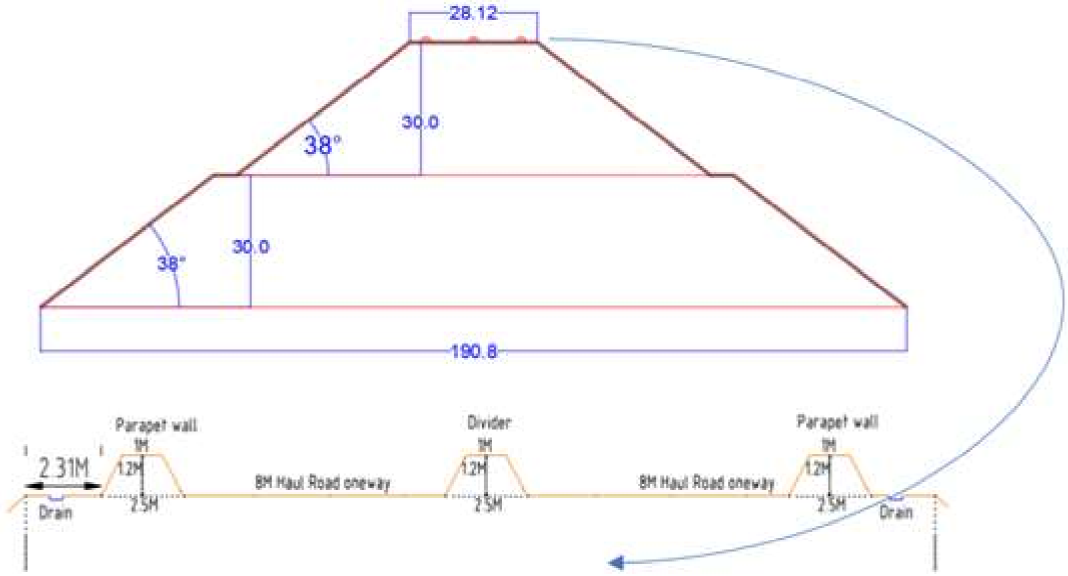

Fig 10: Cross Section of Embankment

This initiative is expected to significantly reduce the environmental impact of fly ash disposal, contributing to the sustainable rehabilitation of the mine while adhering to regulatory standards.

CONCLUSION

The growing accumulation of fly ash, which now exceeds 1,670 million tonnes, presents a significant environmental challenge. At Jindal Power Ltd. (JPL), we have successfully use of mine voids for fly ash backfilling, which has significantly reduced the environmental impact of fly ash disposal. By mixing fly ash with overburden (OB) and backfilling it in abandoned mines, we not only address the problem of fly ash disposal but also contribute to mine reclamation, demonstrating the potential for circular economy practices within the coal mining and power generation sectors.

While our efforts at JPL have proven successful, there is an urgent need to scale these initiatives across the industry. This requires further policy support, regulatory measures, and incentives for both mining and power sectors to adopt sustainable fly ash disposal and utilization practices. The following recommendations outline the key actions required to accelerate the implementation of fly ash backfilling and utilization, ensuring a cleaner, greener, and more sustainable future.

RECOMMENDATIONS

Promoting the Use of Fly Ash-Based Bricks

In states such as **Madhya Pradesh, Chhattisgarh,** Odisha etc, red clay bricks are already banned or heavily restricted within a 300 km radius of thermal power plants. This measure should be extended nationwide in the whole State to preserve topsoil, reduce pollution, and effectively utilize fly ash—a key industrial byproduct. Adopting fly ash-based bricks will help prevent soil depletion and align construction practices with sustainable development goals.

Inter-Mine Overburden (OB) Mixing for Fly Ash Backfilling

When the OB dump site within a mine is far from the fly ash disposal area, transportation costs and diesel emissions increase significantly. In contrast, an adjacent mining lease may have its OB dump site closer, making **concurrent inter-mine OB backfilling**—where surplus OB from one lease is mixed with fly ash for backfilling in a neighboring lease—a more economical and eco-friendly option. This approach reduces haulage distances, cuts fuel consumption, and ensures better compaction, ultimately promoting sustainable mine reclamation practices. The Ministry of Coal (MoC) should thus consider enabling OB dumping between nearby/adjacent leases to optimize fly ash disposal and minimize environmental impacts.

Inclusion of Fly Ash Management in Mine Closure Costs

The costs associated with fly ash management (handling, covering, and backfilling) shall be included as part of the mine closure plans. This would ensure that both miners and power producers are financially accountable for the environmental impact of fly ash. Regulatory frameworks should be updated to make this a mandatory part of mine closure cost, which would promote greater responsibility for the long-term impact of fly ash on the environment.

Incentives for Implementation of Fly Ash Management Practices

To encourage the adoption of sustainable fly ash management practices, introducing financial incentives for those companies that invest in and implement fly ash backfilling. These incentives could take the form of tax breaks, subsidies, or even recognition programs that highlight companies' commitment to sustainability. This would encourage more players in the mining and power sectors to take action and incorporate fly ash utilization into their operations.

Utilization of Mines with Lower Stripping Ratios for Fly Ash Disposal

Mines with lower stripping ratios, such as those operated by Mahanadi Coalfields Limited (MCL), Northern Coalfields Limited (NCL), and South Eastern Coalfields Limited (SECL), present significant opportunities for fly ash backfilling. These mines have more available capacity to accommodate additional fly ash, which would help reduce the environmental burden associated with fly ash disposal. Prioritizing such mines for fly ash backfilling would be a strategic step towards better managing fly ash.

Fly Ash Use for Suppression of Bench Fires in Open-Cast Mining

Fly ash should be considered for use in suppressing bench fires in open-cast mining operations. It can be effectively used to smother these fires, which not only reduces the environmental hazards posed by bench fires but also prevents the release of harmful gases into the atmosphere. The application of fly ash for fire suppression would improve both safety and environmental compliance in mining operations.

Collaboration with the Chemical Industry for Paste Fill Research

The chemical industry must come forward to collaborate with the mining sector to research and develop fly ash-based paste fill materials that can be used in underground mining, caverns, and tunnels. These materials could also be beneficial for stabilizing areas prone to landslides. By exploring the use of fly ash for paste fill in a variety of applications, the chemical industry can help improve the safety and stability of mining operations while also promoting sustainable fly ash utilization.

Long-Term Government Support and Policy Development

The government should take proactive steps to develop policies that support the research, development, and implementation of fly ash management practices. This includes funding research into new uses of fly ash, providing technical assistance to power plants and mining operations, and creating a regulatory framework that encourages the adoption of best practices for fly ash disposal and utilization.

LIMITATIONS

Long-term Environmental Implications

Fly ash backfilling in opencast mines has demonstrated potential as a sustainable waste management strategy. However, its long-term environmental impact warrants comprehensive study, particularly with respect to the potential leaching of heavy metals and other contaminants. Prolonged exposure to fly ash may alter **groundwater quality**, **soil composition**, and **biodiversity**, necessitating both laboratory-scale and field-scale investigations to establish robust environmental safeguards and post-closure monitoring protocols.

Geological and Geotechnical Considerations

Evaluating the **stability of fly ash dumps** requires an in-depth assessment of the regional geology and the specific geotechnical properties of the proposed reclamation site. Understanding parameters such as **rock mass characteristics**, **overburden behavior**, and **hydrogeological regimes** is crucial to ensure the structural integrity of the backfilled area. Designs must incorporate slope stability analyses, drainage control measures, and compaction criteria to mitigate failure risks.

Operational Challenges During Monsoons

The monsoon season introduces additional complexities, primarily due to the high influx of water and increased potential for **erosion**, **slope failures**, and **leachate generation**. Effective water management strategies, including diversion channels, drainage systems, and protective coverings, should be planned to minimize the infiltration of rainwater into the fly ash dumps and subsequent contamination or structural instability.

Limitation in Mines with Steeper Gradients

Mines with steeper gradients pose unique challenges for large-scale fly ash disposal. The flowable nature of fly ash—especially when moist—makes slope stability difficult to maintain and complicates layering and compaction. This demands more rigorous engineering controls and concurrent backfilling will be difficult to implement.

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Overburden Slope Stability Assessment Using Fly Ash: A Case Study

Sanjay Singh* Amit Kumar Verma** Suraj Kumar* T.N. Singh***

ABSTRACT

The stability of mine overburden (OB) dump slopes is a critical factor in ensuring safe and economically viable mining operations. This study explores the use of fly ash (FA), an abundant industrial byproduct and waste material, as a stabilizing agent to enhance the geotechnical properties of OB materials and improve dump slope stability. Experimental analyses were performed by blending FA with OB material in various proportions, followed by a thorough evaluation of the geotechnical properties of the mixtures, including compressive strength and cohesion. Numerical modeling, employing the finite difference method, was utilized to assess the stability of the FA-OB mixtures and determine optimal dump heights for different slope angles. Advanced characterization techniques, such as Energy Dispersive X-ray Spectroscopy (EDX) and Field Emission Scanning Electron Microscopy (FESEM), were applied to investigate the mineralogical composition and microstructural features of the FA-OB mixtures, which play a crucial role in influencing their stabilization performance. The findings revealed that a mixture containing 20% FA (by weight) and 70% OB material (by weight) exhibited the highest compressive strength and cohesion. Furthermore, the incorporation of FA significantly reduced the shear strain rate, demonstrating its potential as an effective material for enhancing OB dump stability and promoting safer mining practices.

Keywords: Shear Strain Rate, geotechnical properties, Mine overburden, Fly ash.

INTRODUCTION

Fly ash, a byproduct of coal or lignite-based thermal power plants, poses a significant environmental challenge due to its increasing production. According to the Central Electricity Authority (CEA) report for 2021-22, India generated approximately 239.06 million tonnes of fly ash from these power plants[1]. This underscores the urgent need for effective management and broader utilization of fly ash to mitigate its environmental impact. Currently, about 67.13% of the fly ash produced in India is utilized, with the construction sector accounting for a significant portion. Specifically, 26.49% is used in cement manufacturing, while other applications include brick production, concrete manufacturing, and road construction[2,3]. However, expanding its use into other sectors is essential to reduce the environmental strain.

One promising area for increased fly ash utilization is addressing slope instability in the mining industry. Slope instability, often caused by poor design or inaccurate assessments, poses risks to safety, infrastructure, and operations. Using fly ash to stabilize slopes offers a dual advantage: improving safety in mining operations and reducing the environmental burden of fly ash disposal. Slope stability depends on factors like water content, slope load, geological conditions, and slope angle. Due to its unique properties such as low specific gravity, good frictional behavior, minimal sensitivity to moisture changes, and excellent drainage fly ash is well-suited for geotechnical applications[4,5]. Studies have demonstrated that fly ash can significantly improve the properties of soft and expansive soils, including their Atterberg limits, compaction characteristics, compressive strength, permeability, swelling behavior, and shear strength[6–8].

Additionally, coal mining generates large quantities of OB materials, which include various soil types, shale, and coarse to fine particles. These materials must be removed to access coal seams, further highlighting the need for sustainable management solutions.

OB materials are usually stored either as external dumps away from the mine or as internal dumps close to the coal seam. External dumping helps keep mining operations safe and running smoothly, but it comes with

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challenges like needing extra land, environmental concerns, and high costs for moving and handling the material, which can increase the overall cost of coal production[9].

OB materials have different properties, so it's important to study them carefully to find the right amount of fly ash to use. This study looks at how mixing fly ash with OB affects its geotechnical properties and stability. It tests three mixtures: pure OB, OB with 10% fly ash, and OB with 20% fly ash. The study also suggests safe slope angles for each mixture to make sure the slopes are stable and safe.

AREA OF STUDY

Chhattisgarh holds 16% of India's coal reserves and is the second-largest coal-producing state, contributing about 18% of the country's total coal output. Thermal Power Station is located in Korba, Chhattisgarh, within the Korba Coalfield, which lies in the Hasdeo River valley, a tributary of the Mahanadi River. The Korba Coalfield is situated between latitudes 22°15'00º N to 22°30'00º N and longitudes 82°15'00º E to 82°55'00º E, within the north-south oriented Gondwana basin. Known for its high-quality coal, this coalfield plays a vital role in supporting the efficient operation of thermal power plants.

MATERIALS AND TECHNIQUES

Overburden (OB) material was collected from a major open-pit coal mine in the Korba coalfield, Chhattisgarh, India, and fly ash was sourced from the coal-based Thermal Power Station in Korba East, Chhattisgarh. The grain size distribution of the OB sample was analyzed following ASTM D6913/D6913M-17 standards. A model OB sample was prepared using parallel gradation techniques to reduce particle size while maintaining similar coefficients of curvature (Cc) and uniformity (Cu) for further geotechnical testing.

The Atterberg limits of both OB and FA were determined using ASTM D4318-17 standards. Microstructural properties were examined with a Field Emission Scanning Electron Microscope (FESEM), providing detailed images of surface morphology and structural features. Energy Dispersive X-ray Analysis (EDX) was used for qualitative elemental composition analysis, offering insights into the distribution and presence of elements through point and area mapping.

These methods provided a comprehensive understanding of the structural and chemical characteristics of OB and FA. Additionally, slope stability was analyzed using Rockscience Slide software, which calculated the factor of safety (FOS) to ensure accurate and reliable results in the study.

Sample Preparation and Procedures

Samples were prepared by combining various proportions of OB material and fly ash, as detailed in Table 1. The samples were prepared by combining OB material and fly ash in proportions based on their dry weights, followed by conducting additional tests on these blended mixtures.

Table1: Description of overburden samples with different proportions of fly ash

Sample name	Sample Mix (Weight %)		Description
S1	100%OB	0% FA	100% Overburden
S2	10% FA	90%OB	90% Overburden mixed with 10% fly ash
S3	15% FA	85%OB	85% Overburden mixed with 15% fly ash
S4	20% FA	80%OB	80% Overburden mixed with 20% fly ash
S5	100% FA	0% OB	100 % Fly ash

Geotechnical characteristics

This study evaluated the geotechnical properties of backfill materials composed of coal ash and overburden (OB) mixtures. Laboratory tests assessed key parameters, including Atterberg limits (liquid limit, plastic limit, and plasticity index) to understand the material's consistency and behaviour under varying moisture conditions. The liquid limit ranged from 30% to 200%, with undrained shear strength averaging 17 g/cm² at this limit, determined using Casagrande's apparatus per IS:2720 (Part V):1965 [26].

Specific gravity, Bulk Density and Porosity

Specific gravity tests showed that fly ash (FA) has a value of 2.21, while overburden (OB) has a value of 2.60, indicating that FA is less dense than OB. Bulk density measurements showed 1.35 g/cm³ for FA and 2.009 g/cm³ for OB, indicating their respective compactness. These metrics were determined using standard procedures (BS 733) and are crucial for assessing the material's suitability for engineering applications [27].

Angle of Repose

In the test, the natural angle of repose was measured for various OB and FA mixtures, including 100% OB, 95% OB with 5% FA, and 90% OB with 10% FA. This involved allowing the material to fall freely and measuring the slope angle formed, providing insights into the stability and flow characteristics of the mixtures.

Grain Size Analysis

Grain size analysis was conducted to classify soil based on particle size distribution, providing insights into its engineering properties. A 1 kg sample of dried soil was placed on a series of sieves arranged from coarse to fine and shaken for 10 minutes. The weight of soil retained on each sieve was recorded (Table 2), and the percentage retained was calculated. A graph was then plotted to show the relationship between grain size and cumulative percentage of fines. Figures 1 and 2 depict the distribution of fine and coarse particles across different sieves. For fly ash, wet sieve analysis involved washing the samples through increasingly finer sieves with water and measuring the retained weights to determine the particle size distribution.

Figure1: Sample of fly ash collected on a pan, with particles categorized by (a) 75 ìm and (b) 150 ìm sieve

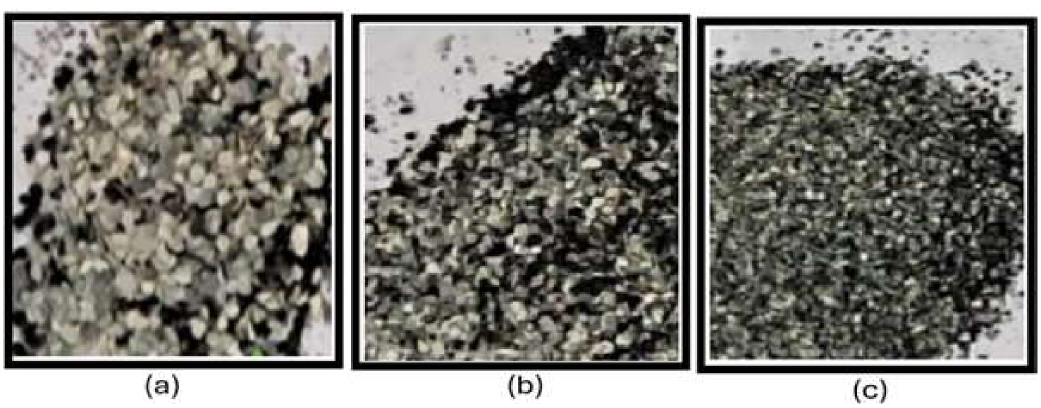


Figure 2: Fly ash sample collected on sieves with mesh sizes of (a) 600 ìm, (b) 425 ìm and (c)300 ìm respectively.

Figures 1 and 2 show the distribution of fine and coarse particles across various sieves. The wet sieve analysis for fly ash involved rinsing the samples through increasingly finer sieves with water and recording the retained weights to analyze the particle size distribution.

Table 2: Grain Size Distribution of Overburden and Fly Ash Samples

Sieve Size (in mm)	Cum. % retained OB	Cum. % retained FA
4.75	0.00	0.00
2.36	0.00	0.00
1.18	0.00	0.00
0.6	0.25	0.20
0.425	6.25	2.63
0.3	35.57	4.05
0.15	59.05	10.30
0.075	60.84	14.13
0	100.00	100.00

A wet sieve analysis was performed on fly ash samples to assess their particle size distribution. This process involves rinsing the fly ash through a series of sieves with decreasing mesh sizes, using water to ensure finer particles pass through while larger particles remain on each sieve. The weight of the particles retained on each sieve was then measured and recorded.

Direct Shear Test

In this study, direct shear tests were performed on various fly ash (FA) and overburden (OB) soil mixtures to assess their shear strength. Samples with different FA-OB ratios were placed in a 60x60 mm shear box, and shear strength parameters like cohesion (c) and internal friction angle (φ) were determined using the Mohr-Coulomb formula: $\tau = c + \sigma \tan \varphi$. The samples were mixed at optimal moisture content, compacted, and subjected to horizontal force until failure, with varying normal stresses applied by adding weights. The results showed how FA content affects the shear strength and stability of OB soil.

SLOPE STABILITY ANALYSIS

Numerical modeling for slope stability offers faster and more detailed solutions compared to traditional methods, enabling better management of overburden (OB) dumps during operations. This approach provides insights into failure patterns, shear strain rates (SSR), vector velocities, and flow directions[10]. Various numerical techniques, such as limit equilibrium, continuum, discontinuum, and finite element methods, are commonly used for dump stability analysis. In this study, slope stability was analyzed using the two-dimensional finite element method (FEM) in PLAXIS 2D and limit equilibrium analysis in SLIDE 2D. PLAXIS 2D simulated geotechnical behavior, while SLIDE 2D calculated the factor of safety (FOS) under different conditions.

Bishop's Simplified Method (BSM), a slice method for slope stability analysis, was also applied in this research. BSM divides the sliding mass into slices, as shown in fig 3 and uses stresses to calculate the normal forces at the base of each slice, making the factor of safety (FOS) a function of the resisting forces [11]. This method requires an iterative approach to determine the FOS, as shown in Eq. 1, Eq. 2, and Eq. 3.

$$\mathrm{F} = \frac{\sum \text{maximum forces of resistance around the arc}}{\sum \text{moving forces around the arc}} \quad (1)$$

$$FOS = \frac{1}{\sum W sin\alpha} \sum \left[\frac{c\beta + W tan\emptyset - \frac{c\beta}{FS} sin\alpha \; tan\emptyset}{m_\alpha} \right] \quad (2)$$

$$\mathrm{m}_\alpha = \cos\alpha + \frac{\sin\alpha \; \tan\emptyset}{\mathrm{FOS}} \quad (3)$$

where c = cohesion; Φ = angle of friction; W = slice weight; β = geometric parameter; α = inclination of slice base

PLAXIS 2D is a user-friendly finite element software used for analyzing geotechnical parameters like deformation, stresses, and stability throughout a project. It features an intuitive graphical input system, allowing quick model development and meshing. The software supports both plane strain and axisymmetric models, ideal for different structural types. It offers three meshing options (fine, moderate, coarse), with fine meshing providing the most accurate results. PLAXIS 2D also includes various material models, such as Mohr-Coulomb and linear

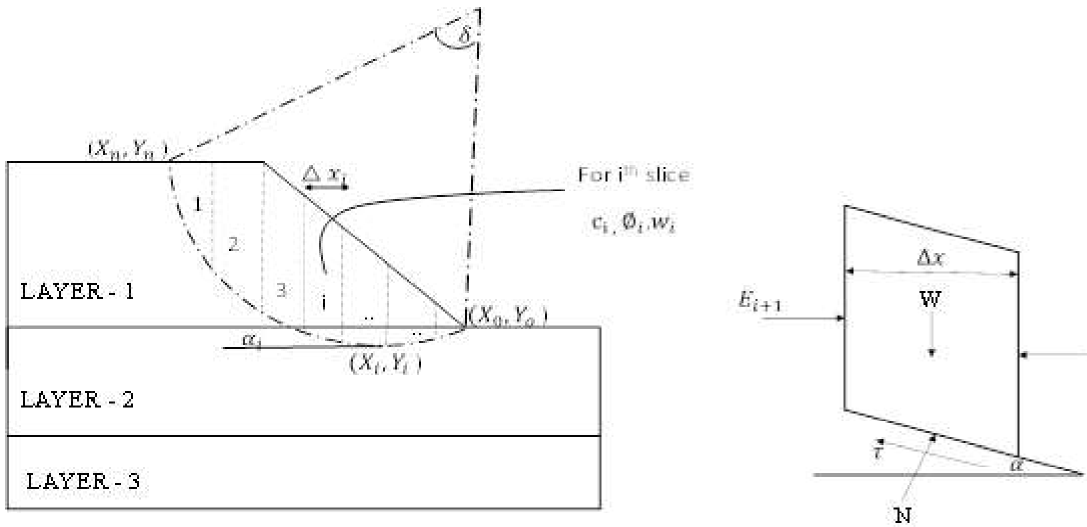


Figure 3: A representative soil profile modified from Sabri et al[12].

elastic, to simulate soil behavior, making it suitable for the simulations in this study.

In recent years, SLIDE 2D has become a key tool in slope stabilization, particularly for calculating the Factor of Safety (FOS) using the Mohr-Coulomb criterion. This software simplifies complex stability analyses, allowing engineers to focus on interpreting results and optimizing designs, improving efficiency in geotechnical engineering tasks[13].

RESULT AND DISCUSSION

Atterberg limit tests were performed on mixtures of overburden (OB) soil and fly ash from a captive power plant to evaluate their properties. This method, widely used in research, is effective for predicting material behaviour [14–16]. Results showed that all mixtures, regardless of fly ash content, exhibited non-plastic behaviour, even with up to 100% fly ash. The findings are summarized in Table 3, highlighting the consistent non-plastic nature of the OB and fly ash mixtures.

Table 3: Atterberg's Limit test result for various mixed composition of overburden and fly ash samples

Sample Name	Sample Mix (weight %)	Atterberg Limit (L.L%)
S1	100% Overburden	
S2	10% fly ash + 90% Overburden	
S3	15% fly ash + 85% Overburden	Non-Plastic
S4	20% fly ash + 80% Overburden	
S7	100% fly Ash	

ANGLE OF REPOSE

The results showed a positive correlation between the angle of repose and the FA content in the mixtures. As the proportion of FA in the OB-FA mixtures increased, the angle of repose also increased, indicating improved stability and cohesiveness of the material. The specific angles of repose for each mix composition are detailed in Table 4, demonstrating the impact of varying FA content on the overall behaviour of the mixtures. It should be noted that angle of repose for OB without FA corresponds to 42.78˚. However, increasing the FA content, angle of repose first decreases and then increases, which is close to 100% OB material, as illustrated in table 4. The mixing of FA to OB material not only enhanced the strength but also utilizing the environmental waste as dumping materials.

