Indian Journal of Modern Research and Reviews

This Journal is a member of the '*Committee on Publication Ethics*'

Online ISSN:2584-184X

Research Article

Illumination Survey and Lux Contour Mapping in Surface Mines: A Case Study on Safety and Operational Efficiency

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DOI: https://doi.org/10.5281/zenodo.20266692

Abstract

Effective illumination is a critical determinant of safety, productivity, and operational reliability in surface mining operations, where large-scale mechanization and round-the-clock production schedules are common. Inadequate illumination in opencast mines contributes significantly to operational hazards such as dumper collisions, equipment failure, worker fatigue, and reduced visibility during night shifts. The present study conducts a comprehensive illumination survey in a surface mine to evaluate existing lighting conditions against the standards prescribed by the Directorate General of Mines Safety (DGMS). The study employed digital lux meters and systematic field measurements to quantify light intensity across operational zones such as haul roads, drilling areas, workshops, coal stockyards, and heavy earth moving machinery (HEMM) operating zones. Lux contour maps were generated using interpolation techniques to visually represent the spatial distribution of illumination levels and identify low-light "dark zones." The results revealed that although several operational areas complied with DGMS standards, many sections of haul roads and stockyard peripheries exhibited illumination values below the prescribed threshold. The study demonstrates that lux contour mapping can serve as an effective decision-support tool for improving mine illumination planning, reducing accident risks, and enhancing worker efficiency. Recommendations include strategic placement of portable lighting towers, adoption of LED-based lighting systems, and implementation of periodic illumination audits for sustainable mine safety management.

Manuscript Information

- **ISSN No:** 2584-184X
- **Received:** 04-04-2026
- **Accepted:** 12-05-2026
- **Published:** 18-05-2026
- **MRR:**4(5); 2026: 147-151

- **Plagiarism Checked:** Yes
- **Peer Review Process:** Yes

How to Cite this Article

Rishi S K, Pal C, Kumar A, Munda G, Ranjan S, Illumination Survey and Lux Contour Mapping in Surface Mines: A Case Study on Safety and Operational Efficiency. Indian J Mod Res Rev. 2026;4(5):147-151.

Access this Article Online

www.mrrjournal.in

KEYWORDS: Surface Mining, Illumination Survey, Lux Contour Mapping, DGMS Standards, Occupational Safety, Mine Illumination, HEMM Safety.

1. INTRODUCTION

The rapid expansion of the mining industry and the increasing global demand for coal and minerals have significantly intensified the use of mechanised mining methods in surface mines. Modern opencast mines operate continuously throughout the day and night using large Heavy Earth Moving Machinery (HEMM), including dumpers, shovels, draglines, drills, and loaders. Such continuous operations require an efficient and scientifically designed illumination system to ensure safe and productive working conditions during nighttime operations. According to DGMS guidelines, inadequate illumination in mining areas is one of the major contributing factors to accidents involving machinery movement, slips and falls, and poor operational visibility [1].

Surface mines differ substantially from underground mines in terms of operational area, changing topography, and dynamic bench advancement. Since mine faces and haul roads shift continuously with excavation progress, establishing permanent lighting arrangements becomes difficult. Consequently, mine operators rely heavily on portable floodlights, tower-mounted illumination systems, and machine-mounted lights to maintain adequate visibility during night shifts [4]. Poor illumination adversely affects operator judgment, reaction time, and depth perception, thereby increasing the probability of accidents and equipment damage [18].

Several researchers have emphasized the importance of scientific illumination practices in industrial and mining environments. Bandyopadhyay [5] reported that improper lighting in opencast mines leads to visual discomfort and operational inefficiencies. Hartman et al. [11] observed that illumination quality directly influences the productivity of machine operators and maintenance personnel. Similarly, Boyce [18] explained that insufficient lighting contributes to visual fatigue, stress, and reduced human performance in industrial workplaces.

The Directorate General of Mines Safety (DGMS) has prescribed minimum illumination standards for various mining operations under Coal Mines Regulations, 2017 [1]. These standards specify the minimum horizontal and vertical illuminance values required in operational areas such as haul roads, drilling sites, workshops, and stockyards. However, despite the existence of such regulations, many mines fail to maintain uniform illumination because of dust accumulation, poor maintenance, and improper placement of lighting fixtures [6].

Recent advancements in illumination engineering, particularly the use of Light Emitting Diode (LED) systems and digital lux contour mapping, have enabled mining engineers to scientifically assess and optimize mine lighting systems [13]. Lux contour mapping provides a graphical representation of illumination distribution across a working area and helps identify low-light zones that require corrective action. Such visualization techniques are increasingly being used in mining safety studies to improve lighting design and operational safety [16].