Table 4: Test results for an angle of repose for fly ash.

FA (Percentage)	Angle of Repose (degrees)
0	42.78
10	32.00
15	35.58
20	36.53

Grain size distribution

Figures 2 and 4 demonstrate the particle size distribution of FA samples across various sieve sizes. Coarser particles were retained on larger meshes (600 μm, 425 ìm, and 300 μm), while finer particles passed through smaller meshes (75 ìm and 150 μm), highlighting FA's retention efficiency and suitability for specific applications. Similarly, Figure 4 shows the particle size distribution of OB material, which retained more coarser particles on larger sieves (600 μm and 425 μm) and fewer finer particles on smaller meshes (75 μm), reflecting OB's coarser composition.

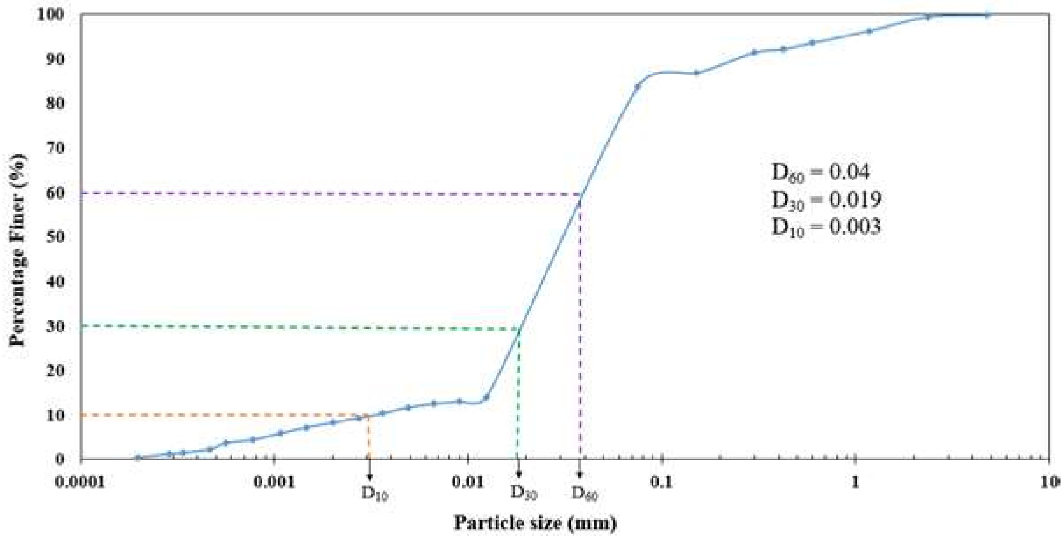
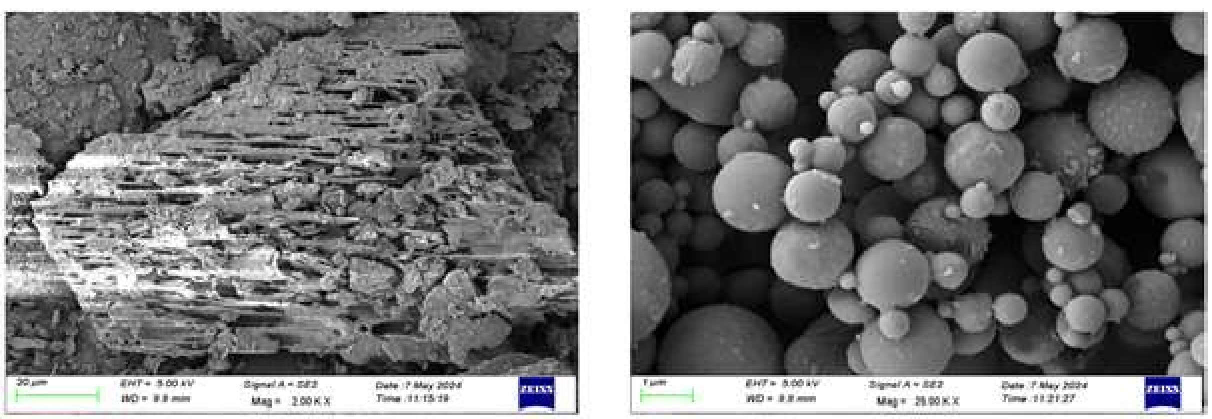


Figure 4: Wet sieve analysis of FA

FESEM/EDX Analysis

Figure 5: SEM image of (a) OB material and (b) fly ash FESEM/EDX analysis was conducted on OB material and fly ash to examine their mineral structures and chemical compositions. SEM imaging revealed that OB material has irregular, angular shapes, while fly ash features spherical particles as shown in fig 5. EDX analysis showed similar elemental compositions in both materials, with minor differences in elements like molybdenum (Mo) and titanium (Ti), which could affect stabilization processes. These findings highlight the potential of FA-OB mixtures for soil stabilization and strength enhancement.

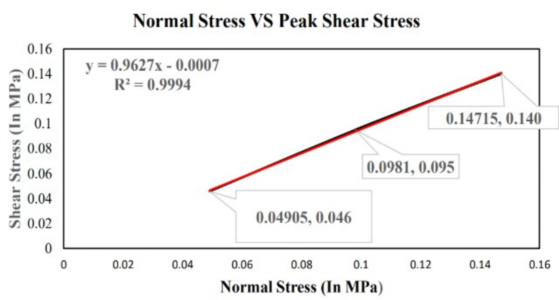


(a) (b)

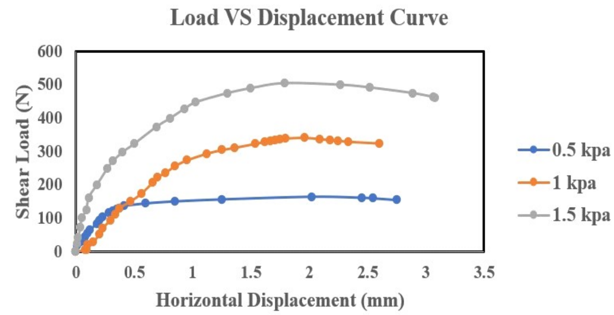
Figure 5: SEM image of (a) OB material and (b) fly ash

Direct Shear Test

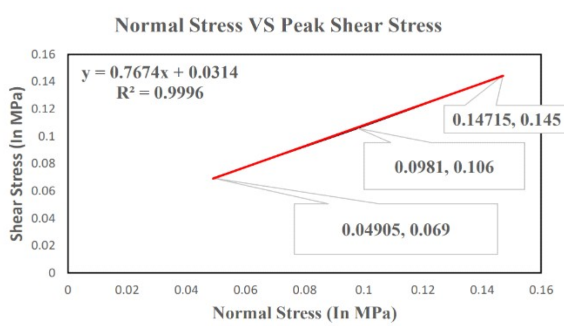
The direct shear test is a widely used method for measuring shear strength parameters, including cohesion (c) and the internal friction angle (ϕ). Table 5 presents these parameters for the tested materials. The results indicate that increasing the fly ash content reduces the internal friction angle. However, adding 10% and 20% fly ash to OB material increases cohesion by 19.1% and 25.8%, respectively. This improvement is attributed to enhanced bonding and compaction within the OB material due to fly ash addition.



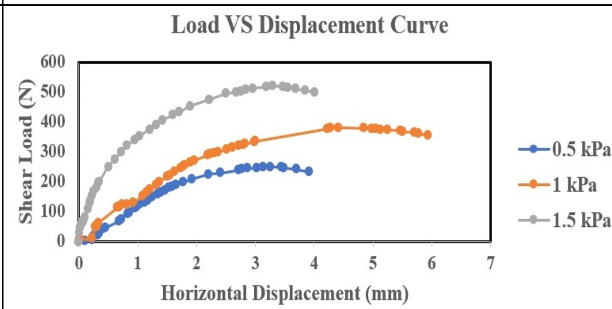
(a) 100% OB



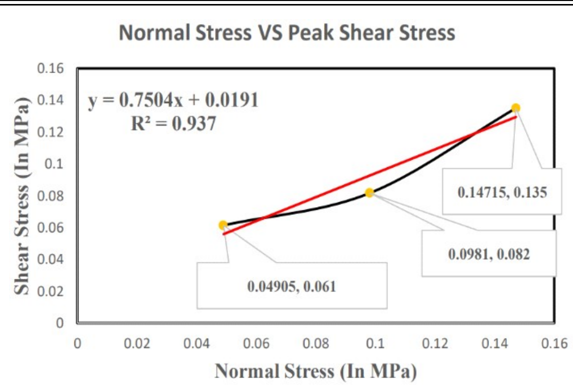
(b) 100% OB



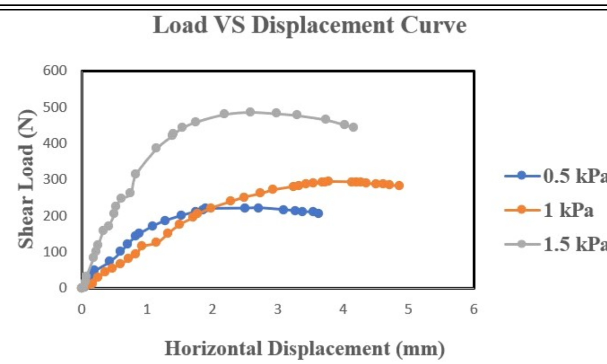
(c) 100% FA



(d) 100% FA



(a) (90%OB + 10%FA)



(b) (90%OB + 10%FA)

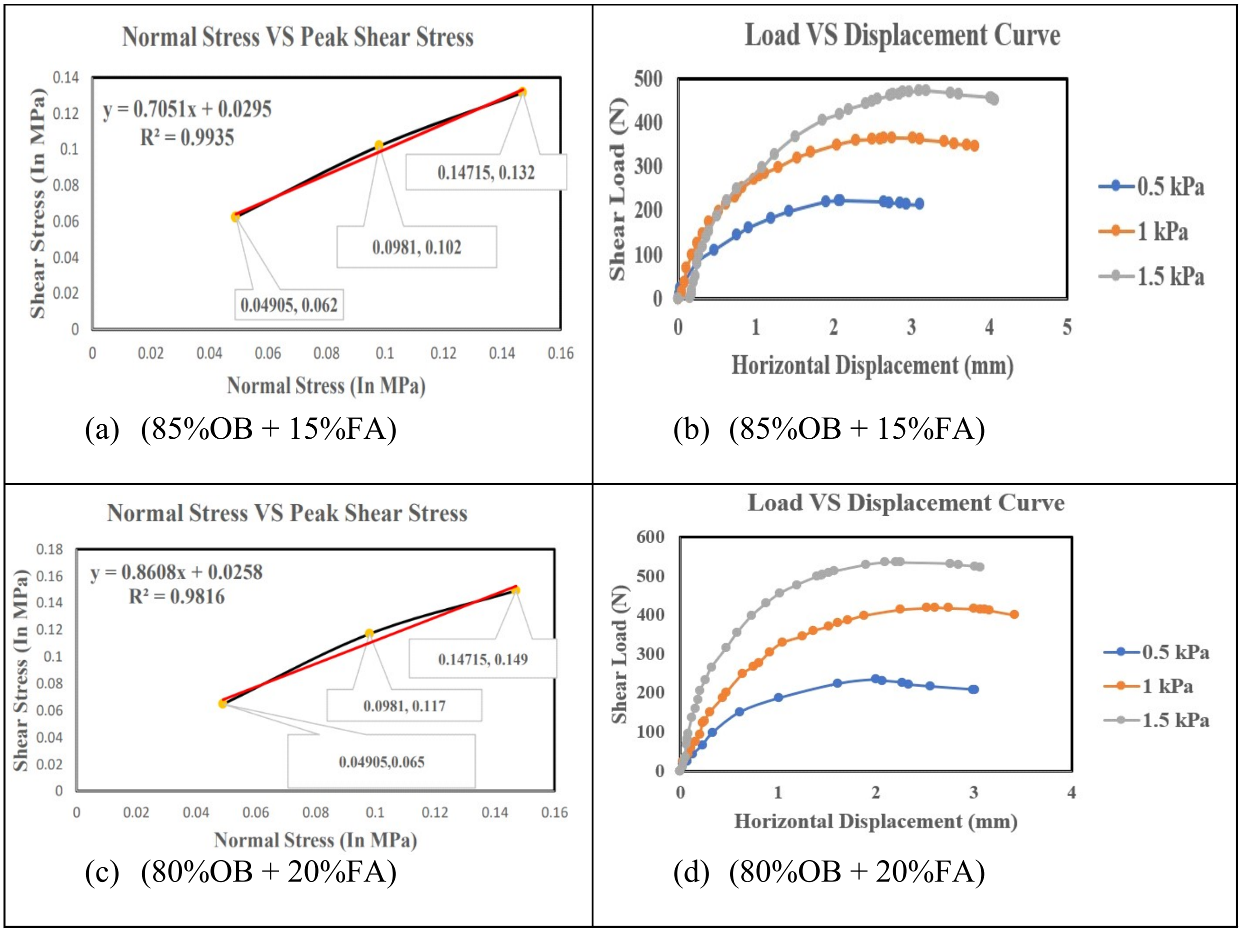


Figure 6: Analysis of Normal Stress versus Peak Shear Stress and Load versus Displacement

Table 5: Direct shear test result for overburden and fly ash

Sl.No	Sample Mix	Direct Shear Test	
		Cohesion (kPa)	Angle of Internal Friction (Degrees)
01	100%Overburden	0.00	43.96
02	10% fly ash + 90%Overburden	19.3	36.86
03	15% fly ash + 85%Overburden	29.5	35.17
04	20% fly ash + 80%Overburden	25.9	40.73

Figure 6 illustrates the shear behavior of different combinations of overburden (OB) and fly ash (FA) under varying normal stresses, providing insights into their mechanical properties. For 100% OB (Figures 6(a) and 6(b)), the regression equation y=0.9627x”0.0007y = 0.9627x - 0.0007 with an R2R^2 value of 0.9994 indicates a strong correlation between normal stress and peak shear stress. Peak shear loads occur at approximately 100 N, 200 N, and 450 N for normal stresses of 0.5 kPa, 1 kPa, and 1.5 kPa, respectively, reflecting strong shear strength with a slight post-peak decline.

For 100% FA (Figures 6(c) and 6(d)), the regression equation y=0.7674x+0.0314y = 0.7674x + 0.0314 with an R2R^2 value of 0.9996 also demonstrates a strong linear relationship. Peak shear loads are around 150 N, 250 N, and 450 N for the same normal stresses, indicating that pure FA exhibits considerable shear strength and deformation properties.

In the 90% OB and 10% FA mixture (Figures 6(e) and 6(f)), the regression equation y=0.7504x+0.0191y = 0.7504x + 0.0191 with an R2R^2 value of 0.937 shows a good correlation. Peak shear loads remain at 150 N, 250 N, and 450 N for normal stresses of 0.5 kPa, 1 kPa, and 1.5 kPa, respectively, indicating that adding 10% FA retains significant shear strength while slightly modifying deformation behavior.

For the 85% OB and 15% FA mixture (Figures 6(g) and 6(h)), the regression equation y=0.7051x+0.0295y = 0.7051x + 0.0295 with an R2R^2 value of 0.9935 highlights excellent correlation. Peak shear loads are consistent at 150 N, 250 N, and 450 N, maintaining substantial shear strength and stable deformation characteristics.

In the 80% OB and 20% FA mixture (Figures 6(i) and 6(j)), the regression equation y=0.8608x+0.0258y = 0.8608x + 0.0258 with an R2R^2 value of 0.9816 indicates a strong correlation. Peak shear loads increase to approximately 150 N, 300 N, and 500 N for normal stresses of 0.5 kPa, 1 kPa, and 1.5 kPa, showing enhanced load-bearing capacity and improved shear strength.

Overall, incorporating FA into OB materials enhances shear strength and modifies deformation behavior, with the extent of improvement depending on FA content. These findings confirm FA's potential to improve the mechanical properties of OB materials for engineering applications.

CONCLUSION

This study provides valuable insights into the geotechnical properties, composition, and behavior of materials obtained from a thermal power station through detailed experimental testing and analysis. Grain size analysis successfully classified the soil into fine or coarse grains, offering a clear understanding of its engineering properties based on particle distribution. Wet sieve analysis of fly ash (FA) revealed its particle size distribution, a critical factor in assessing its physical characteristics and suitability for specific engineering applications. By combining sieving with hydrometer analysis, a comprehensive understanding of FA particle size distribution was achieved, aiding in predicting its behavior under various conditions. However, the tests were conducted on materials from a single thermal power station, limiting the study's ability to capture variability across different locations. Moreover, particle size and wet sieve analyses were based on a limited number of samples.

The results indicate that adding fly ash up to 30% improves cohesion, with the highest cohesion observed in the mix containing 80% overburden (OB) and 20% fly ash. Beyond this point, cohesion decreases with further fly ash addition. Elemental composition analysis of OB and FA samples identified various elements crucial for evaluating their applications and environmental impacts. Energy Dispersive X-ray Spectroscopy (EDX) provided essential insights into elemental composition, though it may not detect trace elements or specific chemical bonds. Angle of repose tests conducted under controlled conditions offered valuable data but might not fully represent real-world scenarios.

Future research should address these limitations by sampling and testing materials from multiple power stations to capture broader variability. Field studies should be conducted to observe real-world behavior, alongside detailed environmental impact assessments. Further optimization of FA and OB mix compositions, integration of advanced numerical modeling techniques, and a focus on sustainable practices and policies will help refine practical applications and inform regulatory frameworks in geotechnical engineering.

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Ground Water Management in Opencast Lignite Mines for Safe Mining Operations

Hemant Kumar*

ABSTRACT

Opencast mining of sedimentary deposits involves the removal of a huge amount of overburden to reach the deposit. This process may disturb the underlying confined aquifers, resulting in the release of stored water at high pressure into the working area. Such an influx of water can make mining difficult and unsafe. Similar challenges are encountered in the mines of the Neyveli area.

Mining lignite from NLCIL's mines in Neyveli presents a unique hydrological challenge due to the presence of confined aquifers below the lignite seam. These aquifers exert upward pressure, which, if not controlled, could jeopardize the entire mining operation. Hydrogeological investigations and pumping tests conducted in this field have demonstrated that the most practical and economically viable solution is the depressurization of the confined aquifer. This is achieved by maintaining the pressure head either constantly below the lignite seam (initial technique) or just above the lignite seam (positive head—improvised technique). This is accomplished through large-scale continuous pumping from a series of large-diameter pump wells, strategically located at hydrologically pre-planned and calculated distances from the active excavation zone.

To manage this, depressurization of the aquifer is carried out to maintain the pressure head at the lignite bottom through strategically placed pumping wells in or near the excavation zone. The pressure surface is controlled using an adequate number of large-diameter pumping wells (drilling diameter: 36 inches, casing diameter: 20 inches), with capacities of 1,000 and 500 gallons per minute.

Effective groundwater pressure control has been achieved by relocating drilling and pumping wells closer to the lignite excavation area, thereby addressing previous issues of high groundwater pressure that had prevented full extraction of available lignite. Over time, groundwater and stormwater management practices have been refined to better support lignite mining operations.

The groundwater pumped from the mines is utilized in thermal power stations for power generation, while surplus water is treated and supplied for community use. Proper planning of pumping locations and the selection of effective methods are crucial for maintaining a suitable working area for excavation.

This article provides a detailed analysis of various groundwater control and management methods in mines to ensure a safe and efficient mining process, as well as to assess the effectiveness of groundwater control measures.

INTRODUCTION

Opencast mining of sedimentary deposits involves the removal of a large amount of overburden to access the deposit. This process may disturb the underlying confined aquifers, causing the release of stored water at high pressure into the working area. Such an influx of water can make mining difficult and unsafe due to the risk of flooding in the working pit. Similar challenges are faced by mines in the Neyveli area.

The hydrogeological basin of Neyveli (Fig. 1) is well known for its extensive lignite deposits. The discovery and development of large lignite reserves in this region have established Neyveli as Asia's largest lignite mining center, securing its prominence on India's energy map.

**Executive Director/NLCIL*

NLCIL operates three lignite mines—Mine-I, Mine-IA, and Mine-II—with a combined lignite production capacity of 28.0 million tons per annum (MTPA). The company also runs pit-head thermal power stations with a total capacity of 3,390 megawatts (MW) in Neyveli, Cuddalore District, Tamil Nadu. For sustainable lignite development, the monitoring and management of the Neyveli hydrogeological basin are crucial to ensuring environmental responsibility.

The Neyveli hydrogeological basin spans approximately 3,500 square kilometers and consists of a multi-layered aquifer system with four distinct aquifers. Of these, two are located above the lignite formation, while the other two lie below it. The aquifers above the lignite are classified as semi-confined and unconfined, whereas the ones beneath it are known as the upper and lower confined aquifers. This powerful aquifer system is carefully managed through controlled pumping to ensure safe mining operations without exceeding the Ministry of Environment and Forests (MoEF) permissible pumping limit of approximately 149.70 million cubic meters (MCM). Currently, NLCIL extracts around 12.85 MCM of groundwater, which remains well below the MoEF's prescribed limit.

The water pumped from the mines is entirely utilized for thermal power generation. Through integrated groundwater management, NLCIL has successfully optimized the use of available water resources for safe lignite mining and power production while maintaining ecological balance in the fragile coastal region of Cuddalore District, Tamil Nadu. This achievement has been made possible through advanced groundwater management and development studies involving remote sensing, land use and land cover analysis, groundwater modeling, and artificial recharge studies.

In the absence of perennial rivers in this region, groundwater utilization is of critical importance. The depressurization of the artesian aquifer located just below the lignite seam is essential for safe mining operations. This localized depressurization is achieved through continuous pumping from large-diameter wells, based on hydrogeological tests such as pump tests and R&D studies.

The hydrogeological basin of Neyveli is illustrated in Fig. 1 below.

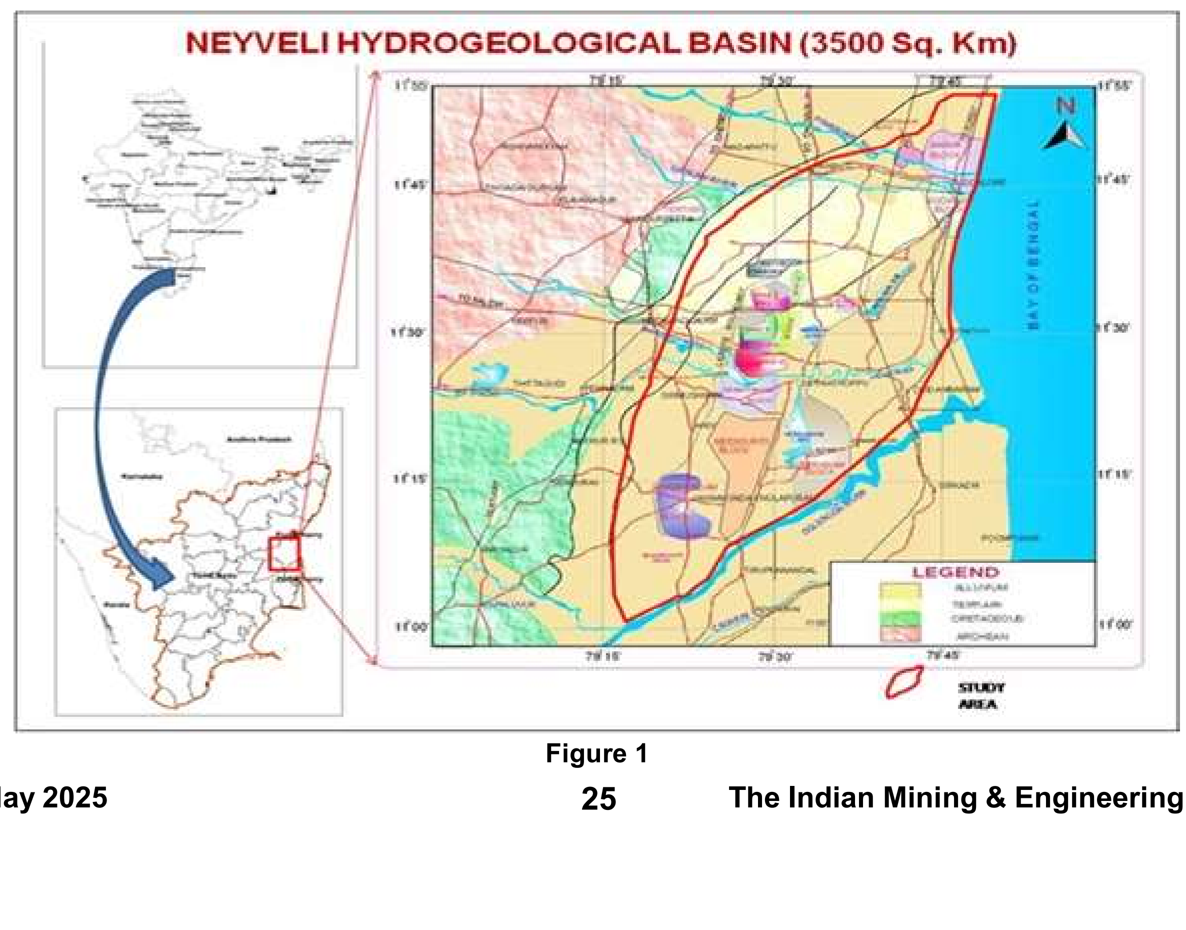


Figure 1

AREA OF STUDY- BRIEF DESCRIPTION OF NEYVELI LIGNITE MINES

The Neyveli lignite deposit region is located in the northern sub-basin of the Cauvery Basin, specifically within the Ariyalur-Pondicherry sub-basin. It spans the coastal plains of Pondicherry and Tamil Nadu, approximately 200 kilometers south of Chennai. The area features a flat landscape that gently slopes from north to south and west to east, with the land primarily used for agriculture. Within the Neyveli sub-area, numerous water tanks are present, some of which are filled with water year-round, while others are seasonal.

The study region is well-connected to Chennai and other major towns in South India through an extensive rail and road network.

Mine-II is the southernmost of the two active mines operated by NLC. It is situated to the south of Mine-I/ Mine-IA, with both mines separated by a small pillar through which the road from Vridhachalam to Vadalur passes. To the south, Mine-II's mining area is bordered by a main road (Vridhachalam to Setiatope) that experiences heavy traffic. Additionally, to the east of Mine-II, the mining area known as Block-B is connected.

HYDROGEOLOGICAL SET UP OF NEYVELI BASIN

The lignite Mines are located in the Neyveli hydro-geological basin covering an area of 3500sq km. Detailed Hydrological study has indicated the presence of three prominent multi-layered aquifers system in the area

- Unconfined aquifer (shallow water table aquifer)
- Semi-confined aquifer above the lignite seam
- Confined aquifer below lignite seam

SHALLOW WATER TABLE AQUIFER (PHREATIC)

This aquifer is extensive over large part of the area and varies in thickness from 2 meters to 30 meters. The aquifer consists of laterites, lateralized sandstones, clayey sandstones and mottled ferruginous sandstones. The sandstone are generally fine to medium grained and are well cemented by clayey or ferruginous matrix. Coarse grained, porous sandstones are not common. Recharge to this shallow water table aquifer is effectively carried out by direct precipitation.

SEMI-CONFINED AQUIFER

It occurs just above lignite seam in the southern parts of Mine-I and is predominant in M- II and further south. Its thickness varies between 5 and 10mts. There is no considerable ground water pressure and the water from this aquifer is being tackled by constructing the pump wells in both semi-confined and confined aquifers as a combined well, in addition to the toe drains, provided for tackling the seepage of water from this aquifer.

CONFINED AQUIFER

This aquifer is present in the entire Neyveli region. The maximum thickness is around 400 metres in the core lignite region and pinches in the west. Within the lignite bearing area there is almost continuous thick barrier clay at a depth of around 30 to 40 metres which divides the aquifer into two parts viz. Upper and Lower confined aquifer in the lignite bearing area. The upper confined aquifer exerts an upward hydrostatic pressure of about 5 to 8 kg/sq.cm within the mining area. This aquifer is mainly recharged due to rainfall in the demarcated recharge area.

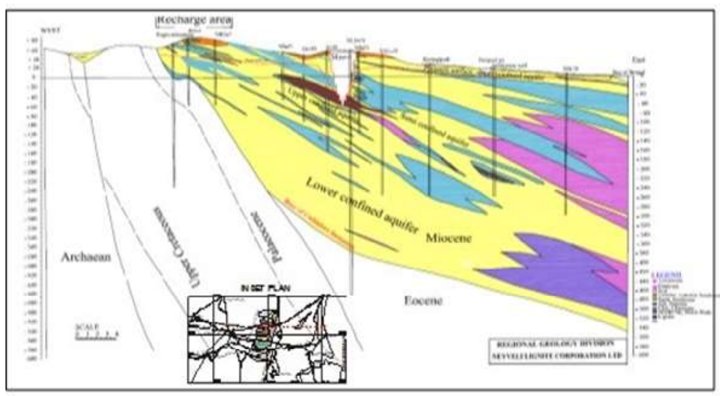


Fig-2-: West to East Geological Cross Section in the center of Hydro geological basin

METHOD OF MINING

In Neyveli Mines,

- Overburden which is soft clayey sandstone with sandy clay beds, is removed in bench levels deploying specialized mining equipment's & conveyor systems are operated to exclusively for overburden removal. The excavated OB is conveyed through conveyors and backfilled in the mined out area.

- Neyveli mines of NLCIL adopts continuous mining technology which uses Bucket Wheel Excavator and Conveyors for the excavation of overburden and lignite.
- The lignite is being excavated by bucket wheel excavators which are the discharged to conveyors and transported to stackyard and then ultimately to pit head thermal plants of Neyveli for power generation.

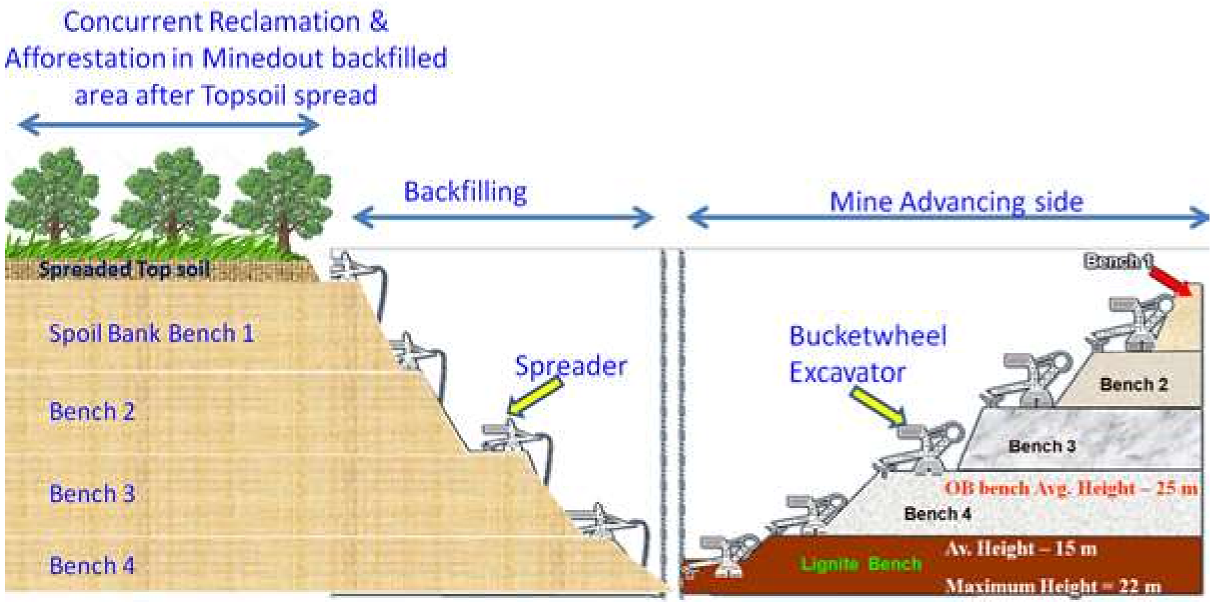


Figure-3: Method of Opencast Mining in Neyveli

NEED FOR GROUNDWATER DEPRESSURIZATION

Mining of lignite from NLCIL mines in Neyveli is faced with a unique hydrological problem due to the presence of powerful aquifers below the lignite seam exerting an upward pressure, if not controlled, it could jeopardize the entire mining operations.

Therefore, the depressurization of the aquifer is essential during mining operation to maintain the pressure head constantly at the lignite bottom at the depth of 80 to 120 m, and to bring down the pressure surface locally very closer to mine cut region through pumping operations by strategically located pumping wells in the lignite mines/ close to excavation zone.

In addition to the groundwater from confined aquifer, seepage water from semi-confined and unconfined aquifer zones are also causing problem while mining. All these water is managed by judicial pumping to achieve safe mining operation without exceeding the MoEF permissible limit of pumping.

Method of existing groundwater control operation with optimum pumping w.r.t MoEF&CC stipulated conditions: The hydro-geological investigation and pumping tests conducted in this field proved that most practical–cum-economic solution to this problem is depressurization of confined aquifer and maintaining the pressure head constantly below the lignite seam (initial technique) or just above lignite seam (positive head- improvised technique) by large scale continuous pumping operation from the series of large diameter pump well located /situated at hydrologically pre-planned /calculated distances from the active excavation zone. The ground water solution is exhibited in below (FIG-4).

GROUNDWATER CONTROL (GWC) OPERATIONS IN NLCIL NEYVELI MINES

The pressure surface is being controlled through pumping from large diameter wells (Drilling: 36 inches/Casing: 20inches) strategically located at pre-determined places and taken down to depths determined from hydrological tests.

Huge submersible pumps initially of 175 HP and later upto 250 HP with heads of 150 m are now lowered and pumped at optimum discharge of around 1000 GPM &500 GPM / well.

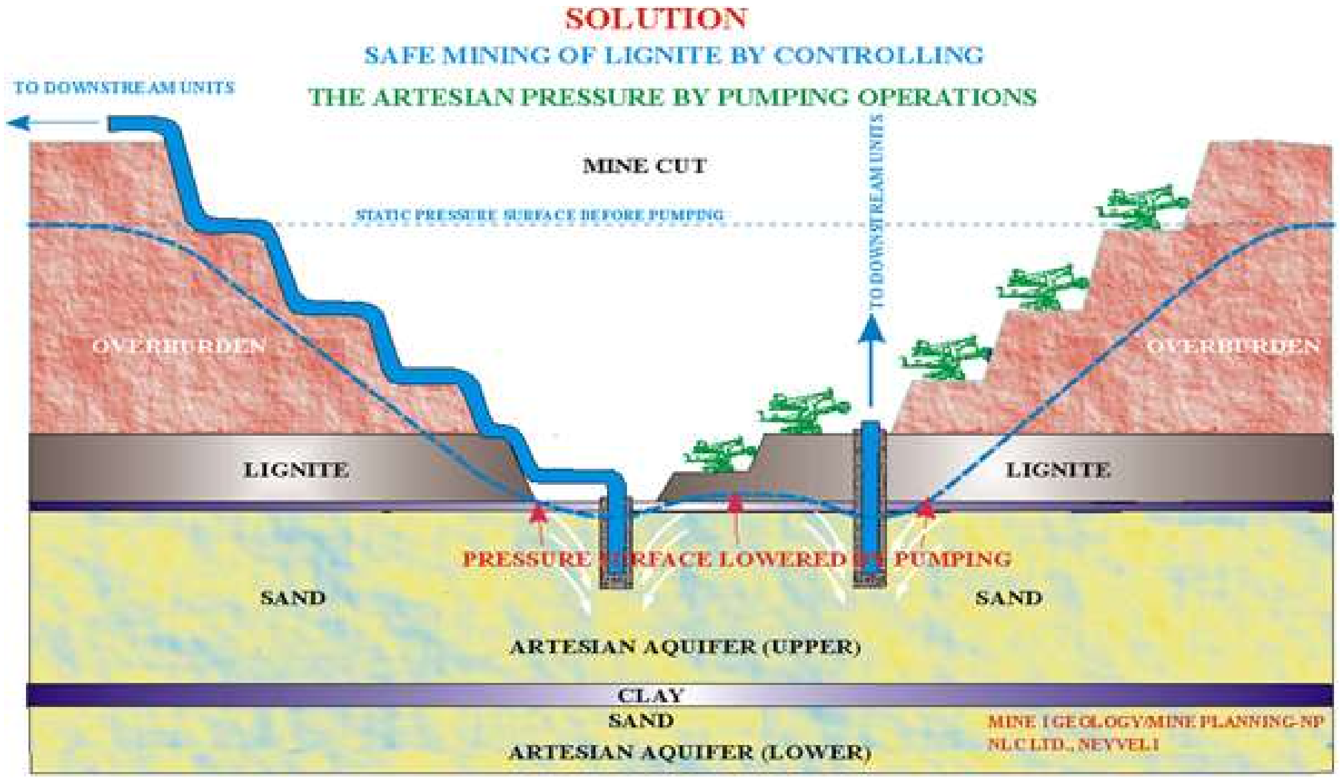


Figure 4

INTEGRATED MINE WATER MANAGEMENT, UTILIZATION AND AUGMENTATION IN OPENCAST LIGNITE MINES, NEYVELI HYDROGEOLOGICAL BASIN

The groundwater which is being pumped out from the mines is being used in Thermal Power Stations of Neyveli area for power generation and the surplus water is supplied for community use in after proper treatment.

- NLCIL is pumping about 42000 GPM of groundwater from its mines for safe mining operations, which is entirely consumed by Thermal Power Stations (4 Nos.).
- The storm water and seepage water accumulated in mines is pumped out on an average of 26500 GPM, of which 6800 GPM is consumed for drinking water use after treatment.
- The drinking water requirement of 6806GPM in Neyveli Township is met from treated storm water from Mine-I.
- About 19700 GPM of storm water is being let out into Sengal odai, Kanya odai, and Paravanar feeding to walaja tank and Perumal eri by which 20000 acres of land is cultivated by local farmers.
- NLCIL has plans for treatment of entire quantity of storm water in future as a step towards conservation of groundwater.

Reverse circulatory drill positioned for drilling large diameter well for depressurization

Figure 5: Location of GWC Wells for Ground water pumping operations)

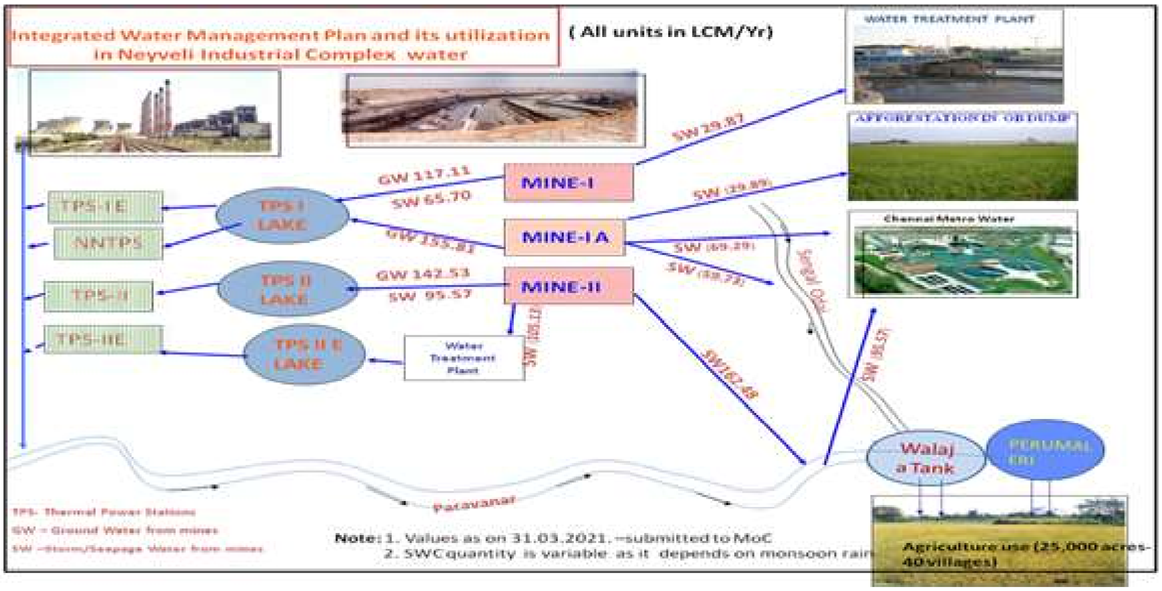
Regional Groundwater Management In Neyveli Hydrogeological Basin

- ❖ NLC is involved in monitoring the ground water levels and quality through series of dug wells and tube wells established in the hydro-geological basin.
- ❖ NLC is taking up studies on sea water –freshwater interface in the coastal region from Pondicherry in the north to Chidambaram in the south.
- ❖ NLC is constantly involved in enhancing the ground water potential of the region through integrated studies viz: Rainwater Harvesting, recharging deep seated aquifer through establishing of artificial recharge structures such as check dam, percolation wells, Infiltration wells and de-silting of reservoirs etc.

CONCLUSION

NLCIL has developed an effective system for Ground water control and management system for sustainable development with integrated mining and industrial complexes at Neyveli after adopting the latest techniques. To enhance the recharge potential to basin, NLCIL has

The flow diagram and table showing the water distribution to various uses are given below (FIG-6)



established many artificial recharge structures like Check dams, percolation wells, Infiltration wells in and around Neyveli and proposed to construct many new artificial structures in suitable places. NLCIL is judicially managing the Mine water (ground water & storm water) resources available in the Neyveli hydro-geological basin for safe lignite mining for power generation in sustainable manner and also to the community by maintaining the eco-fragile system in the coastal region of Cuddalore district of Tamil Nadu.

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Q-Methodology Assessment of Stakeholder Perceptions in Small-Scale Limestone Mining: A Case Study from Katni District, Madhya Pradesh

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ABSTRACT

Small-scale limestone mining plays a dual role in rural India, providing livelihoods while posing environmental and health challenges. This study applies Q-methodology to systematically assess stakeholder perceptions of health, livelihood, and environmental concerns in three small-scale limestone mines of Katni District, Madhya Pradesh. A concourse of 40 statements aligned with seven Sustainable Development Goals (SDGs 1, 2, 3, 6, 8, 11, 13) was Q-sorted by 60 participants representing miners, local residents, mine operators, and officials. Factor analysis (using KADE software) extracted three distinct viewpoints: (1) Livelihood-Centric Realists, who emphasize mining's economic benefits (SDG 1, 2, 8) with minimal concern for long-term environmental impacts; (2) Health and Environmental Advocates, who prioritize public health, water, and ecological issues (SDG 3, 6, 13) and demand corporate responsibility; and (3) Health-Concerned Pragmatists, who balance livelihood gains with recognition of health service gaps. Together, these factors explain 43% of the variance in perspectives. The results reveal critical divergences: for some, mining is a vital lifeline out of poverty, while others view it as a source of pollution and risk. Aligning interventions with these narratives is essential for sustainable development. The study's people-centered insights, in conjunction with objective environmental data, inform more inclusive policy strategies in line with SDGs, aiming to enhance miner welfare, community health, and environmental management in small-scale mining regions. These insights are crucial for designing more inclusive policies in alignment with SDG targets.

Keywords: Q-methodology; Sustainable Development; Stakeholder Analysis; Stakeholder Perception; Limestone Mining; Small-Scale Mining; Health Impacts; Katni District; Sustainable Development Goals (SDGs).

INTRODUCTION

Mining remains a vital part of India's economy, yet its benefits are often unevenly distributed. In Katni District, Madhya Pradesh, small-scale limestone mining provides essential livelihood support to rural communities, contributing to poverty reduction, food security, and employment. These activities align with Sustainable Development Goals (SDGs) 1 (No Poverty), 2 (Zero Hunger), and 8 (Decent Work and Economic Growth), particularly through local income generation and job creation for youth in remote areas.

However, these socioeconomic gains are frequently accompanied by significant environmental and health trade-offs. Many resource-rich regions experience what is commonly referred to as the "resource curse," where mineral wealth does not translate into improved living standards (Sachs & Warner, 2001; Venables, 2016). In the absence of sustainable practices and governance, such areas may suffer from pollution, deteriorating public health, and ecological degradation.

In Katni's limestone zones, major concerns correspond to SDG 3 (Good Health and Well-Being), SDG 6 (Clean Water and Sanitation), and SDG 13 (Climate Action). Dust emissions, noise, and blasting pose respiratory and auditory health risks, while quarry runoff and inadequate sanitation threaten water quality. Deforestation and particulate emissions contribute to ecosystem stress and local climate disturbances.

Environmental monitoring conducted in the area found most pollutant levels to be within national limits. However, elevated concentrations of PM_{10} and $PM_{2.5}$ during the post-monsoon season signaled potential health hazards. While these objective measurements are valuable, they do not fully capture the lived experiences and subjective

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concerns of the affected population. Understanding stakeholder perceptions of mining impacts is essential. Such perceptions influence behavior, determine social acceptance, and often highlight overlooked priorities. Addressing them supports SDG 11 (Sustainable Cities and Communities), which calls for inclusive, safe, and resilient development.

A notable gap remains in systematically capturing the subjective viewpoints of key stakeholders, miners, villagers, and local officials. Although traditional surveys and environmental audits provide useful data, they often overlook the complex trade-offs individuals face between livelihood opportunities and health or environmental risks. Emerging research underscores the need for integrative approaches. Studies from Odisha and central India have reported cumulative health impacts and water stress in mining regions (Das & Mohapatra, 2022; Kumar & Joseph, 2023). Roy et al. (2024) employed Q-methodology in Madhya Pradesh to reveal diverse community narratives on displacement and environmental risk.

This study adopts Q-methodology to address this gap. As a mixed-method approach, Q-methodology combines qualitative insights with quantitative factor analysis to systematically capture subjectivity (Stephenson, 1935; Brown, 1980). By having stakeholders rank a set of opinion statements related to mining, it identifies clusters of shared viewpoints that traditional methods may miss.

The objectives of this study are to: (1) analyze stakeholder perceptions of small-scale limestone mining's impacts on health, livelihood, and environment; (2) identify areas of consensus and divergence; and (3) align these findings with relevant SDGs. The study aims to inform more inclusive and sustainable mining policies that balance economic benefits with public health and environmental protection.

LITERATURE REVIEW

Sustainable mining requires balancing economic gain with social well-being and environmental protection. The Brundtland Report defined sustainability as meeting present needs without compromising the future (WCED, 1987), yet many mining areas in developing countries fall short. Small-scale mining, with limited mechanization and lease size, contributes to rural livelihoods but poses environmental and health risks (Hilson, 2002). In India, small mines, often below 25 hectares, are vital for rural income (Ghose, 2003) but operate largely informally (Chakravorty, 2001). The Indian Bureau of Mines (IBM, 2022) classifies them by modest output and labor. Since 2016, regulatory scrutiny has increased through state-level environmental bodies (Ministry of Mines, 2023).

Environmental studies show consistent stress. Tiwari et al. (2023) found dust from limestone units affects vegetation and health. Noise and blasting cause headaches and hearing loss (Das & Mohapatra, 2022), while water sources face pressure from quarry runoff (Kumar & Joseph, 2023). Injuries and chronic illness from unsafe conditions are common (Singh & Prasad, 2023), challenging SDG 8 on decent work. Despite these issues, mining remains a key livelihood. Incomes, though unstable, improve food and education access, addressing SDGs 1 and 2 (Das & Nandi, 2020). Yet, the trade-off between economic benefits and environmental harm creates varied stakeholder views.