The present study aims to conduct an illumination survey in a surface mine and generate lux contour maps for assessing lighting adequacy in critical operational zones. The study further compares observed illumination values with DGMS standards and proposes suitable corrective measures for improving mine safety and operational efficiency.

2. LITERATURE REVIEW

Illumination engineering has become an important aspect of occupational safety management in mining and industrial operations. The concept of workplace illumination is based on ensuring sufficient visibility for workers to perform tasks safely and efficiently. The Illuminating Engineering Society (IES) defined illumination as the density of luminous flux incident on a surface and recommended specific lighting standards for industrial workplaces [2].

Bandyopadhyay [5] conducted one of the earliest studies on illumination practices in Indian opencast mines and highlighted that inadequate floodlighting in haul roads and stockyards was responsible for increased accident frequency during night operations. The study recommended systematic illumination surveys for evaluating lighting adequacy.

Ray [4] discussed that haul roads in surface mines are among the most critical operational areas because dumpers operate continuously under dusty conditions and varying gradients. According to the study, insufficient illumination on curves and intersections significantly increases the likelihood of vehicle collisions and overturning accidents.

Hartman et al. [11], in the SME Mining Engineering Handbook, emphasized that illumination systems in mines should not only satisfy regulatory standards but also ensure visual comfort and minimum glare for equipment operators. The authors further noted that poor lighting adversely affects operator concentration and reduces overall equipment productivity.

The International Commission on Illumination (CIE) [8] recommended the use of lux contour mapping for evaluating outdoor workplace lighting conditions. The study stated that contour mapping enables visualization of illumination uniformity and helps identify regions where lighting redesign is necessary.

Singh and Sinha [16] investigated lighting system design in surface mines and reported that LED-based illumination systems offer higher luminous efficacy, lower energy consumption, and better operational life compared to conventional mercury vapor and metal halide lamps. Their study concluded that strategic placement of LED floodlights improves illumination uniformity and reduces maintenance costs.

NIOSH [13] examined the role of LED lighting systems in mining safety and found that improved lighting significantly enhances hazard detection capability and reduces worker fatigue. The report also highlighted that modern lighting technologies improve color rendering and depth perception for machine operators.

Boyce [18] extensively studied the human factors associated with workplace lighting and concluded that poor illumination causes eye strain, stress, fatigue, and reduced alertness. The author emphasized that lighting design should consider both engineering and ergonomic principles.

Laurentin and Guthrie [20] investigated lighting efficiency in industrial environments and reported that periodic cleaning and maintenance of luminaires are essential for maintaining the maintenance factor (MF) and overall lighting efficiency. Dust accumulation on lamp surfaces can reduce illumination intensity by more than 30%.

Despite significant advancements in mine illumination technology, limited studies have focused specifically on lux contour mapping in Indian surface mines. Therefore, the present research attempts to bridge this gap by conducting a detailed illumination survey and generating lux contour maps for evaluating operational safety in opencast mining environments.

3. Theoretical Framework

Illumination studies are primarily based on photometric principles that quantify the characteristics of visible light. The International System of Units (SI) and Illuminating Engineering Society (IES) standards are commonly used in illumination engineering.

Luminous Flux, measured in lumens, represents the rate of flow of light energy emitted by a source. Illuminance is defined as the amount of luminous flux falling on a unit surface area and is measured in lux (lx), where:

$$1\,\text{lux} = 1\,\text{lumen}/\text{m}^2$$

Luminance refers to the brightness of a surface as perceived by the human eye and plays an important role in visibility assessment during nighttime operations.

The illumination survey in this study is based on two fundamental laws of illumination:

3.1 Inverse Square Law

The illumination produced by a point source is inversely proportional to the square of the distance between the source and the illuminated surface:

$$E = \frac{I}{D^2}$$

Where:

- E = Illuminance (lux)
- I = Luminous intensity (candela)
- D = Distance from source (m)

3.2 Lambert's Cosine Law

Lambert's Cosine Law states that illumination on a surface varies directly with the cosine of the angle between the direction of incident light and the normal to the surface:

$$E = \frac{I\cos\theta}{D^2}$$

Where:

- θ\thetaθ = Angle between incident light and surface normal

These laws are essential for understanding light distribution patterns in surface mining operations and for designing effective lighting arrangements.

4. METHODOLOGY

The study adopted a field-based experimental approach involving illumination surveys across critical operational zones of a surface mine. A reconnaissance survey was initially conducted to identify areas with high operational significance and potential illumination deficiencies. The selected zones included haul roads, drilling locations, coal stockyards, maintenance workshops, loading points, and HEMM operating areas.