Q-methodology helps capture such subjectivity by grouping people based on shared perspectives, rather than demographics (Stephenson, 1935; Brown, 1980). It is increasingly used in mining research. Roy et al. (2024) applied it in Madhya Pradesh to understand displacement concerns, while global studies highlight priorities like mine safety and rehabilitation (Xavier et al., 2021).The Sustainable Development Goals provide a framework to assess mining impacts.

This study contributes by integrating SDGs into a Q-method framework to identify how mining stakeholders in Katni perceive development trade-offs and sustainability outcomes.es.

METHODOLOGY

Study Area and Stakeholders

The research was conducted in three small-scale limestone mines in Katni District, Madhya Pradesh, which is part of India's central highlands known for extensive limestone deposits. Each mine operates on a modest lease area (under 25 ha) with an approved annual production between 50,000 and 100,000 tonnes, fitting the Indian criteria for small-scale mining. The surrounding communities are rural, with economies closely tied to mining and agriculture. Key stakeholder groups were identified to include: mine workers (both regular and casual labor), mine leaseholders and managers, nearby village residents (including panchayat local leaders), local government and health officials, and NGO representatives active in the area. This ensured a broad representation of perspectives from those economically dependent on mining to those responsible for oversight and welfare. A total of 60 participants were purposively selected for the Q-study, reflecting this stakeholder diversity. The sample size follows Q-methodology's emphasis on capturing a range of viewpoints rather than statistical representativeness (Watts & Stenner, 2012). Roughly half of participants were mine laborers or their family members, one-third were community members not employed by the mine, and the remainder included government officers (from health, environment, or mining departments) and NGO staff familiar with the mining issues. This composition allowed us to observe contrasts between, for example, a miner's personal experience and a regulator's viewpoint. All participants gave informed consent and were briefed on the purpose of the study.

Table 1: Participant Categorization for Q-Methodology Study

Group	Number of Participants	Description
Mine Workers	30	Labourers engaged in extraction and related operations across selected mines
Local Residents	20	Villagers residing within the nearby villages of the mine lease areas
Government Officials	10	DGMS officials, Mining officer/inspectors, IBM officials and State govt. officials

Table 2: Demographic Profile of Study Participants by Stakeholder Group

Stakeholder Group	Participants	Age Range	Gender (M/F)	Education Levels
Mine Workers	30	22–54	26/4	Mostly primary to secondary education
Local Residents	20	20–60	12/8	Ranging from illiterate to graduate level
Officials	10	25–58	8/2	All with diploma or university-level education
Total	**60**	–	**46 / 14**	Varied across groups

CONCOURSE DEVELOPMENT AND Q-SET DESIGN

In Q-methodology, the concourse refers to the complete range of possible statements people might express about a topic (Stephenson, 1935; Brown, 1980). For this study, a concourse on the impacts of small-scale mining on health, livelihood, and the environment was developed using multiple sources to ensure thematic breadth and stakeholder relevance.

Statements were first generated from field interviews and informal conversations with miners, villagers, and local officials. Commonly raised issues such as dust-related coughing, water scarcity, and the absence of healthcare facilities were translated into candidate statements. Literature reviews, policy documents, and NGO reports on mining in India contributed additional perspectives, including themes like corporate responsibility and community investment. Field-based environmental data were also adapted into plain-language perceptions, for instance, converting measured dust levels into statements about air pollution concerns. Internal health and safety audits provided input for formulating items on accident risk and protective equipment use.

This multi-source approach ensured that technical content was represented alongside social concerns in accessible language. The preliminary concourse was then refined into a final Q-set of 40 statements through an iterative screening process. Selection criteria prioritized diversity, clarity, and relevance. Redundant or narrowly framed items were excluded to minimize bias.

Statements were mapped to key Sustainable Development Goals, including SDG 1 (poverty), SDG 2 (nutrition), SDG 3 (health), SDG 6 (water), SDG 8 (work), SDG 11 (community infrastructure), and SDG 13 (climate). For example, statements under SDG 3 addressed respiratory illness, medical access, and workplace injuries, while SDG 6 included items on water quality and sanitation. Each item was phrased in neutral, simple language and presented bilingually in English and Hindi to accommodate varied literacy levels. The final Q-set was pilot-tested with participants from different stakeholder groups to ensure clarity and elicit a range of opinions.

Table 3: Q-Statements, Insights and Relevant SDGs

S.No.	Statement Text	Purpose/Expected Insight	Relevant SDG(s)
1	Mining gives poor families a way to earn and survive.	Explores the perceived economic benefit of mining in lifting families out of poverty.	SDG 1
2	Without mining, poverty levels would increase in nearby villages.	Assesses mining's role as a poverty buffer in rural areas.	SDG 1
3	Income from mining is irregular and uncertain.	Highlights livelihood vulnerability and economic insecurity despite job access.	SDG 1, 8
4	Lack of financial stability causes stress in miner households.	Connects economic instability to mental and emotional well-being.	SDG 3, 8
5	Government schemes have not reached most mining families effectively.	Evaluates the effectiveness and reach of social protection schemes.	SDG 1
6	Some children in mining homes suffer from malnutrition.	Links mining income to nutritional outcomes and food security.	SDG 2
7	Mining income is often insufficient to ensure a nutritious diet for families.	Assesses adequacy of earnings in addressing household food needs.	SDG 2
8	Local mining companies should contribute to food security programs.	Checks stakeholder expectations on CSR and hunger reduction.	SDG 2, 11
9	Better income from mining has helped reduce hunger in nearby community.	Perceived positive impact of mining income on food availability.	SDG 2
10	Seasonal unemployment in small scale mining worsens food security in the area.	Connects work seasonality with hunger and under nutrition risks.	SDG 2, 8
11	Many miners cannot afford to visit a doctor when they are sick.	Evaluates healthcare affordability and access among workers.	SDG 3
12	Most miners do not get health check-ups regularly.	Indicates preventive health service gaps in mining zones.	SDG 3
13	Miners often lack or avoid using safety gear.	Assesses awareness and behaviour related to occupational safety.	SDG 3, 8

14	There is little awareness about long-term health risks of mining.	Explores informational and awareness barriers in risk prevention.	SDG 3
15	Health workers rarely visit remote mining areas.	Indicates limitations in health outreach services.	SDG 3, 11
16	Injuries and illnesses from mining affect the whole family, not just the worker.	Assesses ripple effects of mining-related health issues on families.	SDG 3
17	Health outreach programs and mobile clinics are needed in mining areas.	Evaluates stakeholder demand for mobile and inclusive health services.	SDG 3, 11
18	Most small miners are not trained in workplace health and safety.	Reveals capacity gaps in occupational safety training.	SDG 3, 8
19	Stress and exhaustion are common in mining work.	Explores mental and physical strain of labour intensive work.	SDG 3
20	Mental health support is rarely available in mining areas.	Identifies lack of psychological services in mining communities.	SDG 3
21	Mining has polluted many natural water sources used by villagers.	Assesses perceived environmental degradation due to mining.	SDG 6, 13
22	Miners and their families often use unsafe water for daily needs.	Links water quality concerns with health outcomes.	SDG 3, 6
23	Poor sanitation around mining areas leads to waterborne disease.	Connects sanitation with illness prevalence in mining zones.	SDG 3, 6
24	There are no proper toilets near most mine sites.	Assesses basic sanitation infrastructure gaps.	SDG 6
25	Safe drinking water is not easily available in many mining villages.	Evaluates access to clean water in affected communities.	SDG 6
26	Miners usually work without contracts or job security.	Highlights informality and precarity of mining employment.	SDG 8
27	Long working hours in mines lead to physical strain.	Assesses workload and its impact on health.	SDG 3, 8
28	Mining jobs are poorly paid despite being physically demanding.	Evaluates wage fairness in relation to effort and risk.	SDG 8
29	Children are sometimes seen working near mines.	Raises concerns over child labour in mining areas.	SDG 8, 1
30	Small scale mining offers poor work conditions.	General critique of unsafe and harsh working environments.	SDG 8, 3
31	Dust control in small-scale mining is poor.	Assesses environmental compliance and air quality issues.	SDG 3, 13
32	Some villages lack health centers even though mining is nearby.	Evaluates disconnect between resource extraction and health services.	SDG 3, 11
33	Urban planning rarely considers the risks faced by mining communities.	Highlights policy-level neglect of mining populations in development.	SDG 11
34	The community is not consulted in health or safety planning.	Evaluates inclusivity and participatory planning practices.	SDG 11

35	Miner's families often live in poorly constructed housing near the mine.	Assesses housing vulnerability and safety for mining families.	SDG 11
36	Air pollution from mining affects both workers and nearby villagers.	Identifies shared environmental health burden of mining emissions.	SDG 3, 13
37	Climate change is making outdoor mining work more difficult.	Perceived effect of changing climate on work conditions.	SDG 13
38	Mining has increased the number of heat-related illnesses in our area.	Connects mining exposure and climate-induced health risks.	SDG 3, 13
39	Trees and green cover around mining areas are disappearing.	Assesses deforestation and ecosystem loss from mining.	SDG 13, 11
40	Extreme weather and heat waves are becoming more common near mines.	Stakeholder perception of climate variability and health impacts.	SDG 13

Q-SORT PROCEDURE

Sixty participants completed a Q-sort by ranking 40 statements based on their level of agreement or perceived importance. A forced quasi-normal distribution was used, ranging from +4 (most agree or most important) to +0 (neutral) to –4 (most disagree or least important), following standard Q-methodology practices (Watts & Stenner, 2012). This structured grid encouraged participants to prioritize and make trade-offs in expressing their views. Participants initially reviewed all statements and grouped them into three categories: agree, neutral, and disagree. They then refined this categorization by placing each statement into the ranking grid, either on a printed sheet or a custom digital interface designed for the study.

The interface supported Hindi and allowed drag-and-drop sorting, improving clarity and convenience. About half the participants used the digital version, while the rest, particularly older or less digitally familiar individuals, used printed cards on a physical board. All manual sorts were later digitized by the research team. Each Q-sort produced a rank order from 1 to 40 for that participant. The sorting process took approximately 30 to 45 minutes. Participants were encouraged to reflect on their choices, and while their verbal comments were not formally analyzed, they provided useful context during interpretation. Researchers maintained neutrality throughout, offering clarification when requested without influencing responses.

DATA ANALYSIS (KADE)

After completing all Q-sorts, participant rankings were compiled and analyzed using Ken-Q Analysis Desktop Edition (KADE). The data were structured as a participant-by-statement matrix. KADE was used to compute a correlation matrix reflecting the similarity between each pair of Q-sorts. Principal components analysis (PCA) was then applied to extract latent factors, consistent with standard Q-methodology practice (Brown, 1980).

PCA initially suggested up to eight factors with eigenvalues greater than 1.0 (Kaiser's criterion). However, most of these had limited explanatory value. A three-factor solution was selected based on eigenvalues, explained variance, scree plot interpretation, and conceptual coherence. The three retained factors had eigenvalues of 11.24, 9.35, and 4.62, accounting for 43% of the total variance (Factor 1: 19%, Factor 2: 16%, Factor 3: 8%). This level is acceptable for Q-method studies, where a few factors typically capture the major shared perspectives.

Varimax rotation was applied to enhance interpretability. This orthogonal rotation clarified how each participant loaded onto the three factors. A factor loading threshold of ±0.40 was used to determine significance at the 0.01 level, in line with common Q-method conventions. Of the 60 participants, 30 loaded significantly onto a single factor (11 on Factor 1, 10 on Factor 2, 9 on Factor 3). The remaining participants either had cross-loadings or low loadings and were excluded from narrative construction. KADE was used to generate factor arrays, idealized Q-sorts that represent the weighted average ranking of statements for each factor. These arrays provided standardized Z-scores indicating the relative importance of each statement within each factor. Statements ranked at the extremes and those that distinguished one factor from others were used to construct narratives. Although participant comments during sorting were not formally coded, they informed the interpretation. Each factor was then labeled based on its core perspective, and its relation to relevant SDGs was articulated.

RESULTS

Overview of Extracted Factors

The Q-method analysis revealed three distinct stakeholder perspectives on the impacts of small-scale mining in Katni. Each factor represents a coherent viewpoint shared by several participants, effectively summarizing a particular way of understanding the trade-offs between mining's livelihood benefits and its health/environmental costs. Table 4 presents the key statistics of the three factors:

Table 4: Summary of Factor Statistics

Factor	Eigenvalue	% Variance Explained	No. of Defining Sorts
Factor 1	11.24	19%	11
Factor 2	9.35	16%	10
Factor 3	4.62	8%	9

Table 4 summarizes the statistical characteristics of the three factors. Below, we describe each factor's core narrative and its alignment with the seven Sustainable Development Goals (SDGs) relevant to this study.

Factor 1: Livelihood-Centric Realists with Basic Health Support

This viewpoint emphasizes the economic importance of small-scale mining. Participants associated with Factor 1 view mining as essential for local survival and poverty reduction. Highly ranked statements included "Mining gives poor families a way to earn and survive" and "Better income from mining has helped reduce hunger in the community," aligning strongly with SDG 1 (No Poverty) and SDG 2 (Zero Hunger). These respondents see mining as the main livelihood option and reject critiques about its insufficiency, disagreeing with statements such as "Mining income is insufficient for a nutritious diet."

Although primarily focused on economic benefits, this group also acknowledges immediate health risks. They supported statements like "Injuries and illnesses from mining affect the whole family" and "Health outreach programs and mobile clinics are needed," suggesting practical acceptance of basic health interventions under SDG 3 (Good Health and Well-Being). There was mild agreement with concerns about heat stress and work difficulty, indicating limited awareness of climate impacts (SDG 13), especially when tied to labor conditions.

However, environmental issues were generally downplayed. Participants disagreed with statements about water pollution and rising illness, and rejected the suggestion of child labor near mining sites. This may reflect lived experience, limited environmental awareness, or prioritization of economic needs over ecological concerns.

Overall, Factor 1 reflects a pragmatic, survival-driven perspective common among mine workers, their families, and local actors benefiting from mining income. Their priorities lie in sustaining livelihoods, with conditional support for basic health services. Environmental and broader social concerns are viewed as less urgent unless they directly disrupt economic activity. This factor aligns most strongly with SDGs 1, 2, and 8, with limited engagement with SDGs 3, 6, and 13.

Factor 2: Health and Environmental Justice Advocates

Factor 2 participants prioritize public health, environmental protection, and social justice, expressing skepticism towards mining's economic benefits. They strongly endorsed statements highlighting environmental degradation, such as pollution of natural water sources, air pollution affecting villagers, and loss of vegetation cover, aligning closely with SDGs 6 (Clean Water) and 13 (Climate Action). Infrastructure deficits were also emphasized, including poor sanitation and lack of safe drinking water, underscoring critical health concerns (SDG 3 and 6). Additionally, they supported corporate responsibility, advocating for mining companies to contribute to community welfare programs (SDG 2 and 11).

These participants strongly disagreed with claims emphasizing mining's role in poverty reduction or food security. They viewed the purported economic benefits of mining as inadequate compared to the negative impacts, reflecting doubts about the number, quality, and sustainability of mining jobs.

This factor represents stakeholders such as NGO representatives, local health officials, and environmentally aware community members. They envision a scenario where mining occurs responsibly, minimizing pollution and supporting local development. Their perspective calls for stronger enforcement of environmental regulations, better health infrastructure, and corporate-funded community initiatives. Factor 2 highlights essential tensions between economic priorities (SDGs 1 and 8) and long-term sustainability and health (SDGs 3, 6, and 13).

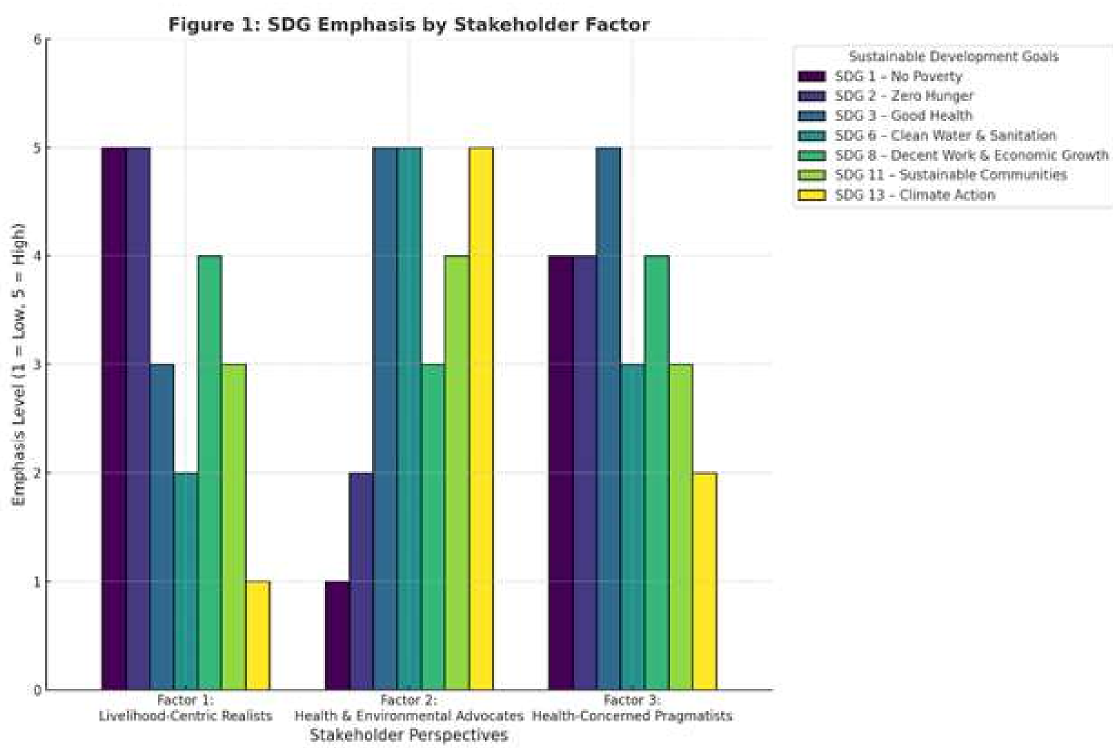
Factor 3: Health-Concerned Pragmatists with Mixed Priorities

Factor 3 embodies a balanced perspective, recognizing mining's economic necessity while also emphasizing health and social issues. Participants aligned closely with Factor 1 on economic benefits, strongly agreeing that mining significantly reduces local poverty and hunger (SDGs 1 and 2). However, they differed by highlighting substantial concerns about health education and healthcare access, indicating low awareness of long-term health risks and poor availability of medical services (SDG 3). They also emphasized the lack of adequate workplace safety training, connecting to SDG 8 (Decent Work Conditions).

Unlike Factor 2, this group did not prioritize environmental and climate issues, typically disagreeing with statements about climate impacts or increased weather extremes. Their stance on environmental concerns, such as water pollution and deforestation, was neutral or moderate. This pragmatic perspective likely characterizes community leaders, health workers, and some mining supervisors who recognize mining's role in sustaining local economies but advocate improved health and safety provisions. They support practical interventions like regular health services, safety training, and nutritional programs without challenging the mining activities themselves. Factor 3 participants could serve as intermediaries in stakeholder dialogues, bridging economic and social needs, though their limited environmental awareness could present challenges for sustainability.

COMPARING FACTORS AND SDG ALIGNMENT

Each identified factor highlights distinct stakeholder narratives regarding the relationship between small-scale mining and sustainable development goals (SDGs). Figure 1 (conceptual diagram) summarizes the emphasis placed by each perspective on the relevant SDGs:



Factor 1 (Livelihood Centric Realists) strongly emphasizes SDG 1 (poverty alleviation) and SDG 2 (hunger reduction), with moderate support for SDG 8 (job creation). While they acknowledge basic health service needs (SDG 3), their proactive stance on health risks is limited. Environmental concerns related to SDGs 6 (water) and 13 (climate) receive minimal attention. Their approach to SDG 11 (sustainable communities) is indirectly through improved individual economic outcomes rather than infrastructure or community planning.

Factor 2 (Health and Environmental Advocates) prioritizes SDG 3 (health), SDG 6 (water and sanitation), and SDG 13 (climate action and environmental protection). This group strongly advocates corporate responsibility under SDG 11 and decent working conditions under SDG 8. However, they question mining's effectiveness in addressing poverty (SDG 1) and hunger (SDG 2). Overall, they emphasize quality of life and sustainability over economic benefits alone.

Factor 3 (Health-Concerned Pragmatists) acknowledges mining's contribution to reducing poverty (SDG 1) and hunger (SDG 2), similar to Factor 1. They also support health interventions (SDG 3) and improved working conditions and safety training (SDG 8). This group is less concerned with climate impacts (SDG 13) and has moderate interest in water issues (SDG 6). They recognize community development efforts (SDG 11) primarily through corporate social responsibility measures.

Despite differences, commonalities exist across factors. All acknowledge some negative aspects of mining, particularly health-related risks, though their importance relative to economic benefits varies. While only Factor 2 strongly highlights environmental concerns, Factors 1 and 3 do not entirely dismiss these issues. Similarly, Factor 2 concedes mining generates jobs but remains skeptical about the broader socioeconomic benefits.

These shared concerns offer potential opportunities for stakeholder dialogue and collaborative policy interventions. Health initiatives, dust control, and water management programs could gain broad stakeholder support if framed appropriately. Conversely, any decline in mining's economic returns might reduce local support, shifting stakeholders toward more critical views.

Overall, these findings reveal a stakeholder landscape comprising three narratives: mining as an essential livelihood, mining as a serious health and environmental concern, and mining as a necessary economic activity requiring significant improvements. The next section discusses these perspectives in the context of policy implications and sustainable development pathways aligned with SDG targets.

DISCUSSION

The emergence of three distinct stakeholder perspectives provides nuanced insights into the socio environmental dynamics within Katni's small scale mining context. The identified factors highlight a critical sustainability challenge: balancing economic livelihood improvements (SDGs 1 and 2) with essential health, environmental, and social welfare goals (SDGs 3, 6, and 13).

Factor 1 (Livelihood Centric Realists) emphasizes mining's critical role in alleviating poverty and reducing hunger through local employment, consistent with previous research (Hilson, 2002). Yet, their minimal concern for environmental and long term health risks highlights potential vulnerabilities. Economic improvements may become unsustainable if persistent health and ecological damages undermine gains by increasing medical expenses and reducing productivity, thus reiterating arguments for quality growth rather than merely growth (Sachs and Warner, 2001).

Conversely, Factor 2 (Health and Environmental Advocates) foregrounds serious environmental and health impacts, such as contaminated water sources and respiratory diseases, directly aligning with SDGs 3 and 6. This group challenges the effectiveness of mining as a sustainable poverty alleviation tool, advocating instead for comprehensive corporate and governmental accountability measures, environmental controls, and community investments. Their viewpoint resonates with India's recent policy shifts toward stricter environmental oversight (Ministry of Mines, 2023).

Factor 3 (Health Concerned Pragmatists) offers a bridging perspective, recognizing the livelihood benefits of mining yet advocating strongly for improved health services, safety measures, and nutritional awareness. This pragmatic view highlights opportunities for policy and community interventions that do not compromise economic stability but enhance overall worker and community welfare, meeting elements of SDG 8 (decent work conditions).

Policy implications derived from these perspectives suggest targeted interventions. For communities aligned with Factor 1, stable employment conditions and basic healthcare services (e.g., mobile health clinics, first aid training) should be prioritized, building trust and enhancing livelihood sustainability. Regular social audits could also ensure ongoing compliance with labor standards and protection against exploitation.

Addressing Factor 2 concerns involves rigorous enforcement of environmental regulations and proactive community development initiatives such as dust control measures, reforestation projects, water treatment solutions, and periodic health screenings. Mining leases could incorporate community benefit criteria, institutionalizing corporate social responsibility (CSR) and compliance with environmental and health standards.

Factor 3's moderate viewpoint recommends initiatives focused on education and training health risk awareness programs, nutrition education, occupational safety training, and financial literacy to empower communities. These interventions help mitigate mining related risks without polarizing the debate between environmentalists and livelihood proponents.

Table 5: Consensus Interpretation Table

Statement No.	Statement	Consensus Interpretation
5	Government schemes have not reached most mining families effectively.	Agreed across all factors
10	Seasonal unemployment in small scale mining worsens food security in the area.	Neutral or mild agreement
12	Most miners do not get health check-ups regularly.	Neutral or mild agreement
17	Health outreach programs and mobile clinics are needed in mining areas.	Agreed across all factors
20	Mental health support is rarely available in mining areas.	Neutral or mild agreement
22	Miners and their families often use unsafe water for daily needs.	Neutral or mild agreement
26	Miners usually work without contracts or job security.	Disagreed across all factors

Consensus across stakeholders on specific issues, such as the need for health outreach programs and improved governance of mining schemes, underscores potential areas for unified action. Moreover, explicitly mapping stakeholder perceptions against SDGs reveals critical trade offs and synergies. Integrating economic activities with healthcare and environmental safeguards can convert perceived trade offs into sustainable synergies.

Community engagement remains vital. Perception management, transparency, and participatory dialogues can bridge stakeholder divides. Incorporating community monitoring and participatory methodologies could elevate local awareness and foster mutual understanding. Q methodology itself demonstrates potential as a reflective, educational, and consensus building tool, beneficial for policy formulation and community dialogues.

Limitations of this study include a modest sample size, potentially overlooking niche perspectives. Contextual generalizations require caution due to the localized nature of the research. Nonetheless, identified stakeholder archetypes offer transferable insights. Future longitudinal studies and comparative analyses across different mining contexts are recommended, combining subjective perceptions and objective environmental health metrics for comprehensive sustainability assessments. Integrating both qualitative perceptions and quantitative environmental data can enhance risk communication strategies and provide holistic insights critical for sustainable mining governance.

CONCLUSION

This study effectively employed Q methodology to capture the complex web of stakeholder perceptions in the context of small-scale limestone mining in Katni District. By engaging diverse stakeholders including miners, villagers, and regulators, the research uncovered three principal perspectives. The Livelihood Centric Realists emphasized the critical economic support mining offers to vulnerable populations, reinforcing the necessity of safeguarding livelihoods. The Health and Environmental Advocates highlighted the importance of integrating sustainable health, ecological protections, and human rights into mining practices. The Health Concerned Pragmatists pointed towards balanced solutions that allow mining to continue while significantly improving health, safety, and community services.

Connecting these perspectives with the Sustainable Development Goals (SDGs), the study illustrates the inherent tensions between economic development (SDGs 1 and 8) and environmental and health imperatives (SDGs 3, 6, and 13). Identifying these specific gaps can enable policymakers to target effective interventions more precisely. Ensuring health protection (SDG 3), preventing environmental degradation (SDGs 6 and 13), and maintaining economic opportunities (SDGs 1 and 8) emerged as core concerns for the community.

Practitioners and policymakers can use the insights from this research to avoid generic approaches and adopt strategies that address the nuanced needs of different stakeholder groups. For instance, livelihood improvement strategies should incorporate stable income and improved job conditions, while health and environmental strategies must robustly address local ecological and health concerns. Furthermore, targeted communication strategies informed by stakeholder perceptions can significantly enhance local engagement and trust in interventions.

The study highlights the value of systematically capturing stakeholder voices to inform balanced, inclusive, and sustainable mining development policies. Such participatory methodologies are essential for ensuring that mining benefits are maximized without compromising environmental and community well-being. The insights gained from this research underscore the importance of integrating subjective community experiences into policy design and adaptive management processes.

In conclusion, achieving sustainable development in mining regions is fundamentally a social negotiation, demanding continuous balance between economic growth, health, and environmental stewardship. Policymakers, researchers, and industry stakeholders should replicate similar participatory approaches across diverse contexts to ensure that development interventions remain responsive to local realities and contribute effectively to achieving global sustainability goals. “Future mining policies must be informed not only by economic feasibility but also by the voices of those most affected. This is a shift that Q-methodology helps make possible.”

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Investigation of Slake Durability Indices of Coal Measure Rocks in Sohagpur Coalfield, South Rewa Gondwana Basin, India

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ABSTRACT

Understanding the durability behavior of coal measure rocks is essential for ensuring the long-term stability of underground and surface structures in coal mining regions. This study presents a systematic investigation of the slake durability indices of key lithological units from the Sohagpur Coalfield in the South Rewa Gondwana Basin, India. Representative samples of shaly sandstone (grey), shaly sandstone (black), coarse grained sandstone, medium grained sandstone, fine grained sandstone and fine grained sandstone with shaly laminations were subjected to slake durability testing in accordance with ASTM - D 4644 and ISRM standards to assess their resistance to weathering under cyclic wetting and drying conditions. The results indicate a wide range of second-cycle slake durability indices , with coarse grained sandstone exhibiting notably low durability compared to more competent sandstones. Detailed petrographic and mineralogical analyses reveal that clay mineral content and textural fabric significantly influence the slaking behavior. These findings provide valuable insights into the geomechanical performance of coal measure rocks under field conditions and have important implications for slope stability, underground support design, and mine planning in the Sohagpur Coalfield and similar geological settings.

Keywords
Slake durability index ; Coal measure rocks ; Sohagpur coalfield; weathering ; Gondwana Basin.

INTRODUCTION

Background and Significance

The durability of rock materials is a critical factor in the design and stability of civil, mining, and various other geotechnical structures. In particular, coal measure rocks, such as shales and interbedded sandstones, are prone to weathering and degradation, especially when subjected to wetting and drying cycles common in tropical and sub-tropical climates. This degradation affects the performance of slopes, embankments, underground excavations, and other rock engineering projects. Therefore, evaluating the slake durability of such rocks is essential to predict their long-term behavior under environmental loading conditions.

The Slake Durability Index (SDI), introduced by Franklin and Chandra (1972), is a widely accepted quantitative measure of the resistance of weak or weatherable rocks to disintegration under cyclic wetting and drying. The test is particularly relevant for argillaceous rocks such as shales, mudstones, and clay-rich siltstones, which commonly occur in coal-bearing sequences (Yýlmaz et al. 2011; Singh et al. 2012). It has been used extensively in engineering geology to assess the degradation potential of rocks in various geological environments (Bell 2007; Altun et al. 2010).

Coalfields within the Gondwana Basin of India are characterized by a sequence of sedimentary rocks that include coal seams interbedded with sandstones, shales, and carbonaceous mudstones. Among them, the Sohagpur Coalfield in Madhya Pradesh is one of the most important coal-producing areas in central India, known for its extensive reserves and active underground and opencast mining operations (GSI 2018,CMPDI 2021). However, the long-term performance and stability of mine structures in this region are often compromised by the low durability of the associated rock types, particularly under fluctuating moisture conditions and anthropogenic disturbances.

Objectives of the Study

This study aims to investigate the slake durability indices of various coal measure rocks from the Sohagpur

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Coalfield using standardized laboratory testing protocols. The important objectives are:

- ✧ Determining the first and second cycle SDI values of representative lithologies;
- ✧ Analyzing the influence of mineralogical composition and textural features on the durability performance;
- ✧ Evaluating the implications of slake durability on geotechnical stability and mine design;
- ✧ Contributing to the regional database of engineering geological properties of Gondwana coal measure rocks.

Overview of the Study Area

The Sohagpur Coalfield is located in the eastern part of the Satpura Basin and forms a part of the Central Indian Gondwana coal belt. It encompasses a range of coal-bearing formations, primarily belonging to the Barakar and Motur Formations, characterized by alternating sequences of sandstone, shale, carbonaceous shale, and coal seams (Sarkar and Banerjee 2004; Ghosh and Mukhopadhyay 2010). The climatic setting is predominantly sub-humid to tropical, which accelerates the weathering of exposed rock faces and mine spoil heaps.

Given the widespread mining activities and geotechnical challenges in this region, an assessment of rock durability is not only academically significant but also crucial for improving slope design, underground support systems, and overall mine safety protocols.

GEOLOGICAL SETTING

The Sohagpur Coalfield, located in the eastern part of the Satpura Basin in Madhya Pradesh, India, forms a significant part of the Central Gondwana coal belt, which is renowned for hosting extensive coal reserves. Geographically, the coalfield lies within latitudes 22°152 N to 23°152 N and longitudes 81°302 E to 82°152 E, covering an area of approximately 3,313 km². It is one of the most productive coalfields under the jurisdiction of South Eastern Coalfields Limited, a subsidiary of Coal India Limited (CMPDI 2021; GSI 2018).

Stratigraphy

The stratigraphic succession in the Sohagpur Coalfield belongs to the Lower Gondwana Supergroup, particularly the Talchir, Barakar, and Motur formations.

The general stratigraphic order from bottom to top is as follows:

- ✧ **Talchir Formation**: Consisting of glacial conglomerates, greenish-grey shales, and sandstone layers, the Talchir marks the base of the Gondwana sequence. It acts as a regional unconformity over the Precambrian basement.
- ✧ **Barakar Formation**: The most economically significant unit, the Barakar Formation comprises cyclic sequences of coarse- to fine-grained sandstone, carbonaceous shale, and multiple coal seams. This unit hosts the majority of mineable coal reserves in the region (Ghosh and Mukhopadhyay 2010).
- ✧ **Motur Formation**: Dominated by reddish-brown ferruginous sandstones and siltstones with occasional shale bands, the Motur Formation overlies the Barakar conformably and indicates a shift to a more oxidizing fluvial environment.

Lithological Characteristics

The lithologies of the coal measure rocks include interbedded fine- to medium-grained sandstone, carbonaceous and silty shales, and coal seams of varying thickness. The rocks exhibit prominent cyclic sedimentation, a characteristic feature of Gondwana basins, attributed to repeated phases of subsidence and sediment influx under fluvio-deltaic to lacustrine settings (Sarkar and Banerjee 2004; Casshyap and Tewari 1988). The shales and carbonaceous mudstones, being rich in clay minerals such as kaolinite and illite, are particularly susceptible to weathering and mechanical disintegration under wetting-drying cycles.

Sandstones are typically arkosic to subarkosic in composition and moderately compacted. Their mechanical behavior is generally more stable than the finer-grained shales but varies depending on cementation, grain size, and mineral content.

Structural Framework

The coalfield is broadly synclinal in structure, trending NW–SE, and is dissected by several faults and joint systems that influence groundwater movement and rock mass stability. Localized folding, faulting, and differential compaction have resulted in variations in seam thickness and dip, which pose significant challenges in mining (Tiwari and Mehrotra 2000).

Climatic and Weathering Conditions

The Sohagpur Coalfield experiences a sub-humid to tropical monsoonal climate, with high annual rainfall (~1200 to 1400 mm), most of which occurs between June and September. These environmental conditions promote physical and chemical weathering of exposed rocks, particularly shales and fine-grained sediments, which show rapid degradation under repeated exposure to wetting and drying conditions. This climatic influence makes the assessment of slake durability critically important for understanding the long-term behavior of these rocks in field.

MATERIALS AND METHODS
Sample Collection and Lithological Classification

Rock samples were systematically collected from two boreholes at various depths located within the Sohagpur Coalfield, covering representative lithologies. The rock types included coarse grained sandstone, medium grained sandstone, fine grained sandstone, fine grained sandstone with shaly laminations, shaly sandstone, (grey), and shaly sandstone (black) depicted in Figure 1. Sampling locations were selected based on accessibility, lithological diversity, and geological relevance. The collected samples were wrapped in moisture-resistant material and transported to the laboratory for testing and analysis.

Figure 1 : Lithological Units (Left to Right) - Ferruginous Shale, Argillaceous Limestone, Fine grained sandstone with shaly lamination, Shaly Sandstone (Black), Shaly Sandstone (Grey) , Coarse grained sandstone, Medium grained sandstone , Fine grained sandstone.

Figure 2 : Rock Samples for Slake Durability Index Test

Figure 3 : Vacuum Oven for Drying the Rock Samples

Figure 4 : Experimental Set up for Slake Durability Index Test

Sample Preparation

In accordance with ASTM D4644-16 and ISRM Suggested Methods (1981), the collected borehole rock samples were manually broken using a geological hammer to obtain irregular particles with diameters between 40 mm and 60 mm. Each test sample consisted of 10 clean, dry rock fragments weighing approximately 450–500 grams in total. Care was taken to ensure consistency in fragment size, shape, and mass across different samples to minimize test variability.

Slake Durability Test Procedure

The slake durability test was conducted using a standard slake durability apparatus comprising a rotating drum made of 2 mm mesh screen mounted on a horizontal axis. Each test involved two drying and wetting cycles namely cycle 1 and cycle 2. The dry samples were weighed (W€) and placed in the drum. The drum was partially submerged in distilled water and rotated at 20 rpm for 10 minutes. Samples were then oven-dried at 105°C for 24 hours and reweighed (W). For cycle 2, the same process was repeated using the same sample set, and the final weight after drying was recorded as (W,). First and the second cycle slake durability was then calculated using the theoretical relationship.

RESULTS

Table A: Slake Durability Indices of Coal Measure Rocks

Serial No	Rock Type	SDI_1, %	SDI_2, %	Durability Class (Franklin & Chandra, 1972)
1	CGSS	85.47	77.24	High Durability
2	MGSS	86.09	78.47	High Durability
3	FGSS	93.60	88.85	High Durability
4	FGSS-SL	92.45	87.28	High Durability
5	SSG	91.99	85.60	High Durability
6	SSB	94.16	92.58	Very High Durability

Slake Durability Indices

The slake durability tests revealed a significant variation in the second-cycle slake durability index (SDI,) values among the major lithologies: shale, sandstone, and coal-bearing strata. The results are summarized in Table 1 and shown graphically in Figure .

- ✧ Coarse grained sandstone (CGSS) samples exhibited the lowest SDI, values, which displayed extensive surface disintegration.
- ✧ Shaly Sandstone ,black (SSB) samples, closely followed by fine grained sandstone (FGSS) showed high durability, with minimal mass loss and no visible fragmentation, indicating resistance to slaking under cyclic wetting-drying conditions.
- ✧ Fine grained sandstone with shaly laminations (FGSS-SL) samples (which include interlaminated shale and mudstone) displayed intermediate durability, influenced by both the presence of soft clay-rich layers and carbonaceous matter.

Figure 5 : Coal Measure Rock Samples After Slake Durability Test

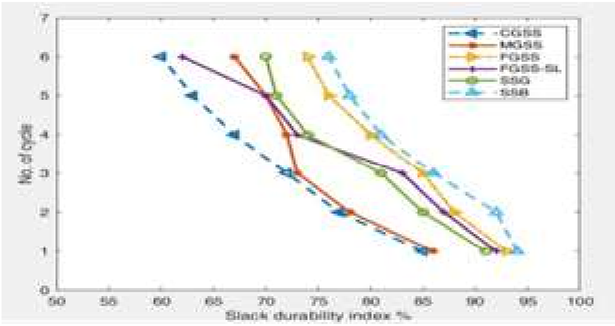

Figure 6 : Influence of Number of Cycles on Slake Durability of Rocks

VISUAL OBSERVATIONS DURING TESTING

Visual inspection during and after the tests confirmed the laboratory measurements. Shaly sandstone (SSG & SSB) fragments softened rapidly upon wetting, with some samples disintegrating into angular chips and fine particles. The Sandstones (CGSS, MGSS & FGSS) retained their structure with minor edge rounding. The intercalation samples (FGSS-SL) showed laminar separation and occasional crumbling along bedding planes. These qualitative observations support the measured SDI values and are illustrated in Figure 5, which shows representative post-test fragments of each lithology.

Petrographic and Mineralogical Correlation

Thin section and XRD analyses provided insights into the mechanisms controlling durability. Shaly sandstones (SSG &SSB) were dominated by clay minerals such as kaolinite and illite, quartz grains, with a fine-grained matrix and weak grain bonding. The presence of dispersed organic matter and micro-fractures increased susceptibility to slaking. Sandstones (FGSS) consisted largely of quartz grains in a siliceous or ferruginous matrix, with low clay content and tight grain interlocking, accounting for their high durability. The intercalation samples FGSS-SL) showed bedded textures with alternating bands of clay-rich shale and carbonaceous layers, leading to heterogeneous slaking behavior. A negative correlation was observed between SDI, values and clay mineral content (r = –0.81), reinforcing the role of mineralogy in rock disintegration under wetting conditions.

DISCUSSION

Influence of Lithology on Slake Durability

The results of the slake durability tests underscore the critical role of lithology and mineral composition in governing the resistance of coal measure rocks to wetting-drying cycles. Among the tested rocks, sandstones (including SSB, SSG, and FGSS) exhibited the higher SDI, values, consistent with their mineralogical composition dominated by quartz and feldspars with limited clay content and strong intergranular bonding. This observation aligns with findings by Yilmaz et al. (2004), who reported similarly high slake durability for quartz-rich sandstones in Turkish coalfields. In contrast, the CGSS showed pronounced degradation, with average SDI, values at 77 %. The presence of clay minerals (kaolinite, illite) and dispersed organic matter likely contributed to water absorption, swelling, and eventual disintegration. This behavior is well documented in previous studies, which have identified clay mineralogy and fabric anisotropy as key determinants of shale durability (Franklin and Chandra 1972; Gokceoglu et al. 2000). The intercalation samples (FGSS- SL), which are interlaminated with soft shales and mudstones, exhibited intermediate SDI values. Their variable response reflects the heterogeneity in bedding composition, with alternating competent and friable layers, making them particularly sensitive to environmental conditions such as moisture fluctuations and freeze-thaw cycles (Dearman 1991).

Role of Mineralogical Composition

The inverse relationship between SDI and clay mineral content (Pearson r = –0.81) is consistent with prior research emphasizing the deleterious impact of expansive and weak clay minerals on rock durability (Basu and Tutuncu 2011). The ability of clay-rich rocks to adsorb water, leading to microstructural weakening and crack propagation, is a primary cause of mechanical deterioration in coal-bearing formations. Additionally, the laminated nature of shale and coal enhances permeability along bedding planes, facilitating water ingress and further accelerating slaking. The XRD analyses confirmed the dominance of kaolinite and illite, both of which are known for their moderate swelling potential. Although not as expansive as smectite or montmorillonite, their platy morphology and high surface area contribute to structural breakdown upon cyclic saturation and drying (Hawkins and Pinches 1997).

Implications for Mining and Rock Engineering

The slake durability of coal measure rocks has direct implications for underground and opencast mining operations, particularly in terms of - slope and highwall stability(shales and coal-bearing strata are prone to rapid weathering and mechanical weakening, increasing the risk of bench failure in opencast mines; support design in underground workings (roof falls and rib degradation in galleries are commonly associated with shale-rich strata that deteriorate under humid or waterlogged conditions (Singh et al. 2007); excavation planning (knowledge of slake durability can assist in optimizing pit designs, spoil management, and long-term monitoring of geotechnical hazards.

Given the tropical monsoonal climate of the Sohagpur region, the observed low to medium durability of the rocks highlights the need for adequate drainage systems, proactive support installation, and weathering-resistant lining or coatings in infrastructure intersecting these formations.

Comparison with Other Gondwana Basins

The durability characteristics observed in the Sohagpur Coalfield are broadly consistent with findings from other Indian Gondwana basins, such as Raniganj, Talcher, and Jharia. For instance, [Sengupta and Ghosh (2005)] reported SDI, values of 45–65% for carbonaceous shales in the Raniganj Basin. Such regional consistency suggests that mineralogical controls on durability transcend local geological variations, reinforcing the value of slake durability testing as a predictive tool for rock behavior in coal mining contexts.

CONCLUSION

This study presents a comprehensive investigation into the slake durability behavior of representative coal measure rocks from the Sohagpur Coalfield, with implications for rock engineering, mine safety, and environmental stability.This integrated approach to assessing the durability of coal measure rocks provides a practical and scientific basis for enhancing mine planning, slope stability management, and environmental protection in coalfield regions.

The key findings can be summarized as follows:

- ✧ The slake durability index (SDI,) varied significantly among lithologies, with sandstones (SSG,SSB & FGSS) showing higher durability (SDI, > 85%), CGSS exhibiting lower durability (SDI, < 72%), and coal- shale bearing intercalations displaying intermediate durability.
- ✧ Mineralogical composition, especially clay content and the presence of kaolinite and illite, was found to be a major factor influencing the slaking behavior. Rocks rich in clays and organic matter degraded more rapidly upon cyclic wetting and drying.
- ✧ Petrographic analysis revealed that microfractures, laminated textures, and matrix bonding quality strongly contribute to the mechanical breakdown of shale and coal-bearing rocks under weathering processes.
- ✧ The inverse correlation ($r = -0.81$) between SDI and clay mineral content confirms that higher clay concentrations reduce durability, supporting previous regional and international studies.
- ✧ The results align with durability patterns observed in other Gondwana coalfields, reinforcing the predictive validity of slake durability testing for Indian sedimentary basins.

RECOMMENDATIONS

Based on the findings, the following recommendations are proposed for engineering and mining applications in the Sohagpur Coalfield and similar geological settings:

- ✧ **Engineering Design**: In mine design, prioritize reinforcement and support in shale- and coal-rich strata due to their susceptibility to slaking and weakening. Avoid placing long-term infrastructure (e.g., haul roads, shaft collars) directly on or within low-durability lithologies unless appropriate ground improvement techniques are implemented.
- ✧ **Drainage and Water Control**: Implement effective surface and subsurface drainage systems in opencast mines to minimize prolonged exposure of shale and coal-bearing strata to water, especially during the monsoon season.
- ✧ **Monitoring and Hazard Mitigation**: Install slake-prone material monitoring systems, including geotechnical instrumentation, in slopes and underground workings that intersect shale-rich zones. Use slope stability models that incorporate durability indices for accurate risk assessment and timely preventive measures.

- ✧ **Material Classification and Use**: Incorporate SDI-based classification into mine waste management, particularly in determining suitability of excavated rock as fill or embankment material. High-durability sandstone may be reused, whereas shale and coal-bearing waste may require stabilization.
- ✧ **Future Research Directions:** Extend the study to include long-term weathering simulations, freeze-thaw testing, and durability under varying pH conditions to better replicate field conditions and predict performance over mine life cycles.