Data collection was performed using calibrated digital lux meters equipped with silicon photo detectors. The instruments featured auto-ranging capability, backlit LCD displays, and internal data memory to ensure accurate and reliable measurements under field conditions. Measurements were carried out during nighttime operational hours under normal working conditions.

A systematic grid-based sampling approach was employed for obtaining illumination readings. The haul roads and stockyards were divided into uniform grids at predetermined intervals to maintain consistency in data collection. Horizontal illuminance measurements were recorded at ground level, while vertical illuminance values were measured on equipment surfaces, mine faces, and operator working zones.

To minimize observational errors, multiple readings were recorded at each sampling point and averaged for analysis. The collected data were processed using contour mapping techniques to generate lux distribution maps representing illumination intensity variations across the study area.

The observed illumination values were subsequently compared with DGMS-prescribed standards under Coal Mines Regulations, 2017 [1].

5. DGMS Illumination Standards

The Directorate General of Mines Safety (DGMS) has prescribed minimum illumination standards for opencast coal mines to ensure safe working conditions during nighttime operations. These standards specify the minimum horizontal and vertical illumination levels required for different operational areas.

Area of Operation	Minimum Horizontal Illumination (Lux)	Minimum Vertical Illumination (Lux)
Workplace of Heavy Machinery	15	25
Drilling Operations	15	25
Manual Work Areas	15	25
Coal Stockyards/Dumps	15	15
Haul Roads	10	—

These standards formed the basis for evaluating the adequacy of illumination in the present study.

6. RESULTS AND DISCUSSION

The illumination survey revealed substantial variation in light intensity across different operational zones of the mine. Lux contour maps generated from field measurements provided a clear visualization of illumination distribution patterns and helped identify low-light regions requiring corrective action.

The haul roads exhibited highly non-uniform illumination due to varying gradients, sharp bends, dust accumulation, and irregular spacing of lighting towers. Several road sections recorded illumination levels below the DGMS-prescribed minimum value of 10 lux. Such inadequate illumination significantly increases the risk of dumper collisions, road-edge accidents, and operator fatigue during night operations.

The coal stockyard areas also showed inconsistent lighting distribution because of the irregular geometry and height variation of coal piles ranging from 10 m to 30 m. Shadow formation around stockpiles created dark zones that impaired visibility and operational efficiency. The study observed that strategically positioned high-mast floodlights improved illumination uniformity and reduced shadow intensity.

Drilling and loading areas generally complied with DGMS illumination standards because these zones were equipped with machine-mounted lighting systems and portable floodlights. However, glare effects from improperly aligned floodlights caused visual discomfort for equipment operators in certain locations.

Maintenance workshops exhibited comparatively higher illumination levels because High Intensity Discharge (HID) lamps and metal halide lighting systems were installed to facilitate precision maintenance work. Adequate lighting in workshops improved visibility for inspection, repair, and assembly activities.

The generated lux contour maps proved highly effective in identifying dark zones and assessing illumination uniformity. These maps can serve as practical tools for mine managers and safety engineers in redesigning lighting systems and optimizing the placement of portable lighting towers.

The results further indicated that dust accumulation on lamp surfaces significantly reduced illumination intensity over time. In poorly maintained lighting systems, the maintenance factor (MF) decreased from approximately 0.8 to 0.6, leading to substantial deterioration in lighting efficiency.

7. CONCLUSION

The present study demonstrates that illumination surveys and lux contour mapping are highly effective tools for evaluating and improving lighting conditions in surface mines. Adequate illumination is essential not only for regulatory compliance but also for ensuring worker safety, operational efficiency, and equipment productivity during nighttime mining operations.

The survey findings revealed that although several operational zones complied with DGMS illumination standards, many haul road sections and stockyard areas suffered from inadequate lighting and poor illumination uniformity. Such deficiencies increase the risk of accidents, visual fatigue, and operational inefficiencies.

Lux contour mapping provided a scientific and visual method for identifying dark zones and evaluating the effectiveness of existing lighting infrastructure. The study concludes that periodic illumination assessments combined with modern lighting technologies can significantly improve safety standards in opencast mining operations.

8. Recommendations

The study recommends the strategic placement and relocation of portable lighting towers based on lux contour analysis to eliminate low-light zones in haul roads and stockyards. The adoption of LED-based lighting systems is also strongly recommended because of their higher luminous efficacy, lower power consumption, and longer operational life compared to conventional lighting systems.

Regular maintenance and cleaning of luminaires should be implemented to minimize illumination losses caused by dust accumulation. Additionally, periodic illumination audits should be conducted to ensure continued compliance with DGMS standards and maintain safe working conditions.

Future research may focus on integrating Geographic Information Systems (GIS), drone-based illumination monitoring, and smart sensor technologies for real-time lighting assessment in surface mines.

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