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Geo-Mechanical Properties and Kinematic Analysis of Different Joints on Hard Rock Manganese Mining

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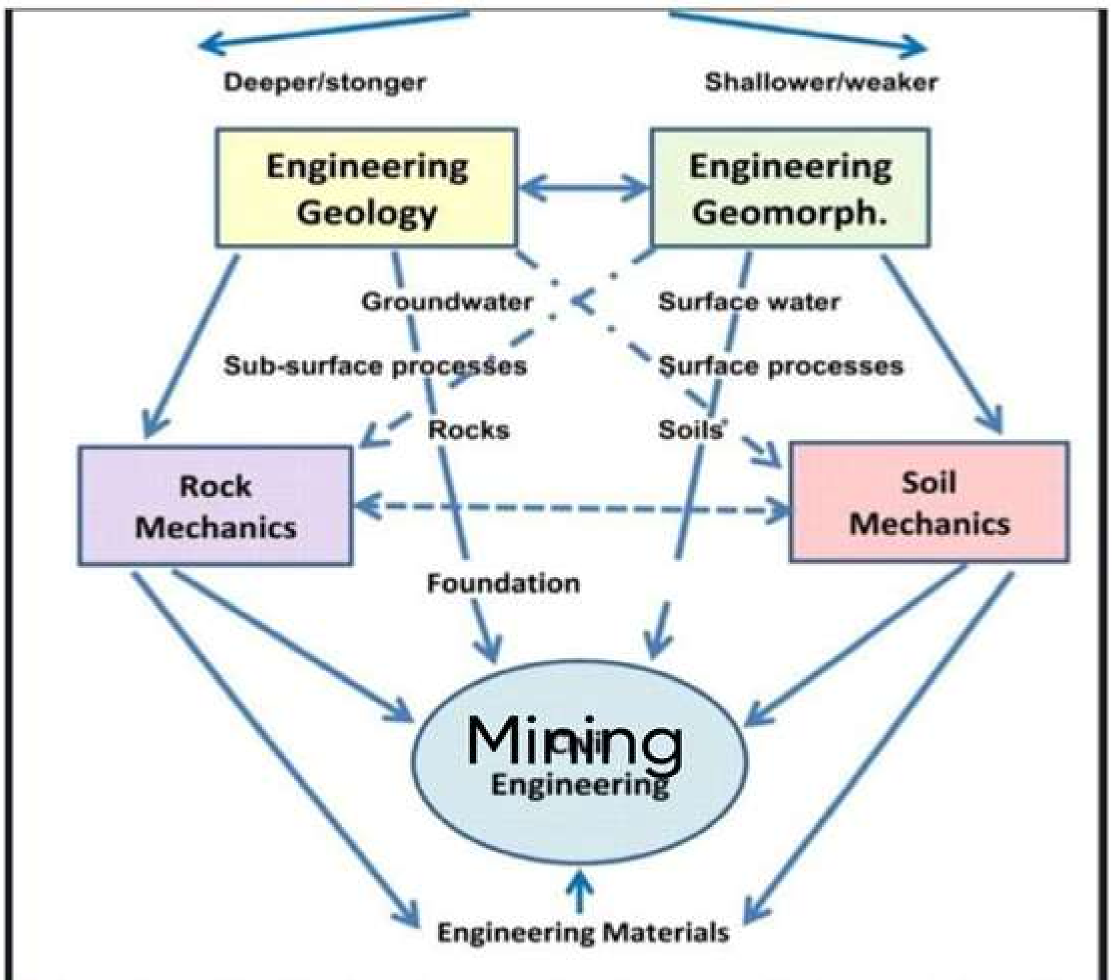
ABSTRACT

Hardrock mining is referred underground metal mining. In this method of mining geology, geotechnical property influence significantly right from the mine development stages. In india there are hard rock mines, Mining gold, copper, silver, Pb-Zinc,Manganese, etc. In most mines the geological setup is very comples and their influence in development & production/ Stoping is very significant.



Schematic of the Engineering Geology/ Geomorphology Relationships
(after Fookes and Lee, 2005)

Figure explains engineering geology & geomorphylogy relationships.

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ANKIT SINGH, SHRINIVAS BUDIME, BHUPENDRA K. MISHRA & RAMESH KANT

An attempt has been made in this paper to highlight role of geomechnical properties and joints , of one of the oldest underground Manganese mine at Bharweli , Balaghat (M.P.). The present research study towards designing of support system of the working stope at 13.5 L as well as of various development headings of Balaghat mine of MOIL Ltd. The MOIL management has already increased the level interval from earlier 30 m to 45 m in-between 12th to 13.5th and underneath levels. The conclusions and recommendations are based on the findings of the scientific study carried out using empirical, mathematical and numerical approaches. Keeping in view stoping operation in overhand cut-and-fill stoping with simultaneous backfilling as a man-entry and based on the findings from application of various approaches. The support system requirement is also devised in the case of various development headings of different cross-sections as well as during the construction of shaft inset. Considering drivages and shaft inset as a permanent type of the structures, 2 m long fully resin grouted rock bolts is recommended along with the required number of bolts and spacing according to the size of the development headings. It is recommended to go for the full-fledged instrumentation monitoring program during the stoping operation in 13.5th Level during the actual stoping operation. This will help towards achieving safer and economical stoping operations with the increased confidence. The instrumentation programme should include rock movement observation from the stope back (MPBX and convergence indicators), in the stope/crown pillars and rib/post pillar (strain gauges/load cell/capsules) etc.
Key world: Geotechnical instrumentation, Strata Control, Manganese Ore.

INTRODUCTION

Bharweli Mine is located in Balaghat District, Madhya Pradesh and is 223 Km from Nagpur. It can be approached by all weathered road. The Balaghat Manganese Mine is 6 Km away from Balaghat railway station. The Mine area falls on topo sheet No 64 C/1 and is situated at 21° 50’ North Latitude and 80° 14’ East Longitude. Mining was started in the year 1902 in this mine (As per GSI Report). Balaghat mine comprises of two leases i.e (a) Lease-I-182.3004 hect lease (b)

Lease-II-0.789 hect lease and (c) Lease-III-76.406 Ha. Therefore the total lease hold area is 259.4984 hectares. Balaghat Mine is deepest and largest underground Manganese Mine in Asia. Central Provinces Prospecting Syndicate at the herald of twentieth century originally acquired the manganese mines. This syndicate was converted into a limited liability company in 1908 and in April 1924 its name was changed to Central Provinces Manganese Ore Company Limited. In July 1962 Govt. of India took control of the company and rechristened it as Manganese Ore (India) Limited with its head office at Nagpur. After partial disinvestment in 2010 now company is known as MOIL Ltd. At present there are three Shafts to provide access to the various levels at the mine. The details are mode of entry are given as under.

Holmes Shaft: It’s a rectangular shaft of 7mX3.05 m. The shaft collar is at MRL 333.58, and it’s working depth is 436 m it serves as mode of entry and egress to 6th Level, 7th Level, 8th Level, 9th Level, 10th Level, 11th Level, 12th Level,13.5th Level, 15th Level & 16.5th Level.

Production Shaft: It’s a circular shaft of diameter 4.5 m. The shaft collar is at MRL 313.34, and it’s working depth is 370 m it serves as mode of entry and egress to 8th Level, 9th Level, 10th Level, 11th Level, 12th Level,13.5th Level & 15th Level.

Edward Shaft: It’s a rectangular shaft of 4.5m X 2.4m. The shaft collar is at MRL 312.65, and it’s working depth is 62 m it serves as mode of entry and egress to 5th Level.

High Speed Shaft: It’s a circular shaft of diameter 7.5 m. The shaft collar is at MRL 305.60, and it’s will be sunk up to depth 750 m. The sinking of high-speed shaft is under progress. Up to March’2021 the depth of high-speed shaft is 683.00 mtrs. It will be serves as mode of entry and egress to 15th Level to 27.5th Level.

GEOLOGY AND ORE BODY CHARACTERSTICS

Bharweli mine is located (21^0 51’ N longitude 80^0 14’ E within Toposheet No. 64 C/1) in Balaghat District of Madhya Pradesh. The Sausar Group rock series traverses a large area representing Balaghat and Chhindwara districts in Madhya Pradesh while, Nagpur and Bhandara in Maharashtra. The Sausar group of meta-sediments extends from Balaghat district in east to Chhindwara district and has strike length of about 210 km with a width of about 25 km. The manganese belt of Madhya Pradesh

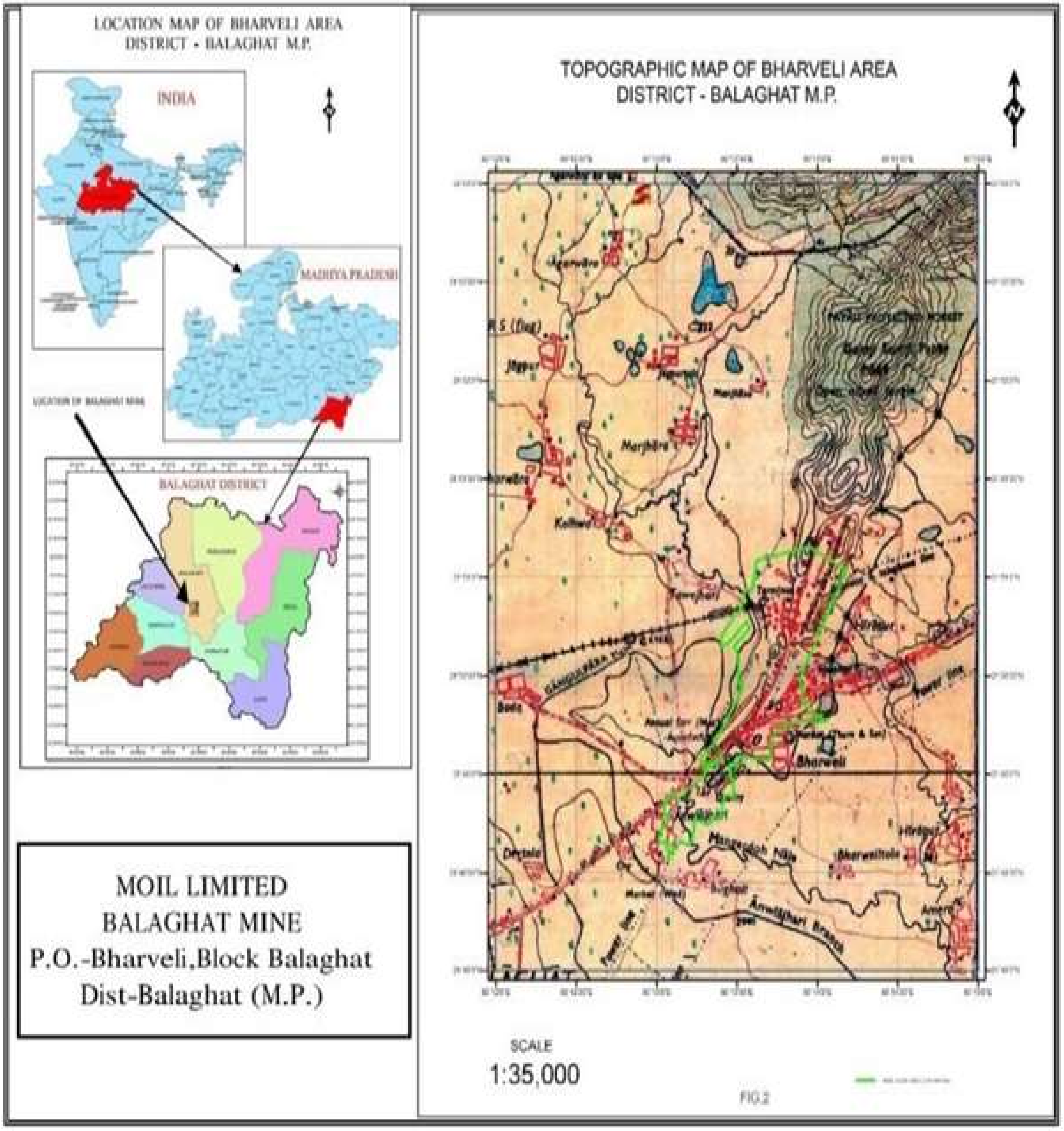

Figure-1.1: Location map of Bharweli mine, Balaghat, M. P.

and the adjoining parts of the Maharashtra forms an arcuate belt.

The major structural features present in and around the Bharweli mine which are affecting the mineralization are as follows: over thrust, faults, recumbent folds, joints along with planar and linear structures like bedding and lineation.

The manganese mineralization in Bharweli manganese deposit is associated with peliric (fine grains) and psammitic (medium grains) rocks of Mansur formation and strata bound in nature. The litho-stratigraphic and the structural are the two main controls for the manganese mineralization in the area. Based on the mineralogical studies, manganese is confined to the sericite schist and

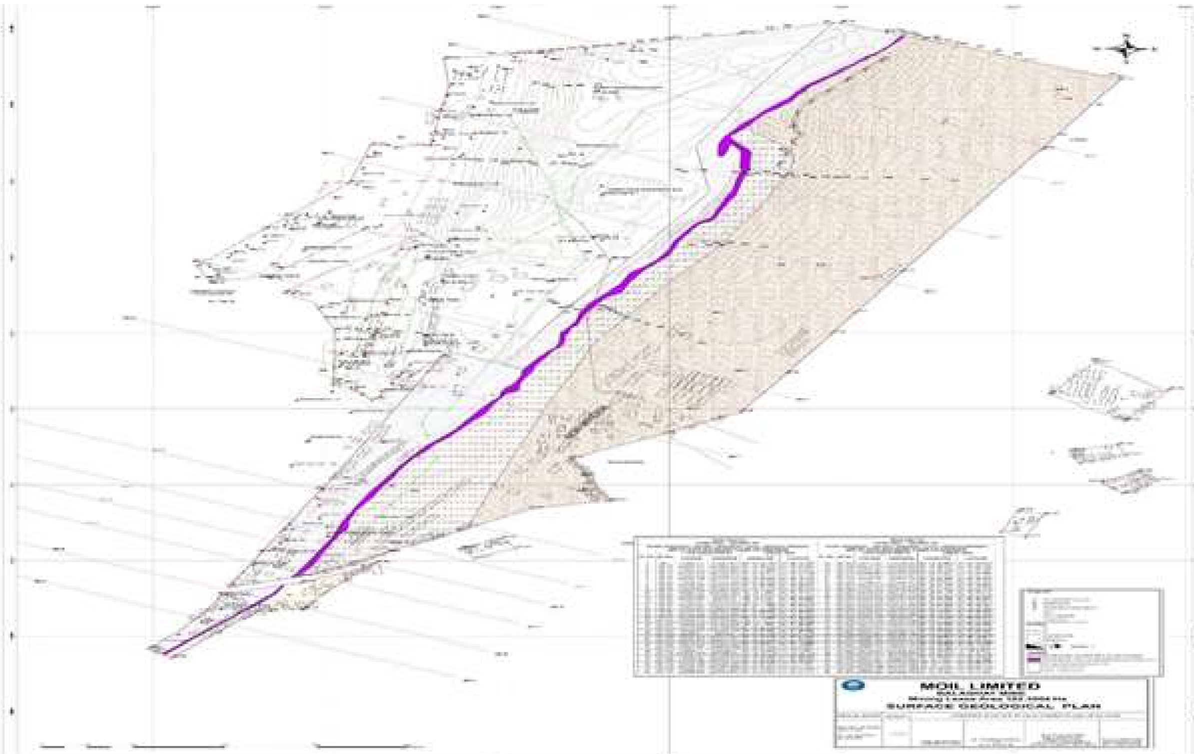

Figure-1.2: Suface Geological plan , Bharweli Mine Balaghat

quartzite rocks. The ore body has a strike direction of N25^0 E-S25^0 E with a dip of 15-850 due W. At some places the banded Manganese formation of folded type is reported. The mineralogical studies also revealed that braunite is the major manganese ore mineral along with hallandite, manganite, psilomelane and pyrolusite.

The ore body is generally varying from 4 to 30 m in thickness, highly jointed, manganese oxide mixed with manganiferous quartzite. The hangwall is mostly comprised of weak schistose types of rock. The hangwall formations are phyllites, phyllitic schist and sericite schist and the footwall formations include weak and clayey feldspathic quartzite and quartz schist.

In Bharweli manganese mine, the ore body is stretching out in almost straight line about 2.8 km in length; the general strike direction is N 25^0 E, dipping towards N 65^0 W. The ore body is thick in the middle portion and in the extremities it is thinning out and ultimately disappears. The maximum thickness in middle portion is about 20 m and minimum is about a meter. However, mostly average thickness of orebody is reported at 6 m. In the southern extremities ore belt is steeply dipping in about 800 where as in the northern extremities it is very flat at about 100 . The middle portion has observed at least two cycles of folding. The Sausar group rocks along with manganese ore structurally are intensely folded into overturned isoclinals and recumbent folds whose axes generally plunges east-ward with low to moderate angles.

The ore body was out-cropped all along the crest of the Eastern ridge. The strike length is 2.90 km with general direction of strike is N25°E – S25°W with westerly dips of the order of 25° to 4 85° except in Northern section where structural complications have resulted in much flatter westerly dips and at few places even it reversed dips. The width of the ore bed ranges between 3-20 m. The ore body is wider towards North having greater thickness (somewhere 20 - 30 m) because of very low order of flat dips at 10 degrees. However at the present in 13.5 L in the case of northern extremities average orebody thickness reported is 8-10 m with dipping varying from 25-60 degrees, while in the case of southern extremities it is 3.5-4.0 m thick with 65-85 degrees dipping.

The measured joint orientations of localized joint sets at different locations at the Balaghat mine is given in Table 1 and kinematic analysis of these joint sets carried out is given in Fig. 2. From the kinematic analysis, it is seen that orientation of discontinuities with respect to the orientation of opening is showing possibility of different types of failure likely to be occurred.

Table 1.: The measured orientation of different joint sets at Balaghat mine

The orientation of different joint sets at Balaghat Mine.							
Location	J1		J2		J3		Remarks from kinematic analysis
	Strike (°)	Dip (°)	Strike (°)	Dip (°)	Strike (°)	Dip	
Footwall (L1): 37 Cross-cut North	224	52	220	30	310	68	Possibility of Planer Failure
Footwall (L2): 35 Cross-cut junction North	42	55	235	12	350	60	Minimum risk to failure
Hanging Wall (L1): Haulage Drive 45 cross-cut	218	84	285	22	332	74	Possibility of wedge failure
Hanging Wall: (L2) 37 Cross-cut North	242	63	20	80	316	72	Possibility of wedge failure
Ore Body: 35 Cross-cut junction North	55	69	165	20	345	70	Minimum risk to failure

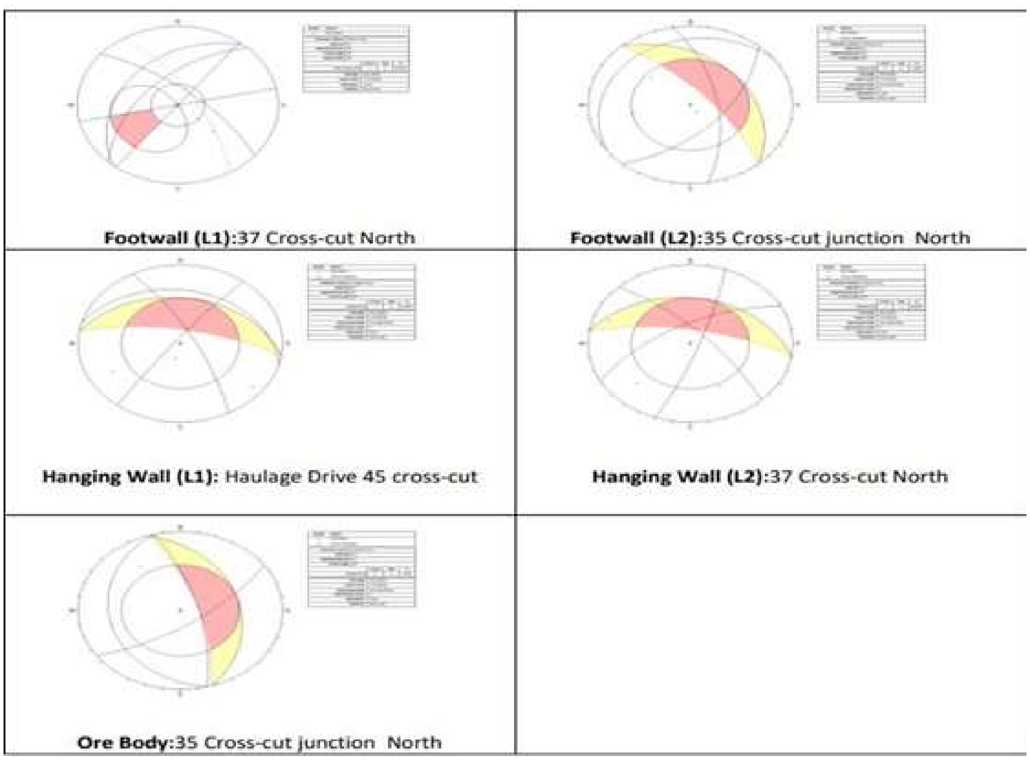

Figure: 1 Kinematic analysis of different joint sets with respect to the opening orientation(Source:- CIMFR 2015)

JOINTS ORIENTATION

The rock mass encountered in these underground excavations is classified as moderately jointed with major two to three joint sets with random. The major joint sets are sub-vertical. The vertical/sub-vertical joints are critical from the stability point of view. The joints are irregularly spaced. The spacing between joints varies from 60-200 mm. The joints are smooth, rough or irregular and planner in nature.

GEO-MECHANICAL PROPERTIES

The geo-mechanical properties of various rock types encountered in the stoping environment is presented in Table 2. The rock cores were obtained from the mine during our visit made in the month of November 2020 and were tested at our Rock Mechanics Laboratory at Dhanbad in December 2021. The representative rock cores obtained from the mine and prepared rock samples for laboratory testing are shown in Fig. 2.

a. Rock cores obtained from the mine

b. Rock samples prepared for laboratory testing

Figure 2: The obtained rock cores from the mine and prepared rock samples for laboratory testing

The various properties determined from the laboratory testing were averaged as shown in Table 2 for respective rock types and grouped according to the hangwall, footwall and ore rock type. The average rock mass properties (Table 3) were determined with the application of Rock Lab Software of RocScience Inc., Canada using intact rock properties as given in Table 2. The obtained rock mass properties were then used in the numerical modeling studies.

Table. 2: The determined physico-mechanical properties of various rock types in laboratory.

Property	Ore body	H/W			F/W			Average for rock mass
		Sericite Schist	Phyllite	Average	Quartz-mica Schist	Feldspathic Quartzite	Average	
UCS (MPa)	59.0	46.0	8.2	27.0	83	57	70	**52.0**
Young's Modulus (GPa)	9.0	11.0	0.1	6.0	16	7	12.0	**9.0**
Tensile Strength (MPa)	7.0	9.0	0.82	5.0	5	10	8.0	**7.0**
Poisson's ratio	0.22	0.3	0.25	0.28	0.3	0.2	0.25	**0.25**
Cohesion (MPa)	7.0	8	-	8	---	8	8	**8**
Friction Angle(°)	61.0	41	-	41	---	56	56	**53.0**
Unit Weight (ton/m³)	3.0	2.8	2.5	2.7	2.7	2.7	2.7	**2.8**
Porosity (%)	0.8	0.37	---	0.37	0.52	0.38	0.45	**0.54**
Slake Durability Index (%)	--	98	---	98	---		---	**98**

Table 3. Average rock mass and fill properties used in numerical modelling studies

Parameter	Orebody	Footwall	Hangwall	Phyllite	Fill Material
Rock mass modulus, E_{rm} (GPa)	2.5	2.5	2.5	0.6	0.2
Poisson's ratio, ν_{rm}	0.25	0.25	0.25	0.25	0.15
Cohesion, c_{rm} (MPa)	2.4	2.4	2.00	0.3	-
Angle of internal friction, ϕ_{rm} (Degrees)	38	38	25	22	-
Density (Kg/m³)	2800	2800	2800	2500	1500

IN-SITU STRESS

The measured in-situ stress values are not available for any underground manganese mine in this area. Since, a theoretical equation for estimating the mean horizontal stress for isotropic rocks proposed by Sheorey (1994) is being used. The mean horizontal stress evaluated using the Sheorey's formula for Balaghat mine as:

$$SH = 4.8 + 0.0138H \quad (1)$$

The vertical in situ stress is taken as the one induced due to gravity

as $Sv = \gamma H$ (2)

where, SH is average horizontal stress (MPa), γ = average rock density in MPa /m = 0.025 and H = depth of cover. Using above equations in-situ stress determined in the case of 13.5th and 15th Levels is provided in Table 4

Table 4. In-situ stresses determined

Level	Depth (m)	S_V (MPa)	S_H (MPa)
13.5 Level	338	8.45	9.46
15 Level	383	9.57	10.08

CONCLUSION

Keeping in consideration stoping operation in overhand cut-and-fill mining as a man-entry and findings as tabulated in the above, the following support recommendations are being made:

1.5 m long fully cement grouted rock bolt at the spacing of 2.0 m in tandem with 12 m long cable bolt in-between during the stoping operation. In the case of resin grouted rock bolt spacing isrecommended at 2.4 m with long cable bolts in-between. In-situ post-, crown- and rib - pillars of 5 m thickness each is to be left out as a natural support to take care of the stoping mining environment. In-situ post pillars are to be left-out after every opening span of 10 m (15 m C/C) in the case of stope width up to 15 m and exceeding 15 m stope width it is suggested at 8 m (13 m C/C). In all the cases in above, proper support as recommended will be needed to achieve the stable stoping mining environment. Also, support system during the excavation and construction of the shaft inset as well as drivages including haulage roadways, cross-cuts and ore drives of various dimensions is being recommended along-with other support and excavation guidelines. The proper Instrumentation and monitoring is recommended during the actual stoping operation to gain confidence and ensure the safe mining environment.

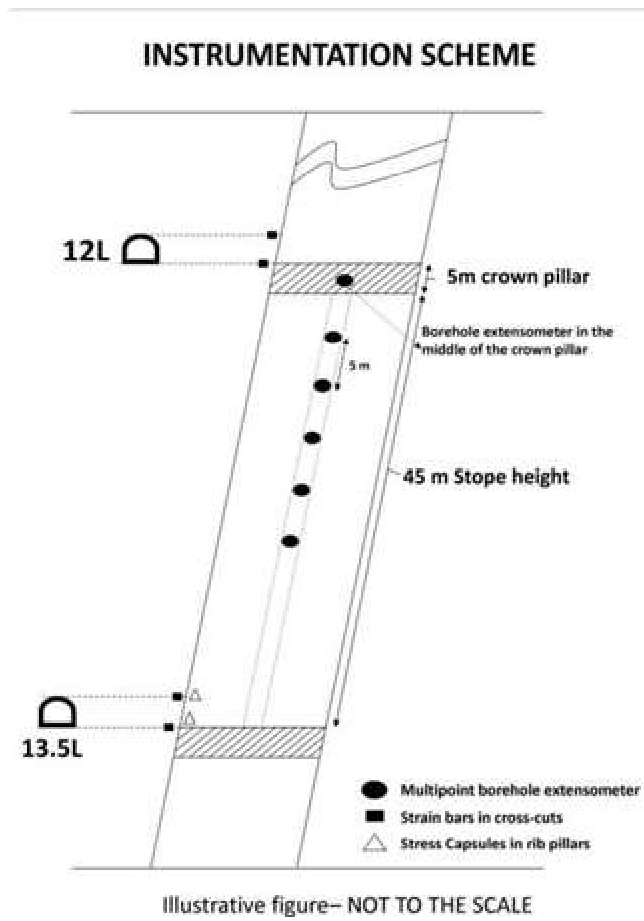

Figure 3.: Instrumentation scheme at Balaghat mine

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Use of Lowgrade Limestone of Sidhi District M. P.

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ABSTRACT

The Sidhi district of Madhya Pradesh, India, is rich in limestone deposits, though a significant portion of this resource is categorized as low-grade. This study explores the potential industrial applications of low-grade limestone, focusing on its chemical and physical properties. Key characteristics such as calcium carbonate ($CaCO_3$) content, magnesium content, silica impurities, and physical form are analyzed to determine suitability for various industries.

Traditionally, high-grade limestone is used in cement manufacturing, steel production, and as a flux material. However, advancements in processing technologies and the increasing demand for cost-effective alternatives have created opportunities for utilizing low-grade limestone.

The findings emphasize the need for beneficiation processes to enhance the quality of low-grade limestone for specific applications. Economic and environmental benefits include reducing waste, lowering raw material costs, and minimizing the environmental footprint of limestone mining. This study highlights the potential for low-grade limestone to contribute significantly to the region's industrial development, provided that innovative processing and utilization strategies are adopted.

Key world: Low-grade Limestone, Innovative processing, Beneficiation processes, utilization strategies.

INTRODUCTION

The Sidhi district, located in the northeastern part of Madhya Pradesh, India, is known for its rich mineral resources, particularly limestone. While a significant portion of this limestone is of high quality and widely used in various industries, a considerable amount is classified as low-grade due to its lower calcium carbonate ($CaCO_3$) content and higher levels of impurities such as silica, alumina, and magnesium. Historically, low-grade limestone has been overlooked or discarded as waste due to its limited direct usability in conventional applications.

With the increasing demand for sustainable resource utilization and advancements in beneficiation technologies, low-grade limestone has gained attention as a valuable material for industrial applications (Mishra and Tripathy 2019; Patra and Gupta 2020). The industrial use of such limestone not only aligns with sustainable mining practices but also offers economic benefits by reducing waste and optimizing resource extraction (Singh 2021; Sinha and Singh 2018).

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This introduction provides an overview of the geological distribution of limestone deposits in the Sidhi district, highlighting the composition and characteristics of low-grade limestone. It also discusses the challenges associated with its utilization, including processing and quality enhancement. Furthermore, it emphasizes the growing interest in alternative applications across various industries, including cement manufacturing, construction, environmental management, agriculture, and chemical production.

By identifying and leveraging the potential of low-grade limestone, this study aims to contribute to regional industrial development, promote sustainable practices, and address the broader goal of efficient resource utilization.

Portland cement is one of the most widely used construction materials, produced by sintering a mixture of raw materials primarily composed of calcium oxide (CaO), silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), and iron oxide (Fe_2O_3). The process involves a high-temperature reaction of a lime-rich material with components containing silica, alumina, and iron, resulting in the formation of clinker. The clinker is then ground with gypsum to produce cement.

The mineralogical composition of clinker includes four primary phases:

- **Cƒ S (Tricalcium Silicate):** Responsible for early strength.
- **C, S (Dicalcium Silicate):** Contributes to long-term strength.
- **Cƒ A (Calcium Aluminate):** Affects setting time and heat evolution.
- **C„ AF (Tetracalcium Aluminoferrite):** Provides color and some strength.

The quality of cement depends on the proportions of these compounds, which in turn are influenced by the chemical composition of the raw materials. The ideal composition for Portland cement clinker includes CaO (60–65%), SiO, (22–24%), Al, Oƒ (4–7%), and Fe, Oƒ (2–4%), with minor components such as MgO, alkalis, and SOƒ constituting less than 10%.

High-grade limestone, characterized by its high CaO content and low impurities, is ideal for clinker production, as it ensures the formation of sufficient Cƒ S and C, S phases. Conversely, low-grade limestone, with reduced CaO and elevated levels of SiO, and MgO, presents challenges in maintaining the required mineralogical balance in the clinker. The variability in chemical composition can complicate the control of raw mix modulus, such as the lime saturation factor (LSF), silica modulus (SM), and alumina modulus (AM), critical for clinker formation.

India possesses vast limestone reserves, varying widely in quality across different geological formations from the Archaean to the Tertiary period. However, the geographic distribution is uneven, with some regions lacking significant limestone deposits. The Sidhi district of Madhya Pradesh, known for its substantial but largely low-grade limestone resources, exemplifies this variation.

This study underscores the importance of understanding the thermal, chemical, and mineralogical behavior of low-grade limestone in clinker production. By addressing the challenges associated with its utilization, the cement industry can expand its raw material base, reduce dependency on high-grade resources, and promote sustainable practices.

REGIONAL GEOLOGY

The limestone of Majhgawan lease area belongs to Rohtas Stage of Semri Series of Lower Vindhyan System of Indian Stratigraphy. Ghaghar quartzite overlies the Rohtas Stage that forms a part of the Kaimur Hills. Semri Series overlies Glauconite Beds of Son Valley area. The regional strike of limestone deposit is ENE – WSW with a northerly dip varying from 10º to 15º into the hills. The Rohtas Limestone belt is extending over a distance of about 150km in the Sidhi District along the southern escarpment of Kaimur Plateau from Majhgawan, Sarda, Gorhatola to Sihawal in Sidhi District and further east of it upto the border of UP State in the District of Mirzapur (Hartman et al 2002). The western part of the belt extends into Satna District from Hinauti to Jigna village and beyond it. The Kaimur comprising of sandstone, quartzite is exposed in the north of the limestone belt and form a prominent plateau, rising to about 600mRL. To the south at a considerable distance limestone and sandstone is exposed followed by procellanite and basal beds, all classified along with Khenjua Stage. Further south of it, i.e., Beyond Khenjuans it is metasediments of Bijawars. The limestone is inter-bedded with shale and high magnesian limestone. The presence of shale bands becomes far more conspicuous in the lower part of the deposit, thus deteriorating its quality from the view point of its suitability for cement making.

The limestone of Rohtas Stage and the overlying Kaimur sandstone are the only litho units that can be observed on the spurs formed along the hill slopes. The valley and hilly area is under a cover of mixed soil and talus. No structural disturbance like folds, faults, and unconformity is observed in the area. The usable limestone horizon exposed as well as encountered during exploration is generally grey to dark grey in colour and fine grained banded in nature. for the quality point of view High MgO limestone is normally light grey coloured and primary beddings are obliterated. The intensity of shale bands generally increases towards the bottom of the horizon. Thin partings of shale intercalation within limestone have degraded the quality of limestone, based on this observation of gradational behavior, the limestone horizon can be further divided into two horizons namely, Upper limestone horizon and Lower limestone horizon.

LITHOLOGY, PETROGRAPHIC & MINERALOGICAL DESCRIPTION

The area consists of Rohtas Limestone which is grey, Dark gray, fine grained, soft and stratified. The thickness as revealed by borehole data is variable. It has got thin calcite veins in some places and also seen as cavity fills. Limestone is concealed below soil cover in the area. The general dip observed is about 10 to 15 dipping towards north.The various litho types encountered in the Mining Lease area are described as below:

1. SOIL Recent formation consists of alluvium/soil.
2. LIMESTONE The Rohitas Limestone directly underlies the Soil/Alluvium, which is grey, Dark gray, fine grained, soft and stratified. The thickness as revealed by borehole data is variable. It has got thin calcite veins in some places and also seen as cavity fills. Limestone is concealed below soil cover in the area (Singh and Gupta 2019; Mehta 2020). The general dip observed is about 10 to 15 dipping towards north. Quality of Limestone shows variation both in lateral as well as vertical direction due to Lithological variations and concentration of deleterious materials such as interstitials clay and shale. The analysis of the limestone is as below:

1 CaO- 44.57% 2 SiO- 27.01%
3 MgO - 5.4%
4 Al_2O_3 - 1.66% 5 Fe_2O_3 - 0.62%

MODE OF OCCURRENCE AND CONTROLS OF MINERALIZATION

The limestone deposit is part of the Semri Group, specifically the Rohtas Formation of the Vindhyan Supergroup, and is situated along the Son River basin. In this region, the Rohtas Limestone is overlain by a thick sandstone unit (Krishnan 2006; Ramakrishnan 2008). The boundary between these two lithological units is distinct and erosional, marked by a thin, sheet-like layer containing pebbles. The limestone sedimentation occurred on a tide-dominated shelf, resulting in a stratified, laminated deposit. The deposit exhibits no evidence of significant geological structures or structural controls on mineralization. Its formation and characteristics are primarily sedimentary, with no major tectonic disturbances influencing the deposit.

EXTENT OF WEATHERING/ ALTERATION

The mining lease area Limestone belongs to semri group, Rohtas formation of lower Vindhyan super group and the area comprise by undulating hilly terrain, in the lease area only west part of the lease limestone are exposed and in current working pit & south side of the lease area cover by the thick soil cover no outcrop of limestone are exposed. The area is predominantly affected by chemical weathering when rainwater reacts with limestone. Evidence of chemical weathering can be seen in areas where limestone is exposed to the water. Rainwater erodes the vertical joints and horizontal bedding planes in limestone, and these vertical joints filled with the soil and can easily see in the lease area and somewhere small cavity also seen.

EXTENT OF MINERALIZATION

The Rohtas Limestone belt is extending over a distance of about 150 km in the Sidhi District along the southern escarpment of Kaimur Plateau from Majhgawan, Sarda, Gorhatola to Sihawal in Sidhi District and further east of it upto the border of UP State in the District of Mirzapur. The western part of the belt extends into Satna District from Hinauti to Jigna village and beyond it. In the lease only center part of the area available with cement grade limestone. The eastern part of the area where dumping is in progress is non-mineralize there is no extension of mineralization was found during the exploration program. The Limestone deposit in the area is having max extension up to 2000 m along strike direction and and average width extension is up to 800 m (Singh and Verma 2018; Sharma 2021).

METHODOLOGY

The depletion of high-grade limestone is a growing challenge for the Indian cement industry, which heavily relies on consistent and high-quality raw materials for smooth plant operations and the production of superior-grade cement. Despite India’s vast limestone reserves, the deposits available for cement manufacturing are increasingly characterized as marginal or low-grade, containing lower calcium carbonate (CaCOƒ) levels and higher impurities.

This issue is compounded by the allocation of low-grade coal to cement plants, which affects fuel efficiency and clinker quality. Many cement plants initially operate with simple, high-grade limestone deposits of uniform composition. However, as these deposits are gradually consumed, the remaining reserves often consist of lower-grade, heterogeneous materials that are more challenging to process (Deshmukh 2008; Hartman et al 2002).

The combination of these factors creates significant operational difficulties for the cement industry, including:

1. **Raw Material Variability:** Low-grade limestone's heterogeneous nature complicates the control of clinker chemistry, impacting cement quality and consistency.
2. **Higher Processing Costs:** Beneficiation and blending of low-grade limestone to meet required standards demand additional investments and energy.
3. **Lower Efficiency:** Both in terms of material utilization and thermal energy consumption due to the suboptimal quality of available raw materials and fuel.
4. **Environmental Concerns:** Increased resource use and waste generation due to the need for more extensive processing and higher emissions from the use of low-grade coal.

To address these challenges, the industry must adopt a multi-pronged strategy:

- **Exploration and Beneficiation:** Enhanced exploration to locate unexploited high-grade reserves and implement beneficiation technologies for upgrading low-grade limestone.
- **Innovative Blending Techniques:** Strategic blending of low-grade limestone with alternative raw materials to achieve the desired chemical balance in clinker production.
- **Alternative Raw Materials and Fuels:** Greater utilization of industrial by-products, such as slag, fly ash, and alternative fuels, to compensate for the declining availability of high-grade resources.
- **Advanced Manufacturing Practices:** Adoption of process innovations, such as low-clinker cements and optimized kiln operations, to improve efficiency and product quality.

The Indian cement industry must focus on long-term resource sustainability by leveraging technological advancements, improving raw material management, and diversifying its resource base. This approach will ensure continued growth and resilience in the face of raw material challenges.

The reserves and resources have been estimated based Geological mapping and Exploration activities (Drilled Boreholes) in Forest as well Nonforest area. 26 Boreholes have been drilled in Forest area and 16 borehoiles have been drilled in nonforest area. Initially 5 boreholes were drilled (363m) by DGM Bhopal and total 37 no of Boreholes have been drilled by lessee in three phases. The Resources have been estimated by the X-sectional area method, influence distance is considering 50% of grid interval on both side from each crosssections. High MgO dolomite is intercallated with Limestone which is not sepratable and used as Limestone from mineral conservation point of view, intercallated High MgO dolomitic limestone having MgO up to 7.19% is considered into Reserves/Resorces estimation, Resources and Reserves of Limestone are computed for entire mineralised area (Forest & Nonforest area). Total mineralised area is 40.973 hect out of which 28.12 hect area is located in forest and 12.853 hect area is located in nonforest area. Although Limestone is proved up to 260 mRL in some of boreholes, whereas the UPL is decided up to 295 mRL, as mineral is blocked due to road safety zone, UPL is considered up to 295 mRL as per the EC condition, the UPL is decided as per the present EC conditions and Limestone below this mRL is considered in 221 category, whenever EC condition is ammended these blocked resources will come into 111 cat Resereves. The high MgO Limestone is suitably blend with Limestone and used for Cement Manufacturing. Geological or in-situ reserves/Resources of Limestone are estimated under 331 UNFC category.

RESULT & DISCUSSION

Bulk Density Study as per M(EMC) Rules, 2015

Method adopted for calculating bulk density of ore and waste IS 2386 Part (III) Bulk density was measured by Caliper method. Length of the sample measured along axis of core; diameter of the sample measured using Vernier caliper, Weigh air dried sample in a balance. Volume of core sample obtained by using formula $V = \pi r2h$ (V = volume, r = radius and h = height or length of the cylindrical core). The bulk density of the sample determined by using the formula B.D =M/V [M= weight of the sample and V= volume

Table 1.0 Bulk density of ore and waste

Sl.No.	Nature of Ore/OB	Mineral	Number of samples	Bulk Density Established (t/m^3)
1	Massive	Limestone	3	2.50
2	Massive and friable	Sandstone & Shale	3	1.60

Table 2.0 Resource Calculation

Sl.No.	Cross Section/Block	Section Area/ Block Area(sq mt)	Influence(m)	Depth in mtr	Volume (m^3)	Bulk Density (t/m^3)	Resource Quantity (t)	Level of Exploration	Type of Land	Name of the radical	Grade (%)	Method used for resource estimation
1	1	17557	104.00	78.00	1825928.00	2.50	4564820.000 00	331	Forest Land	CaO MgO	CaO 41.99% MgO 4.08%	X sectional area method
2	2	21140	120.00	65.00	2536800.00	2.50	6342000.000 00	331	Forest Land	CaO MgO	CaO 43.7% MgO 5.27%	X sectional area method
3	3	19235	103.00	93.00	1981205.00	2.50	4953012.500 00	331	Forest Land	CaO MgO	CaO 41.77% MgO 6.41%	X sectional area method
4	4	19697	87.00	78.00	1713639.00	2.50	4284097.500 00	331	Forest Land	CaO MgO	CaO 46.72% MgO 4.07%	X sectional area method
5	5	14456	173.00	85.00	2500888.00	2.50	6252220.000 00	331	Forest Land	CaO MgO	CaO 38.23% MgO 7.19%	X sectional area method

"Reserves have been estimated considering entire exploration boreholes drilled during the various phases i.e 28 no of BH in 2016-16, 5 BH in 2019-20 & 4 BH in 2022-23 (total meterage of BH are 1679.78m). Total mineralised area is 40.973 hect out of which 28.12 hect area is located in forest and 12.853 hect area is located in nonforest area. Total strike length of mineralised area is 1280 m and average width of Limestone deposition is 350 m. Total Resources are computed up to depth of mineralisation. Although Limestone is proved up to 260 mRL in some of boreholes, whereas the UPL is decided up to 285 mRL, as mineral is blocked due to road safety zone. Assessment has been done for limestone for the entire lease area in Forest land and non forest land separately. All the exploratory holes drilled have been considered for Reserves/Resources computation. Based on above data existing geological plan and sections are updated on 1:2000 scale. A tonnage conversion factor of 2.5 tonnes/m3 for limestone has been considered. Section-wise limestone reserves have been estimated for the entire lease based on the exploration undertaken and the configuration of the mineral body is more or less well established. The limestone reserves are considered based on >34% CaO and 7% MgO content. High MgO Limestone is also occurred within Limestone which is not separatble, the same high MgO Limestone is computed in reserves estimation, the high MgO Limestone will be utilised by systematically bleding with low MgO Limestone to consume it scintifically to conserve the mineral. By adopting above enumerated criteria, section-wise mineral Resources/Reserves have been estimated.

The limestone resources / reserves are considered based on > 34% CaO and <5% MgO as per threshold value specified in CCOM Circular No. 3/2010. The cut off grade and Threshold value of Limestone is same and entire Limestone having CaO >34% and MgO <5% is cement grade and utilsed in captive cement plan for manufacturing of grey cement. Although in Resources/Reserve calculation Limestone having MgO up to 7% are also considered.

The deposit lies on surface and it is being mined by mechanized opencast method of mining with excavator / dumper combination. Deep hole drilling and blasting is being carried out and it is proposed to continue same method of mining. Conversion factor 2.5 has been taken for conversion of volume to tonnage for the purpose of mining of mineral.

CONCLUSION

The study highlights the urgent need for comprehensive exploration of limestone deposits across India to identify and establish additional reserves within the existing resources, in line with the UNFC classification. It is crucial to implement systematic mine planning and multi-mine scheduling to optimize the use of quarry rejects. This should be prioritized for immediate action. Additionally, remote quarry management, particularly for plants within a group, presents an ideal business model for mining operations in the Indian cement industry. This model leverages external expertise, utilizing advanced IT-enabled services and cutting-edge mining software to efficiently monitor mining activities. Further research into cost-effective dry beneficiation techniques for enhancing low-grade limestone is also essential.

Encouraging the production of reactive belite cement, sulfo-aluminate (C4A3S) belite cement, and LC3 in India offers a sustainable solution for preserving high-grade limestone deposits. Sulfo-aluminate belite cements are already being produced commercially in several countries and have proven successful for various applications. These cements hold significant potential for utilizing low-grade limestone and industrial wastes in their production, making them an eco-friendly option due to their lower CO2 emissions compared to traditional Portland cements. It is important to promote the use of cements that require fewer clinker components, contributing to a more sustainable cement industry in the country.

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3Ws (What, Why and How) of Safety

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INTRODUCTION

Good safety practice must control the hazards to personnel, equipment, the mine itself as well as the broader environment. Mine safety should focus on removing health & safety risks to miners, other associated risks and prevent pollution and contamination. Mining is inherently dangerous. This is because mining poses a different set of hazards than other professions, and these hazards can be found anywhere in the world where there are mines. In 19th century, rules for mine safety were simple, mostly because safety rules were pretty scarce. Historically, owners had the final say in mine safety - and considering their vested interest in the success and profitability of their mine, most owners weren't too keen to make safety rules that could negatively impact their profits. But during 20th century, learnings from fatalities necessitated the enactment of Statutory Acts, regulation and Rules, have made stringent guidelines for miners for towards safety and its practice. This has reduced fatalities and paved way for better working environment, with continuous evolution of guidelines by the Apex Regulatory Bodies. Though, highest level standards and practices are made available to the miners but the ultimate success lies in the Individuals understanding, attitude and practice of 3Ws (What, Why, and How) of SAFETY. There is quite lot of literature are available in this context, and this article intends to make it clearer and easier for anyone to understand the perspective of safety and contribute effectively.

WHAT IS SAFETY

Safety is the state of being safe; not being dangerous or in danger. In another words, Safety is "the degree to which accidental harm is prevented, detected, and reacted to". Hazard: Source of potential harm, injury, or loss. Risk: Combination of the likelihood of a specific unwanted event and the potential consequences if it should occur. Consequence: Size of the loss or damage. Consequence of a hazard need not only be in terms of safety criteria but could also be in terms of a money loss, incurred costs, loss of production, environmental impacts as well as public outrage.

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NLCIL

Practically, some of the frontline miners understands, safety as wearing of PPEs for compliance. In author perspective, there are action which are essential for the real-life situations, and those actions are intended for a specific planned outcome. Any unplanned outcome either positive or negative, is detrimental. The ways, methods, procedures and practices used to, prevent the unwanted unplanned outcomes to happen, and to make sure only the desired and planned outcomes to happen is called SAFETY.

To put it simply, let us imagine situation where in a person sitting in a class room, below a ceiling fan in which the mounting bolt is loose which he is not noticed. The planned outcome for sitting below the running fan is to let the air falls on him, but not the fan which is unwanted and unplanned. All the precautionary measures taken to avoid those alike unwanted outcomes and making sure the desired outcome is SAFETY. It is essential to make the common to understand what is safety in a form is effective.

WHY SAFETY

The safer the work environment, the more productive it is. Productive employees are an asset to all companies. For instance, productive employees can produce more output in less time, reducing operational costs. Workplace safety promotes the wellness of employees and employers alike. Better safety equates to better health. Healthier employees do tasks more efficiently, and they are happier in general. There are very few accidents in a safe working environment. This results in less downtime for safety investigations and reduces costs for worker's compensation. This also reduces the time needed for employees to heal from injuries. Damage to industrial equipment creates costs for replacement and repair. Avoiding workplace injuries and damage to industrial equipment will incur fewer expenses and increase profit. Or otherwise in few cases, safety is for compliance of regulatory framework.

Let us look at this perspective as deliberated below. In the same situation explained above, why SAFETY to be ensured;

1. **To save the self**; which at least to be prime objective of anybody. If one notices that the bolt is loose, he will definitely not sit on that chair which just below the ceiling fan since it might fall.
2. **To save Team mates / others**; If he doesn't sit on that chair, somebody else may occupy. Since risk / unwanted outcome is still persist, as a responsible team mate, one should ensure that the others also saved by suitable action; By doing so one is not just saving others life and also avoiding own's loss of confidence, morale, support and productivity due to post incident/accident consequence both from work place and from family.
3. **To save Property**; if no one is occupying the chair, though the personnel are saved, but the properties may get damaged due to unwanted outcomes. In our example, the property may be either chair or fan, but both are cost to the owner, which will reduce profit and finally to the earning of the Individual.

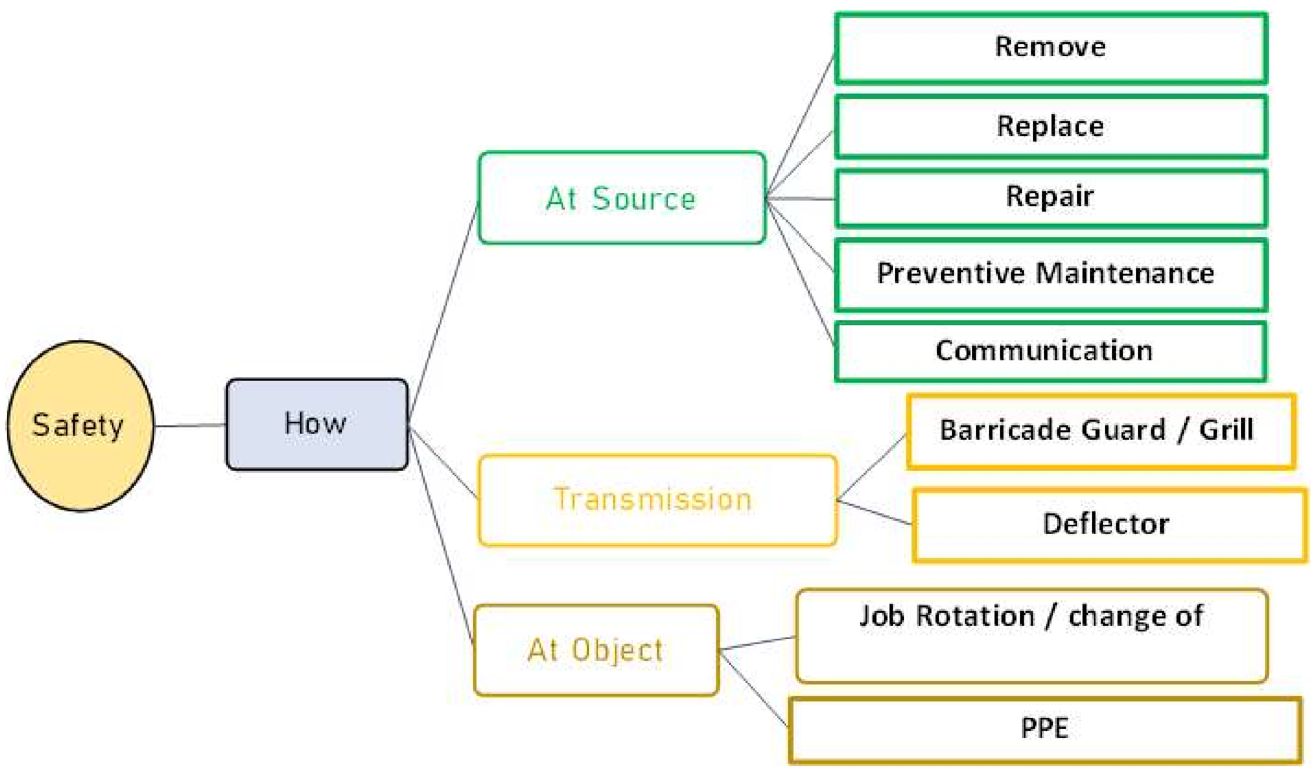
If we analyse these points, it is either directly or indirectly, the beneficiary for ensuring safety measures is Individual. So, one should clearly understand that, so that the interest, reason, and responsibility for upkeeping highest level of safety standards and practices is created voluntarily.

HOW TO ENSURE SAFETY

Any Risk i.e., Combination of the likelihood of a specific unwanted event and the potential consequences, is created at a Source, and has to travel to reach a receiver who/ which is exposed.

Risk Pathway Model

It is quite clear from the risk pathway model, that there is option to stop the risk or avoiding the unwanted outcomes to happen, at three levels, such as at Source, during travel and at Receiving/ Exposing end.



Strategies of Mitigating Risk based on Risk Pathway

Let us consider same example with respect to this risk pathway model, the options available for avoiding the unwanted/ unplanned outcome to happen are;

1. **At Source**; The top priority in risk removal should be at source. Once the risk is noticed, it should be removed immediately without allowing to further aggravate the likelihood. Similarly, it is quite possible, that with suitable repair or replacement work, the risk can be nullified at the source itself. The above actions are possible only if the risk is noticed. One should trade off between the amount loss due to the probable consequence with the amount of time spent on preventive maintenance or inspection works. The Individual shall get motivated with trade off such that no slip is accepted on doing preventive maintenance and regular inspection actions. While doing so, not all individual can undertake removal, repair, replacement work, but being a miner, one must know or made aware that this is a risk and needs to be mitigated, hence the noticed risk at source should me clearly communicated to the person concerned for mitigation at source at the earliest.

2. **At Transmission**: if missed at source, the second option available is during travel. The risk travel duration may vary with respect to the type of risk and exposure likelihood. Some time there is chance at the source itself the consequence is felt to the exposure, but it is with least possible travel duration.

   The unwanted outcome can be stopped during the travel by placing suitable barricade between source and Exposure. This is how all rotating parts are provided with suitable Guards such that it is acting a barricade between the rotating part risk source and the persons in the vicinity the exposure or receiver. While barricade blocks the way, a deflecting mechanism would divert away from the exposure / receiver. Like a damaged roller or any foreign material from source of failure travelling to make damage at the exposing object Drum/belt shall be diverted/ deflected by a V wiper. These options are quite available for any sort of risk, and only thing is one should diligently exercise it.

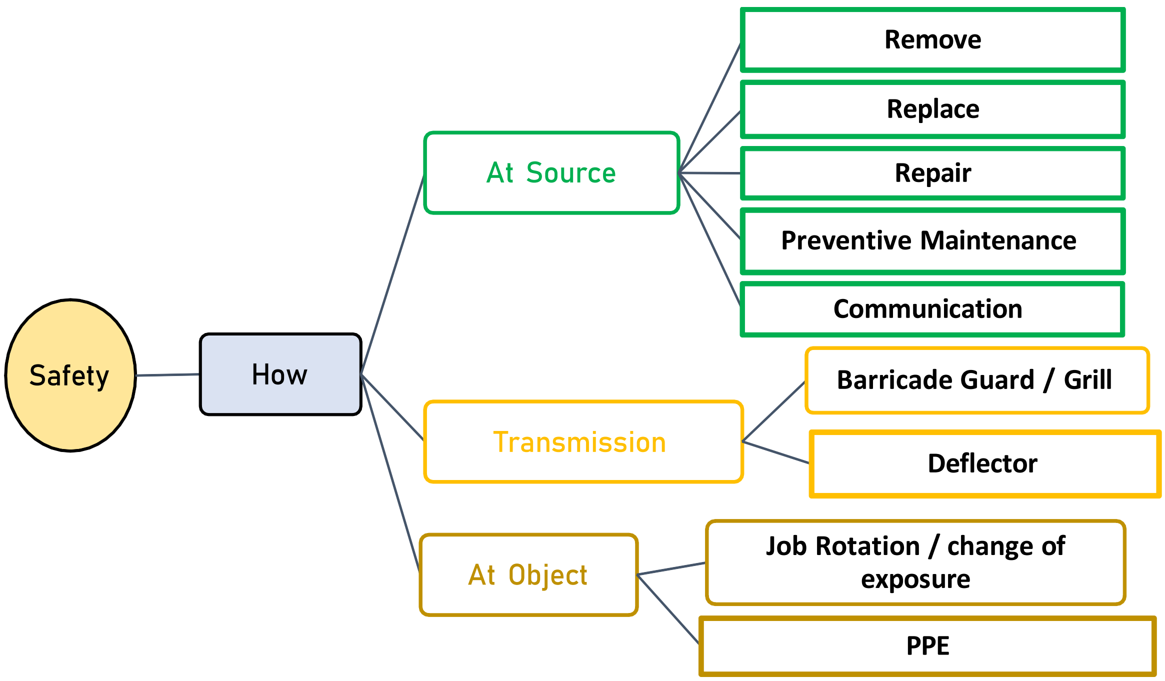
3. **At Exposure/ Receiver**: if options for avoiding the unwanted outcome at Source and during Transmission are not done, the severity consequence can be reduced by changing the exposure, through administrative control like Job Rotation. Wearing Personal Protective Equipment (PPE) is the at the final stage of ensuring safety. Wearing PPEs is can only reduce the severity of damage from the risk/ unwanted / unplanned outcome.

SAFETY IS MY RESPONSIBILITY

In the above mitigation options described, it is to note that each of option is the day- to-day duty of anyone of us in the work spot. It is also clear from the flow that, if somebody has not done their duty, then only the risk is transferred to the next level. It is pertinent to mention here that, as the flow from source to exposure proceeds, likelihood of mitigating the risk/ unwanted outcome is decreasing, so it is always better to deal with it at the source itself, where we have maximum likelihood of eliminating the risk. For doing all these mitigating actions effectively, discharging individual responsibility at all levels promptly needs to be ensured which can be successful cent percent with inculcating the attitude of Safety is My Responsibility.

CONCLUSION

Mining fraternity progressed from scratch to the level of recent technology enabled safety standards and practices with active contribution from Wearable Technology, Robotics and Automation, Radio-frequency Identification (RFID), Drones, and Worksite Simulators. Government is keen on upkeeping safety of workforce and public properties, with stringent and innovative approaches. Directorate General of Mines Safety (DGMS), an Apex Regulatory agency has evolved itself from not just regulator but to act as an enabler for innovation and adoption of best safety practices and continually initiating actions for activating collaborative forum for mutual sharing of knowledge on safety and achieving the common good. Amidst all these efforts, the all success of safety still lies with individual who practice it. Those individuals are from all levels of the organisation, for the clarity in safety with simplistic way is quite needed while the efforts are ON for refreshing and enlightening them on the recent developments. Better the understanding of What, Why and How of Safety shall definitely deliver better and excelled outcomes towards SAFETY.


Safety
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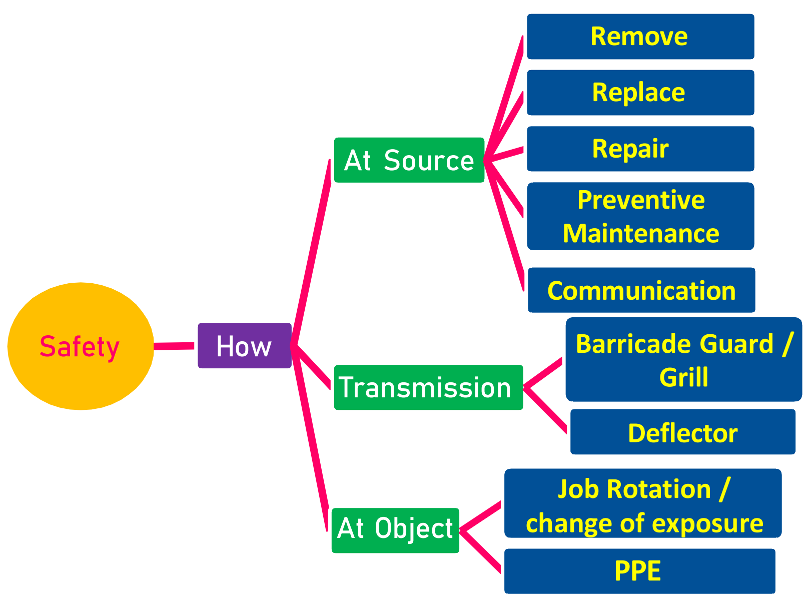
Preventive Maintenance
Communication
Transmission
Barricade Guard / Grill
Deflector
At Object
Job Rotation / change of exposure
PPE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Communication
Transmission
Barricade Guard / Grill
Deflector
At Object
Job Rotation / change of exposure
PPE

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Sustainable Mining-Digital Interventions

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ABSTRACT

Mining and Agriculture are the most ancient professions of humans. Sustainable Mining of finite resources is a myth, however, learned influentials have worked out a midway to adopt best practices in mining making the process clean green, and blood-free. With rapid growth in every sphere along with the population explosion, the world is experiencing tremendous change in doing business and trade, and one of the most vulnerable is mining. Automation, Mechanisation, use of Artificial Intelligence, and the Internet of things have become a prerequisite and criteria for best practice evaluation be it in Non-Coal or Coal Mining enforced by IBM and the Ministry of Mines.

The team has created model mining solutions and picked up a few Mining Operators working for Central & State government mines. It is only in India; that we have a model where MDO/MO must acquire all the Mining Assets from global OEMs and struggle with ever-changing technology-linked operations and maintenance of these HEMMs. To optimize and make the operation and maintenance efficient, the team has partnered with International Automation Solutions providers to customize and localize them into day-to-day work like the use of Drones in Land Management, creating a dashboard for monitoring mining operations, implementing Asset Management Systems to improve OEE of the HEMM and be compliant to the statutory and regulatory requirements. customizing software and coding based on the data and analytical tools has been a tedious task. This digital initiative is getting a very good response from academia, mine owners, regulators, and mining operators as the entire mining process becomes very transparent and efficient.

International Sustainable and safe mining efforts under SDG, ESG, and LME criteria are built into the digital mining model. however, challenges and pressing issues are bothering the initiatives (Tendering process, Bidding process, Asset Acquisition Process, technology availability, and indigenization along with Govt. policies on R&R, Peripheral Development, CSR, Forest Diversions, etc are some of the issues that act as a barrier to Digital Mining) it is only a few more years of wait that Digital Initiatives in Mining will be the norm for evaluating Safe and Sustainable mining practices.

INTRODUCTION

The Mining Industry globally as well as in India is going through a major change, be it capacity utilization, use of technology, migration to automation, and adoption of SDG initiatives. Under such a situation, introducing new and unknown technology to manage mining activities in the open-cast mines is a big challenge. Taking a plunge into this ever-changing landscape, the team has valiantly planned to adopt Smart Mining and HSE compliance for OC mines using the latest Digital Technology.

This idea of migrating from conventional mining to Digital and Autonomous mining is conceived during a study cum research tour to **German Mining Museum Bochum**. Here the Author experienced the everyday life of a miner extremely realistic. Many of the machines on display are kept functional and set in motion at the push of a button; this is a must for every mining enthusiast. Also, he travelled to South Africa Gold Mines, Vietnam Coal Mines, Cambodia Gold Mines, and Several Mines in India to understand the Mining Eco-system, especially the Open Cast mines.

This awareness of mining activities led to various ideas to monitor and measure the mining work in a Digital Platform and accurately forecast the outcomes as planned in the approved documents by the Legal and Statutory authorities who observe compliance.

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The valiant struggle to implement Automation and Digital Solutions in mines started with various projects, but as the eco-system goes, the biggest hurdle is the initial cost of setting up a digital dashboard which is very high, and the ongoing projects cannot afford the set-up cost be it may from the Lease owner or its Contractor.

This led the Author to look for Open Source Solutions and International Applications both in hardware as well as in software, and he started to interact with various OEMs for need-based solutions for all activities involved in mining like surveying, bore-hole drilling, blasting, face cutting, transporting, value addition to the mined ores and handling the wastes, all these activities were initially mapped and documented physically using conventional methods. Studies for applicability and ease of technology use were evaluated using various solutions that are available from various OEMs and a best-fit option was selected that is affordable, easy to use, and can be relied upon on the data captured.

The digitization work started with prospecting various opportunities that are available in the open market and a particular open cast mines work was picked up in very remote and old mine sites. Based on the site condition, a survey was made using a Drone (UAV), and the complete site study was mapped digitally. This led to forecasting a few realistic indicators like selecting the dumpsite, haul road location, elevation, and other dynamics complying with the applicable Compliance Obligations. Face cutting was planned to expose the ore body in various seams and use safe benching. All these activities were planned and reviewed by drone mapping using expert advice from premier Mining Institutes, technology suppliers, software developers, and experts in this field. The author and team got involved in every activity.

Describing the digitization, the Author& team picked up key areas like compliance obligations to start the operation of the mine like the initial survey after allotment of the OC patch, physical site survey, setting up the campsite, sourcing and hiring the best-fit assets (HEMM) as required for OB & Ore extraction and headhunting. The Author used the open-source information that is available on the web and started the long Journey.

The major issue in OC Mines is Land acquisition and relocating the land losers as well as job losers from previous contractors and mine operators that were engaged, every location has a unique challenge and the one under discussion had major issues being in the tribal setting. However, with the help of the client and local authorities, this was resolved to some extent and the work started with development works like haul road development, opening the face, and cleaning the land from vegetation. The initial drone mapping has been immensely helpful in estimating, selecting, and deciding the way forward based on the annualized targets.

The challenge to start the mining work is the humongous paperwork that is required at every step forward: clearance from DGMS, PESO, Labour Dept. Local Authority, Dist. Administration, Fuel Supplier, HEMM Suppliers, and Manpower Suppliers, and hence the tedious journey started.

This process made the team understand the mining ecosystem between what is taught and what is done at the ground level. patch drawings were digitized using high-ended software and a mine excavation plan was prepared using available bore-hole data, area allotted as per initial survey, and targeted production.

Now a days, OEMs have also made digital platforms accessible and affordable with machine learning using telemetry and IoT. Selection of HEMM that best fits the project requires lots of skill and experience of similar work.

Steps taken to digitize the mining work are as follows: drilling and blasting, digging, loading and transport of waste and ore product, benching, dump slope, and haul road, all these were planned using various automation solutions available for all activities, these are briefly explained by the author: use of drone is very precise and is very handy for creating a dashboard view of the entire gamut of services. However, the software used is expensive and complex requiring a very high level of skills.

Outsourced works have little margin for adopting digital solutions that are very costly at the beginning of the project, therefore Regulators and Mine Lease Owners have to invest in the capital cost giving the Mine Operator a complete predesigned platform to work on, the author strongly feels that if this is achieved then Mining Industry in India shall bring landmark changes in terms of compliance obligations, increased productivity and better ore quality as well as Meeting the HSE standards set by National as well as International Regulators.

Another area the mining fraternity suffers is fuel management, the Author has successfully attempted to address this issue using a German-based OEM's hardware and software enabling the mine operator to achieve the best performance with optimum fuel consumption thereby improving the health of the asset deployed and reducing spillage, pilferage, and losses during handling of fossil fuel.

Mine operation requires constant skill up-gradation and capacity building to handle high-end automation and digital solutions. The author has tied up with premier institutions (IIT KGP & ITT BHU) as well as OEMs to provide simulator-based training as well as make the team aware of the technical details of the various automated solutions. Insights to the following solutions adopted are as follows:
Drone Survey: Government Regulators and Monitoring Agencies like the Indian Bureau of Mines, Directorate General of Mines Safety, CMPDI, Geological Survey of India, and Central/State Authorities in Transport, Land Use, Water Use, Energy use as well as other governance matters also opted for digital communication during this Pandemic Crisis and accepted Drone Survey and its reports.

Refer: Ministry of Mines (GSR 780 (E) dt. 03.01.2021 incorporated rule 34 A in the MCDR 2017 for submission of Digital Aerial Images of Mining Lease areas to the Indian Bureau of Mines (IBM).

The advantages of Drone Surveys are to improve the overall efficiency of large mine sites and quarry management by providing accurate and comprehensive data detailing site conditions in a very short time.

The data accuracy and authenticity are better than the traditional survey.

High-resolution (cm level) data from drone surveys provides high accuracy and more precise volumetric measurements than traditional surveying methods. Stockpiles of irregular shapes and exhibiting crates can be easily surveyed with greater precision than traditional survey and calculation methods. Drone surveys are faster, with less human intervention in mines, and easily repeatable mining surveys at low cost. Changes between two surveys can be tracked and highlighted automatically. Drone aerial images can be used to generate point clouds, digital surface models, digital terrain models, and a 3D reconstruction of a mining site, including its stockpiles. Helps in creating a digital database that can be used and retrieved at ease and compared.

Data generated over some time can be stored on a digital platform and the data can be compared. The data can be used for systematic and scientific mine closure planning, monitoring of reclamation, and rehabilitation activities in lease areas. Work in the mines has significantly eased out and structured activities that are planned could be easily executed.

Digitizing Fuel Management: getting a consumer fuel point within the mines site with all approval is a very long process and once this approval is obtained fuel purchase, unloading, transfer to fuel bowser, and fuelling the HEMM and support assets is a constant challenge from the mines operation point of view, the major challenge is witnessing the unloading of fuel from the trailer truck to the fuel tank supplied by the Fuel Company, there is always a messy discussion of shortage and error. This was tackled largely by installing a digital 5-letter fuel dispensing pump along with a digitized flow meter fitted to the unloading pump. This enables the mine operator to witness unloading in-situ and accurately at a remote location in the comfort of his office/anywhere wherever he is.

Fuel being a major resource in Mining, must be judiciously used with all possible controls digitally reducing losses, pilferages, leakages as well as efficiency issues of HEMM and other utilities due to maintenance failures in mine sites.

Digitizing Operation Management: Open Cast Mines that are operated need strategic planning like:

1. **Land Management and obtaining clearance** and marking with pillars as per the initial survey, this is further planned with clear drawings and design for face cutting and removing OB as per the Borehole data submitted by the client. With the available data, a mine excavation plan is prepared using the latest software containing all necessary operating information that would be an input to the planning document for mine excavation.
2. **Site mobilization** and other facilities were planned and established. Here this can be remotely monitored using CCTV, biometrics, and simple auto-cad and Excel spread sheet for monitoring the project progress.

3. **Mine excavation planning and execution**: this starts the mining activity, based on the initial survey and proposed production plan, the development works are started like haul road design and cutting, dump area identification and demarcation, face selection and cutting based on the benching plan, drilling and blasting plan approval based on the bore-hole data available. All these are converted into a pert chart and work begins, nowadays these are digitized, and precise operation and maintenance plans are made using PM software.
4. **Asset Selection and Deployment**: based on the annualized production target for waste and product, the HEMM and other associated equipment are selected, and the hiring cum owning process is initiated. This is an area where a high level of automation could be planned as OEMs are also keen to offer these so that the asset health is retained, and higher productivity could be achieved thus reducing breakdowns and stoppages due to the non-availability of spares and consumables in remote mine locations.
5. **Transportation and evacuation of waste and product:** the project is planned in such a manner that the leads for the trip are pre-decided and accordingly the route plan is prepared. Automation solutions using IoT and AI are available for this and can be customized and adopted.
6. **Survey and estimation of production:** for the OC patch, every fortnightly drone survey is done to review the progress made, and further plan correction is done for the dump slope, haul road gradient/elevation, berm elevation, and curvature width meeting statutory and safety requirements. On a monthly and quarterly basis the production targets are measured traditionally using survey instruments and the findings are matched with the Drone survey reports. This has enabled the project team to document the progressive mining excavation and production.

Since the Author and Co-Author are involved in an ongoing project where automation is adopted progressively, therefore the learning and augmentation have ample scope to further improve upon the technology and latest solutions that could be deployed keeping the price tag and ease of use. Further competence building and Human resource development are constantly taken up with the help of premier Institutes and experienced experts.

CONCLUSION

To achieve green, sustainable, and safe mining, there is no doubt that digitization and adopting best practices can convert any conventional mining into a Smart and Sustainable Mining Project. The journey has just begun and by the next opportunity, there will be very precise solutions as a basket could be proposed for having a dashboard view of the mining from the comforts of our board rooms. The challenges like cost to automate, acceptance by regulators, and ease to employees are just a mile away. While the issues of indigenous and low-cost hardware and software along with retrofitted sensors and instruments are a concern ofthe pandemic, the crisis of semiconductors and other imported chips'non-availability has badly hit the speed at which automation is applied in different projects. Large Mining Companies like CIL, NTPC, NLC, NMDC, and Private Miners must provide the entire digital ecosystem to the Mine Operator and Contractor as a ready-to-use package.

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